Nicoline Myhre Nedza

Dimensioning detention systems for small urban catchments

Suggestions for method improvements

Master's thesis in Civil and Environmental Engineering
Supervisor: Sveinung Sægrov, IBM
June 2019

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Nicoline Myhre Nedza

Dimensioning detention systems for small urban catchments

Suggestions for method improvements

Master's thesis in Civil and Environmental Engineering
Supervisor: Sveinung Sægrov, IBM
June 2019

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

The reason for this thesis being proposed was a Sweco employee's belief that Sweco might be over-dimensioning their detention systems. Thus, the aim became to validate this belief, and to explore alternative methods for dimensioning detention systems. In order to be considered by Sweco, these methods must produce credible results, whilst neither being too time-consuming nor overly complicated. To obtain a possible solution, the use of the software SCALGO and PCSWMM was evaluated, and the importance of runoff coefficients was assessed. All work was completed for the two detention systems *Christinedal* and *Siemens*, both located in urban Oslo. The main goal of the thesis was expressed in the primary research question as "In what ways could Sweco improve upon their dimensioning practice of detention systems". Finding a reliable answer to this question is important, as inadequate dimensioning of detention system can be costly, and should therefore be avoided if possible.

The results from SCALGO neither supported nor disproved the theory of over-dimensioning. The map-based software was used to identify a more accurate runoff contributing area than then the one used by Sweco in their dimensioning. This was done by regarding flow contribution to different locations on the properties. However, for both *Christinedal* and *Siemens*, the area sizes found in SCALGO were similar to those used by Sweco, and thus, the improved results from SCALGO did not have a significant impact on the detention system volumes. Hence, the results produced in SCALGO were neutral regarding the question of over-dimensioning, although the runoff contributing area found was deemed useful as a basis for evaluating the importance of runoff coefficients and for modelling in PCSWMM. Therefore, the use of SCALGO was identified as a possible way for Sweco to improve their dimensioning practice.

Runoff coefficients were found to have great influence on the detention system volume when using Sweco's dimensioning method. A coefficient-increase from 0.4 to 0.5 could potentially cause a 49% increase in volume, and according to findings, such a disparity between selected and actual runoff coefficients is possible. Detailed assessments of the properties were completed to assign fitting runoff coefficients to the different sub-areas. The values were based on guideline values and hydrological consideration. The area averaged runoff coefficients derived were significantly smaller than the ones used by Sweco, which resulted in a 20% and 40% reduction in detention system volumes for *Christinedal* and *Siemens*, respectively. Hence, this analysis supported the belief of over-dimensioning. Although the runoff coefficients found by the author were not necessarily more precise than the ones used by Sweco, the analysis proved the runoff coefficients' importance.

The results from PCSWMM would support the notion of over-dimensioning. The runoff contributing areas and drainage systems connected to *Christinedal* and *Siemens* were modelled in PCSWMM, and several data series representing rainfall events with a 20-year return period were simulated. The simulated maximum volume in the detention system for any of the rainfall events was 73.3% and 69.3% of the actual designed and constructed volume for *Christinedal* and *Siemens,* respectively. Hence, the volume results from PCSWMM and Sweco's dimensioning method differed significantly, and since PCSWMM is thought to be more accurate, switching dimensioning method could be an improvement for Sweco. To obtain similar volume results in Sweco's method as in PCSWMM for both

Christinedal and *Siemens*, permeable and impermeable runoff coefficients of approximately 0.1 and 0.83, respectively, would have to be utilised, contrary to Sweco's common values of, respectively, 0.3 and 0.9.

Based on the findings of this thesis, it is advised that Sweco make changes to their current method of dimensioning. The primary suggestion is a shift towards a model-based method, as this has been found to yield the most trustworthy results. However, if this option is not opted, it is advised that Sweco lower the runoff coefficients they commonly use, to values more similar to those found in this thesis, i.e. 0.1 and 0.83 for permeable and impermeable surfaces, respectively. However, any changes should be made on a trial-basis, and the new method's accuracy, difficulty-level and time requirements should be evaluated once more information is available. Additionally, more data should be gathered to support or disprove the suggested runoff coefficients. The task of estimating stormwater runoff is a difficult one, and with the time available to a company such as Sweco, a certain level of error and uncertainty is unavoidable. Therefore, the proposed suggestions might be improvements, although none of them can guarantee flawless results, free of uncertainty.

Sammendrag

Bakgrunnen for denne masteroppgaven er en mistanke om at flere av Sweco sine fordrøyningsmagasiner i Oslo er overdimensjonert. Denne mistanken ble fremsatt av en av Swecos ansatte sommeren 2018, og vedkommende fremmet et ønske om å utforske dette videre. Oppgaven har derfor blitt skrevet med formålet om å bekrefte eller avkrefte denne mistanken, og samtidig identifisere mulige forbedringsområder ved Swecos dimensjoneringsmetode. Dette er en viktig oppgave, ettersom over- og underdimensjonering av fordrøyningsmagasiner er kostbart og derfor bør unngås. Eventuelle endringer i metoden må kunne resultere i troverdige resultater, i tillegg til å være enkel og rask nok til å kunne brukes av Sweco. For å komme frem til mulige forbedringsområder ble dataprogrammene SCALGO og PCSWMM tatt i bruk, og avrenningskoeffisienter ble evaluert i detalj. Arbeidet tok for seg de to fordrøyningsmagasinene *Christinedal* og *Siemens*, som begge ligger i urbane strøk i Oslo.

Resultatene fra SCALGO hverken støttet eller avkreftet mistanken om overdimensjonering. Den kartbaserte programvaren ble brukt til å identifisere et bedre anslag for avrenningsområdet tilknyttet fordrøyningsmagasinene enn det som ble brukt i Swecos dimensjonering. Dette ble oppnådd ved å betrakte estimert avrenning på området rundt *Christinedal* og *Siemens*. Det viste seg derimot at arealanslaget for begge magasinene var relativt likt det som ble benyttet av Sweco, og arealvalg hadde dermed lite betydning på dimensjonert magasinvolum. Til tross for dette, ble det nye avrenningsområdet ansett som nyttig i videre arbeid med avrenningskoeffisienter og modellering i PCSWMM. Av den grunn, ble bruk av SCALGO erkjent som en potensiell måte for Sweco å forbedre dimensjoneringspraksisen sin på.

Avrenningskoeffisienter har stor innflytelse på det dimensjonerte magasinvolumet ved bruk av Swecos dimensjoneringsmetode. Det ble vist at ved å øke den gjennomsnittlige avrenningskoeffisienten fra 0.4 til 0.5 vil magasinvolumet kunne øke 49%, og at et slikt avvik mellom estimert og faktisk avrenningskoeffisient ikke er usannsynlig. Det ble fullført detaljerte evalueringer av avrenningsområdene, og passende avrenningskoeffisienter ble angitt for de ulike delområdene basert på litteraturanbefalte verdier og overveielse av hydrologisk påvirkning. De gjennomsnittlige avrenningskoeffisientene som ble bestemt resulterte i henholdsvis 20% og 40% mindre volum for *Christinedal* og *Siemens*, enn ved bruk av Swecos verdier. Selv om avrenningskoeffisientene som ble funnet i denne oppgaven ikke nødvendigvis er mer presise enn de som ble brukt av Sweco, underbygde evalueringen påstanden om viktigheten av korrekte avrenningskoeffisienter. I tillegg støttet den mistanken om overdimensjonering.

Resultatene fra PCSWMM indikerte også at de dimensjonerte volumene til *Christinedal* og *Siemens* er for store. Avrenningsområdet og dreneringssystemet til de to fordrøyningsmagasinene ble modellert i programmet, og en rekke nedbørshendelser med en returperiode på ca. 20 år ble simulert. Det simulerte maksimumsvolumet var henholdsvis 73.3% og 69.3% av det faktiske volumet for *Christinedal* og *Siemens.* Dermed var det stor forskjell mellom resultatene fra PCSWMM og Swecos dimensjonering. For å oppnå like volum som dette ved bruk av Swecos dimensjoneringsmetode for begge fordrøyningsmagasiner samtidig, må permeable og impermeable avrenningskoeffisienter på henholdsvis 0.1 og 0.83 tas i bruk, kontra 0.3 og 0.9 som ble brukt av Sweco. Siden resultatene fra PCSWMM er ansett for å være mer nøyaktig, er et bytte til modelleringsprogrammet betraktet som et mulig forbedringsområde for Sweco. Dersom dette derimot ikke skjer, er en reduksjon av avrenningskoeffisientene også betraktet som en mulig forbedring.

Basert på funnene i denne oppgaven anbefales det at Sweco foretar endringer med tanke på deres nåværende dimensjoneringsmetode. Hovedforslaget er at de tar i bruk en modell-basert metode som PCSWMM, da disse resultatene er å anse som mest troverdige.

Alternativt anbefales det at de senker avrenningskoeffisientene de normalt bruker, til verdier mer like de som ble angitt i denne oppgaven, nemlig 0.1 for permeable områder og 0.83 for impermeable områder. Uansett hvilke endringer som velges bør de først gjennomføres som en prøveordning, slik at den nye metodens nøyaktighet, vanskelighetsgrad og tidsbruk kan vurderes på ny før den brukes fast. I tillegg bør mer data innhentes for å støtte eller undergrave avrenningskoeffisientene som ble foreslått i denne oppgaven. Å beregne overvannsavrenning er vanskelig, og med tanke på den begrensede tiden som ofte er tilgjengelig for rådgivende ingeniører, vil en viss grad av usikkerhet være uunngåelig i slike beregninger. På grunn av dette ansees de forslåtte endringene som forbedringer i forhold til nåværende metode, men de kan derimot ikke garantere feilfrie resultater.

Preface

This thesis was conducted at the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology, NTNU Trondheim, and signifies the conclusion to a five-year master's degree programme. The thesis explores ways in which the consultancy company Sweco can improve upon their dimensioning practice of underground detention systems.

The topic of stormwater detention system dimensioning was decided upon due to a summer internship with Sweco the summers of 2017 and 2018. A company employee expressed his suspicions about the accuracy of their stormwater detention system dimensioning, and a wish to investigate this further. Thus, this thesis was written with the aim of supporting or disproving this belief, in addition to seeking potential areas of improvement.

I would like to extend my sincere gratitude and appreciation to those who have motivated and helped me in my work. Firstly, thank you to Øystein Rapp, who gave me the opportunity to work on such an interesting topic, and who acted as my supervisor at Sweco. He provided great help with obtaining necessary data for the stormwater detention systems and answered any questions I might have. Thank you to Sweco for providing the equipment needed to conduct detention system monitoring, and for lending me the tools necessary for completing my thesis. Thank you to Sveinung Sægrov, my primary supervisor at NTNU, who guided me during this writing process, and read though my work in order to provide helpful constructive criticism. Thank you to Marius Møller Rokstad, who guided me on how to use PCSWMM and helped me improve upon my models. Lastly, thank you to Anders Vatland, who endured countless hours of listening to me yap about a topic he has no interest in whatsoever.

Roses are red
Violets are blue
Here is my thesis
I'm finally through

Table of content

Figures

Tables

Initialisms

IDF Intensity-Duration-Frequency

NEA Norwegian Environment Agency (Miljødepartementet)

NW Norwegian Water (Norsk Vann)

SWWA Swedish Water & Wastewater Association (Svensk Vatten)

NPRA Norwegian Public Roads Administration (Statens Vegvesen)

NGU Norwegian Geological Survey (Norges Geologiske Undersøkelse)

1.Introduction

Stormwater runoff is water that runs off roofs, roads, and other impervious surfaces during a precipitation event (Ødegaard, 2014:31), and climate change and urbanisation are two leading causes of accelerated amounts. Stormwater runoff can be handled locally or collected and transported away in drainage systems. However, if it is not handled in a proper manner and the volumes exceed the drainage system's capacity, urban flooding can occur. Urban flooding is a serious problem that can have adverse impacts on environment, economies, and human health, and should therefore be avoided if possible.

Due to the array of potential problems associated with stormwater, multiple local solutions have been established with the aim of minimising urban flooding. An example of one such solution is underground detention systems, which are large containers that collect and detain stormwater during the occurrence of a precipitation event. Sweco is a company that has designed many such systems in the Oslo area, and in the summer of 2018, they proposed an inquiry into the accuracy of their dimensioning. The hypothesis was that their dimensioning method yielded detention system volumes larger than what they aim to dimension for. Correct dimensioning is important as under-dimensioning can lead to urban flooding and its associated consequences, whilst over-dimensioning leads to unnecessarily high costs. With this in mind, the author wrote a specialisation project seeking to determining whether three of Sweco's detention systems were properly dimensioned. This was done by recording precipitation and water levels for the three systems, and re-dimensioning them for the observed events using the same method, to compare expected and observed volumes. The results pointed to the conclusion that two of the detention systems were over-dimensioned, whilst the third was under-dimensioned.

Unfortunately, the results from the specialisation project were deemed unreliable, as the transferability of results from small events to large events was hard to determine. The largest event observed in the fall of 2018 had a return period of approximately one year, whilst the detention systems were all dimensioned for 20-year return periods. Since larger events produce a higher percentage of runoff per amount of rainfall, we cannot directly apply the conclusion from a 1-year return period to a 20-year return period. The author still stands by the conclusion that two detention systems were over-dimensioned whilst the third was under-dimensioned, however, the magnitude of the erroneous volumes is unknown due to the transferability issues. Therefore, this thesis will seek to find other ways of evaluating the dimensioning of the existing detention systems, and to find ways of improving the dimensioning method of future detention systems.

As it was stated in the very last sentence of the specialisation project: The objective of future work should be to find a method and procedure that optimises accuracy of the solution, a feasible level of complication in terms of who will be using the method, and time needed to obtain the results (Nedza, 2018). This will be the primary aim of the current thesis. Heeding the suggestions from the specialisation project, we will be exploring some of the factors that could influence the results, such as the method being used and the procedure for obtaining input to the method. We will also focus on exploring how much the selection of runoff coefficients and area influence the results, how to better obtain these values, and whether there are other methods for dimensioning detention systems. This will be done by introducing two new software tools; SCALGO and PCSWMM. The former will be used in relation to area selection, and the latter for improving upon the method.

To summarise the purpose of the thesis, the research questions are stated below. The first three are secondary questions that will be evaluated by themselves, whilst simultaneously providing input to the final and primary question. The last question summarises the main purpose of the thesis. It is broad and can therefore be answered in multiple ways. The questions are as follows:

1. Can the software tool SCALGO be used to improve upon the identification of runoff contributing area when dimensioning detention systems?

2. How influential are the runoff coefficients on the final volume results when using Sweco's former dimensioning method?

3. Can modelling in PCSWMM yield better detention system volume results than Sweco's already existing method? And if so, is the time and skills needed to model in PCSWMM at an acceptably low level for it to be a feasible alternative for Sweco?

4. In what ways could Sweco improve upon their dimensioning practice of detention systems?

This paper will start by assessing background information related to the topic, either to support its importance or to give an introduction into topics that will be discussed further. Thereafter, hydrology will be reviewed to see what hydrological processes affect runoff and consequentially, the runoff coefficient. This knowledge will be used as input when selecting new runoff coefficients, and aid in the determination of parameter values in PCSWMM. Following this, the software tool SCALGO will be used to analyse stormwater runoff on the properties and to determine the runoff contributing areas of the detention systems. Finally, the newfound area will be modelled in PCSWMM to examine what storage volume is yielded with a more comprehensive runoff model. Once all this work is completed, the research questions will be discussed and eventually answered.

2.Background

Parts of this section will be close to a reiteration of the introduction of the specialisation project, which was written by the author in the fall of 2018. The information has been repeated due to its significance, as many of the topics are considered imperative for understanding the necessity of this work. Therefore, sections 2.1 through 2.8, as well as 2.9, are referenced to Nedza (2018:1-3).

2.1 Climate change

The climate is changing. This is agreed upon amongst most climate scientists, and the changes occurring in Norway are thoroughly assessed in the report *Climate in Norway 2100* (Klima i Norge 2100) (Hanssen-Bauer, 2015). The most important changes pertaining to this thesis are the changes to precipitation, both in frequency and intensity. In the future, both yearly precipitation, number of days with heavy rainfall and the amount of rain on days with heavy rainfall are predicted to increase in Norway. Especially short duration, high intensity rainfall will increase significantly. This change is important for stormwater management, as high intensity storms with short durations produce more runoff and are more likely to induce urban flooding than long duration rainfall events with the same depth of water (Guan et al., 2015:555)

2.2 Urbanisation

In earlier times, Norwegian settlement was characterised by scattered settlements in the countryside (Thorsnæs, 2018). However, in the 19th century, an increase in urban settlement began. This development continued, and from 1950 to 2016 the percentage of the population living in urban areas increased from 51% to 81%. This trend is predicted to continue, and according to the Norwegian statistics bureau (SSB), the population growth in Norway from 2018 to 2040 will primarily occur in urban areas (Leknes, 2018). Unfortunately, urbanisation has drawbacks, some of them relating to water management and water infrastructure. To better understand these effects, we should first understand the simplified water balance equation, which is stated below (Ødegaard, 2014:44). As can be seen from the equation, the amount of runoff (Q) that is generated is dependent on precipitation (P), evapotranspiration (E_t) and changes in storage (S).

$$Q = P - E_t \pm \Delta S$$

According to Davie (2008:180), runoff is defined as "The movement of liquid water above and below the surface of the earth prior to reaching a stream or river". However, in this thesis, only overland flow will be referred to when using the term runoff. This is because it is the above-surface stormwater runoff that is of interest when regarding stormwater detention systems, as this is the water with the potential to cause flooding. Therefore, infiltration to the ground, which is an important process in this thesis, is included in the storage term of the water balance equation, rather than the runoff term.

The water balance in urban areas and natural sites differ significantly (NVE, 2018). A result of urbanisation is increased runoff due to the changes to surface cover, which influences the infiltration rate. For example, a lush forest will infiltrate a much larger portion of water than a concrete parking lot. Hence, urbanisation, which consequentially means more impervious surfaces, will lead to more runoff (NVE, 2018). In addition to reduced infiltration rates, evapotranspiration is also reduced, thus also causing more runoff (NVE, 2018). These effects are represented by Figure 2.1 below, as it illustrates infiltration, evapotranspiration, and runoff for varying degrees of urbanisation.

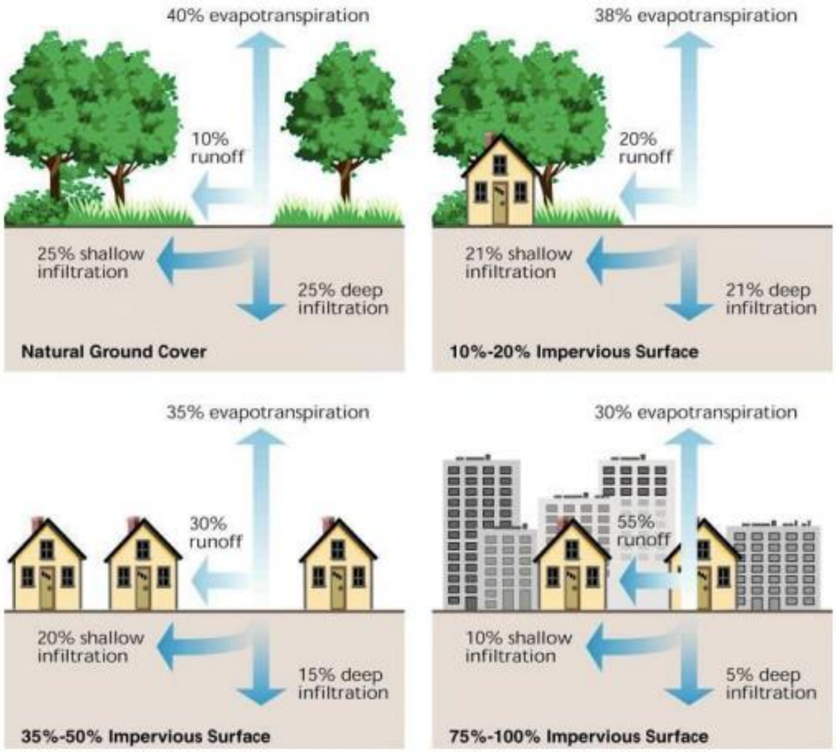


Figure 2.1 Effects of urbanisation on infiltration, evapotranspiration and runoff (FISRWG, 1998:3-23).

Another way of representing the runoff changes due to urbanisation is by studying the hydrograph of a rainfall event. With increasing urbanisation, the peak flow of the rain event will increase, whilst the time to the peak of the flow will decrease (Ødegaard, 2014:53).

2.3 Stormwater

Traditionally, stormwater in Norway has been dealt with by guiding it to closed sewerage pipe systems and transporting it either directly to a recipient or to a wastewater treatment facility (NOU, 2015:65). However, a consequence of increased stormwater runoff is that many pipes will no longer have adequate capacity to transport all the wastewater during heavy rainfall events (Lindholm, 2018). This could lead to untreated and polluted water being released into recipients such as streams, rivers and the Oslo fjord. As well as pollution, a limited pipe capacity could also lead to flooding, erosion or damages to infrastructure, houses or cultural treasures (NOU, 2015:34). Hence, the consequences of these occurrences can be both environmental, economic, and health-related, and this is the reason why stormwater management is of the utmost importance.

Although some pipes are not dimensioned to handle excessive amounts of stormwater, an upgrade in diameter might not always be the most cost-effective solution (Lindholm, 2018). In this case, one should consider local stormwater management practices to mitigate potential damages. Stormwater is then handled in some way other than transporting it to wastewater pipes, by instead utilising for example green roofs, rain gardens or open or closed stormwater detention systems (NOU, 2015:68).

2.4 Three-Step Strategy

As a means of alleviating runoff in the future, Oslo municipality has chosen to follow a three-step strategy for handling stormwater (Oslo Municipality, 2013). This model was presented by Lindholm in 2008 and utilises the concept of local stormwater management. The three steps of the strategy are depicted in Figure 2.2 below. The first step is to capture and infiltrate the water, the second is to delay and detain, and the last step is to secure safe flood paths. What measure is to be adopted depends on locally determined threshold values for precipitation (Ødegaard, 2014).

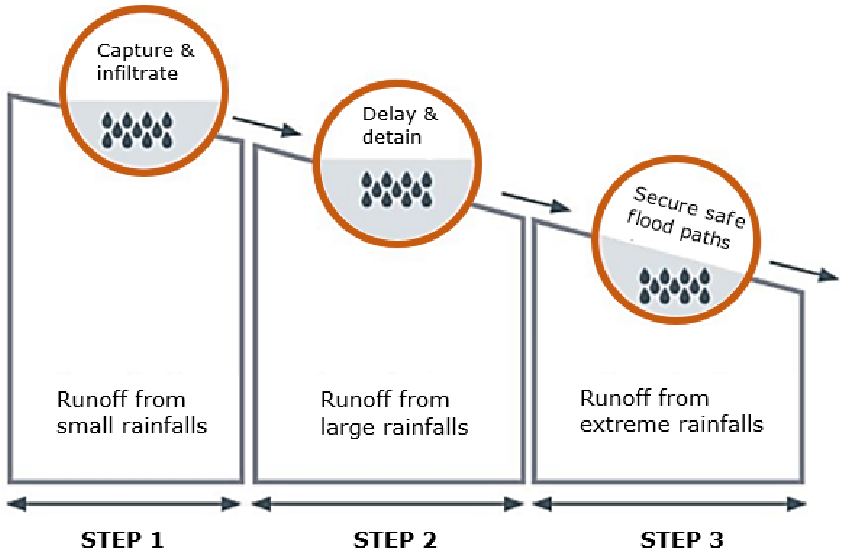


Figure 2.2 Three-step strategy for handling stormwater. The illustration is taken from Åstebøl et al. (2017:17) and translated from Norwegian to English.

2.5 Underground stormwater detention systems

Underground stormwater detention systems are the most widely used solution for local stormwater management today (Ødegaard, 2014), and there have been built many such systems in the last 10-15 years. This solution is an example of the second step in the aforementioned three-step strategy, namely delay and detain.

Simply put; an underground stormwater detention system is a large tank of some sorts that collects and detains water. This way, excess stormwater can be stored safely until the rain event has abated, and at which point, it can be released onto the municipal wastewater network in a controlled manner. As long as the input of stormwater is greater than the release onto the municipal network, or until the system reaches its maximum capacity, water accumulates in the tank. Once the stormwater generation slows down and comes to an end, the water level in the detention system will start to decline. Such systems serve the function of preventing physical damage caused by excessive amounts of water, as well as dampening the effects of pollutant first flush. For additional information on different types of underground stormwater detention systems, along with their benefits and disadvantages, it is recommended to look to the specialisation project (Nedza, 2018:5-8).

Sweco is a company that has designed many underground stormwater detention systems in the Oslo area. For the dimensioning of the systems they use a spreadsheet template that they have created based on the rational equation for runoff. Their current template is based on the Aron & Kibler method described in VA-Miljøblad no. 69, whilst they previously used a similar method based on constant outflow.

2.6 Rational equation

The traditional method for calculating surface runoff for catchments less than 20-50 hectares is the rational equation. It gives the "worst case scenario" for a catchment, i.e. the peak flow for the specific parameter values. The equation can be expressed as,

$$Q = \varphi * A * I(*K) ,$$

where Q is runoff, φ is the runoff coefficient, A is the runoff area, I is the precipitation intensity (Ødegaard, 2014:306), and K is the climate factor which is sometimes included to account for future changes to precipitation intensity. The rational equation is a gross simplification of a complicated process, and the results are therefore more valid for small catchments with somewhat regular shapes. It is assumed that the same rainfall intensity applies for the entire catchment and for the whole duration of the rainfall event, a fact which we know not to be true. There is also great uncertainty regarding the runoff coefficient, as it depends on numerous processes and varies both spatially and temporally for a catchment. It might therefore be hard to estimate correctly. The runoff area can also be complicated to predict, despite methods for determining this. It requires consideration of the terrain slope and an understanding of where the runoff travels. In urban areas we have the added elements of manholes and pipe-networks, which collect and store stormwater, and thus complicate the runoff area estimation.

2.7 SCALGO

The computer tool SCALGO will be used to analyse the movement of water on the surface. According to SCALGO's web page, SCALGO Live Flood Risk can be used to "…map the flood risk from sea, in depressions or from watercourses to get an overview of the combined flood risk of a property, a neighbourhood or an entire municipality". It completes these hydrological analyses by using an elevation model of Norway, which is based on data from the Norwegian Mapping Authority. However, since the tool neither includes infiltration and evaporation losses, nor any manholes or pipe networks, SCALGO has been considered to be of limited help with quantitatively estimating a fitting detention system volume. It has however, been deemed a helpful tool in determining waterways, and to better understand the conveyance of water on the assessed properties. This can further be used to determine the area contributing runoff to the detention systems and their accompanying drainage systems. Therefore, SCALGO will in this thesis be used to determine the runoff contributing area that should have been utilised when dimensioning the detention systems.

2.8 Specialisation project

With the aforementioned information in mind, in the fall of 2018, the author wrote a specialisation project pertaining to Sweco's dimensioning practice of stormwater detention systems. The purpose was to determine whether the dimensioning practice currently used by Sweco is an accurate one. In order to do so, three already-constructed detention system, all designed by Sweco, were implemented with devices to measure water level in the detention systems and precipitation on the property. For seven different rainfall events, the maximum observed storage volume was found. Using IDF-values for the measured rainfall events, the supposed necessary storage volume for each rainfall event was determined using Sweco's dimensioning procedure. Thus, the observed and would-be dimensioned values could be compared, to evaluate whether Sweco's method resulted in accurate dimensioned storage volumes for the recorded events.

The results showed great inconsistency when comparing observed and dimensioned volumes. Two of the detention systems appeared to be over-dimensioned, with observed volumes only 3-20% of the dimensioned volumes for each event. The third detention system was however under-dimensioned, with observed volumes ranging from 180-800% of the dimensioned volumes. Thus, despite all three systems being dimensioned using the same method, the results differed significantly. Based on this, the conclusion was that Sweco's method is somewhat unreliable, and that the volumes yielded cannot be said to be neither consistently over-dimensioned, under-dimensioned nor perfectly dimensioned. Several different reasons for the varying results were suggested in the specialisation project, such as the method lacking representation of hydrological processes, wrongful or oversimplified method, or oversimplified procedure for obtaining input data to the method. Hence, it was the results from the specialisation project that gave the inspiration and basis for the thesis at hand. As stated in the introduction, the aim of this thesis is to look at one or more of these factors, and to come up with suggestions for how Sweco can improve upon their dimensioning method.

Since the results from the specialisation project are referenced in the thesis, it is important to comment on the most significant limitation of the specialisation project. Despite a conclusion being made about the detention system's dimensioning accuracy, it should be noted that there is great uncertainty related to these results, due to the issue of transferability of results from small to large rainfall events. For a 20-year rainfall event, a much larger percentage of the total rainfall will become runoff, since there is a limit to how much water can be infiltrated, intercepted, and retained in depression storage. Sweco dimension for 20-year return periods, however, the largest rainfall event that was recorded in the fall of 2018 had a return period of approximately one year. As was pointed out by a Sweco representative, for such small rainfall events, the aim is usually to capture and infiltrate the water locally in accordance with the first step of the three-step strategy. Thus, the assumption is that a significant portion of the rain from the recorded events infiltrated instead of becoming runoff. This suggests that the transferability of the results is questionable, as we are not able to quantify the difference in percentage of rainfall that becomes runoff for small and large events.

2.9 The detention systems

Due to the continuation of work with two of the detention systems that were evaluated in the specialisation project, it is deemed beneficial to summarise some of the key features of Sweco's detention systems and their surrounding properties. For more extensive information on how Sweco dimensions detention systems and on the three detention systems mentioned, it is recommended to look to the specialisation project being referenced. This section will only contain reiterations of information revealed in the specialisation project, whilst more details about the detention system areas will be uncovered and analysed in later sections of the paper. The properties associated with two of the detention systems are shown in Figure 2.3 below, where the left map shows the property and corresponding property boundary at *Christinedal* and the right shows the property and corresponding property boundary at *Siemens*.

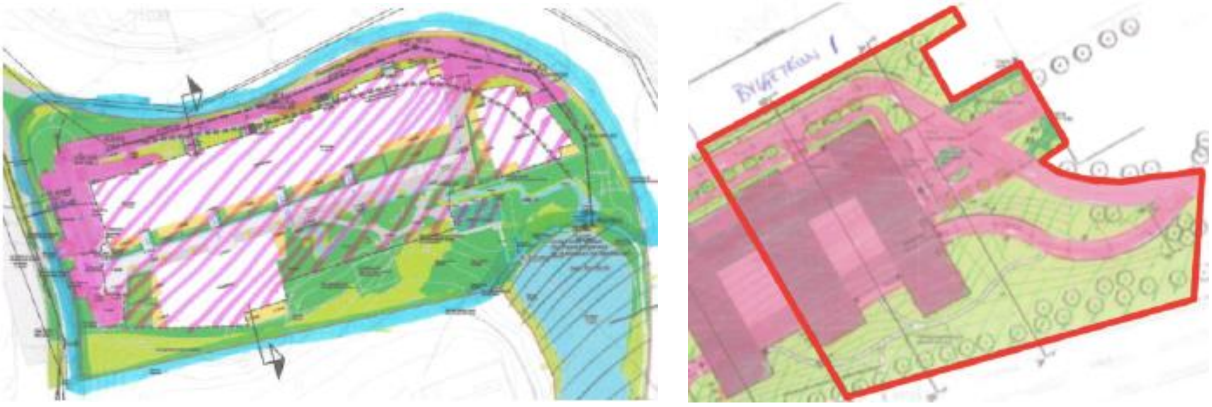


Figure 2.3 The properties associated with the two of the detention systems. Left is Christinedal and right is Siemens.

2.9.1 Christinedal

Christinedal is an underground detention system of the type geocellular storage, located at Bryn in Oslo. On the *Christinedal* property there are three apartment buildings, surrounded by a combination of green permeable landscape and impermeable surfaces. The detention system has been constructed at the lowest section of the property, and from this point, the elevation rises in the southern and eastern directions. The total volume of the constructed detention system is 100.9 m^3. The flow out of the detention system is regulated by a vertical vortex valve, with a maximum outflow allowance of 25 l/s.

When dimensioning, Sweco divided the property into two subareas; impermeable surfaces measuring at 4942 m^2 and permeable surfaces at 2960 m^2. With a runoff coefficient of 0.9 for the impermeable area and 0.3 and 0.15 for each half of the permeable area, the resulting runoff-contributing area was 5053 m^2. In their dimensioning calculations, Sweco used an IDF-curve from Blindern in Oslo, a return period of 20 years and a climate factor of 1.1. The dimensioning also used the 25 l/s maximum outflow allowance as a parameter. All this information was plotted into their dimensioning template, and it was found that the maximum filling is predicted to occur for a rainfall with a 30-minute duration, yielding 99 m^3 of water stored.

Results from the specialisation project pointed towards the notion that the detention system *Christinedal* is over-dimensioned for a 20-year rainfall event. For the largest of the six rainfall events recorded, the percentage of observed volume ranged from about 2-5% of the dimensioned volume for the given rainfall events. In fact, the water level measurements proved that the detention system never served its purpose, as the volume only filled the outlet chamber, and never the detention system itself. Thus, either less water reaches the detention system than what one would expect, pointing to errors in the dimensioning criteria or construction of the drainage system, or the rainfall events recorded were small enough that nearly all the water was captured and infiltrated. If the latter is the case, one could consider this a good thing, as it proves that the first step of the three-step strategy was successful for these small events. However, this once again points back to the dilemma about the transferability of the results from small to large events.

2.9.2 Siemens

The detention system *Siemens* is located at Holtset in Oslo, on the border between an industrious area and an urban living area. The dimensioned property consists of a large office building, paved roads and parking lots, as well as areas covered with tall grass and sparse bushes. The property is characterised by steep slopes both north and south of the office building, which both have permeable surfaces. The detention system is located in the south-eastern corner of the property, under sloping terrain, and is built up of two large concrete pipes. The total volume of the detention system is 223 m^3, and the outflow is regulated by a vertical vortex valve which allows a maximum outflow of 6.5 l/s.

As is their custom, Sweco divided the property into two subareas; 5900 m^2 impervious surfaces, given a runoff coefficient of 0.9, and 5655 m^2 pervious green surfaces, given a runoff coefficient of 0.3. This yielded a runoff contributing area of 7007 m^2. The IDF-curve, return period and climate factor were the same as for *Christinedal*; Blindern, 20 years and 1.1, respectively. Along with the maximum outflow of 6.5 l/s, the values were put into the dimensioning template, resulting in a maximum necessary storage of 223 m^3, occurring for a rainfall duration of 90 minutes.

In likeness to the detention system *Christinedal*, also *Siemens* was determined in the specialisation project to be somewhat over-dimensioned. For the six rainfall events that were assessed, the percentage of observed volume ranged from about 10-19% of the volume dimensioned for the given rainfall events. The largest observed volume, 8.33 m^3, is only 3.8% of the total detention system volume. Hence, this points to the notion of an over-dimensioned detention system, though once again, the transferability of results is uncertain.

2.9.3 Grefsen

The detention system *Grefsen* was the only one concluded to be under-dimensioned, as the filling degree was greater than what was expected for the observed rainfall events. Unfortunately, there is not enough available information to assess the area, as there is insufficient data on the drainage system's placement and elevation. Ideally, this detention system would have been included in the thesis to provide more support for the final conclusion, especially since the perceived accuracy of *Grefsen*'s dimensioning differs from the other two. However, due to the circumstances, further work with *Grefsen* is impossible and will not be conducted.

3.Theory: Hydrology and runoff coefficients

When dimensioning detention systems, there is a need for estimating the amount of precipitation that is converted to runoff, so that we can estimate the stormwater volume that must be collected and dealt with locally. However, this is a complicated task, seeing as many hydrological processes affect runoff generation, and since hydrological conditions vary both spatially and temporally. Since knowing how to properly estimate runoff is of high interest and importance, a literature review of this topic is included in the thesis. First, general information about runoff coefficients will be introduced, followed by literature on hydrology. Lastly, runoff coefficients will be discussed again, this time in relation to the reviewed literature.

3.1 Runoff coefficients – Introduction

One way of describing runoff generation is by the dimensionless runoff coefficient, denoted φ, which is included in the rational equation. The runoff coefficient relates precipitation received to the amount of runoff generated (Ødegaard, 2014:48). Thus, it encompasses the hydrological effects of infiltration, evapotranspiration, interception, and retention, amongst others (UDFCD, 2016), and will be affected by the slope of the catchment, soil type, vegetation type, and antecedent condition, which all influence these hydrological processes. The runoff coefficient is given a value between 0 and 1, where 0 describes a permeable surface where none of the water becomes runoff, whilst 1 describes a highly impermeable surface where all the received rainfall becomes runoff (Ødegaard, 2014:306). Typically, grassy and forested areas have a lower number, whilst asphalt roads and tiled rooftops have a higher number. Selecting a coefficient is not always an easy task, and it requires judgement based on understanding and experience from the engineer (UDFCD, 2016). To obtain a better understanding of the complexity of this selection process, we will be looking further at some of the above-mentioned hydrological processes involved, starting with infiltration.

3.2 Infiltration

Infiltration is the process in which water penetrates the soil through the surface and travels vertically through the soil profile (Ødegaard, 2014:44). The rate at which water infiltrates is dependent on how much water is currently in the soil, as well as the ability of the soil to transmit the water (Davie, 2008:58). The minimum infiltrability of a soil is approximately equal to its saturated hydraulic conductivity (Dingman, 2015:357), which is in turn affected by grain shape and size, as well as grain distribution in the soil. Larger grains with more irregular shapes that are well-sorted, result in larger pores, and thus allow for more movement of water (Dingman, 2015:314).

3.2.1 Soil structure

There are many factors affecting the porosity, and thus the saturated hydraulic conductivity of a soil. Vegetation has a positive influence on porosity due to root growth and decay, which creates pores in the soil that allow for movement of water. Vegetated areas might also be covered by leaf litter, humus and other organic matter that has a high hydraulic conductivity. Additionally, areas such as these could likely be habitats for worms, soil insects and burrowing mammals, which also increase the porosity of the soil (Dingman, 2015:358). Hence, vegetation is considered to increase the infiltrability of a soil. However, there are many ways in which the porosity and infiltrability of a soil could *decrease* also, some of these being rain compaction/clogging, in-washing of fine sediments or anthropogenic influences.

Clogging or rain compaction is when the impact of raindrops deforms the arrangement of soil particles. This compacts the soil on the surface, and thus creates a seal that reduces infiltration into the ground. The effect of clogging is dependent on the kinetic energy of the raindrops (Dingman, 2015:358). In-washing is when fine sediments travel into larger pores, reduce the pore sizes, and thus lead to a decrease in the hydraulic conductivity of the soil (Dingman, 2015:358). It occurs either when there is surface erosion or when mineral grains are brought into suspension by splashing of raindrops. Both clogging and in-washing are more common on soils with sparse vegetative cover.

There are several ways in which humans can modify and change the soil structure. One example of this is by compaction, which could occur for several reasons, such as for example grazing livestock in agricultural areas or by heavy machinery operating on construction sites. The compaction of the soil results in reduced porosity and reduced infiltrability. Human modification could also be more direct, such as changing the nature of the surface, e.g. paving roads or replacing forests with suburban housing. All these factors will influence the runoff generation at the onset of a rainfall event. Soil modification will be a significant factor concerning the properties being assessed in this thesis.

3.2.2 Overland flow

In relation to infiltration, runoff generation, or overland flow, can occur in one of two ways; saturation from above or saturation form below (Dingman, 2015:355). The first process, saturation from above, was hypothesised by Horton, and is therefore sometimes called Hortonian overland flow. In this case the water-input rate exceeds the surface saturated hydraulic conductivity of the soil, and thus, water starts to pond and form runoff. Another common name for this flow type is infiltration-excess overland flow (Davie, 2008:80). In the case of saturation from below, ponding and runoff generation occurs due to the ground being saturated and the water table rising to the surface. Once this happens, runoff can be generated due to either water-input in the form of rainfall, or by return flow from the ground. This type of overland flow is referred to as saturated overland flow and was first suggested by Hewlett and Hibbert in 1967. It is possible for both types of overland flow generation to occur at the same time.

An aspect of Horton's hypothesis that has later been modified is the spatial variability in contribution of overland flow. Horton postulated that infiltration-excess overland flow would occur for the entire watershed, and that the water would travel across the surface as a thin sheet of water (Davie, 2008:80). However, this is not usually the case, and alternative hypotheses have since been contemplated. In 1964, Betson came up with what is referred to as the partial areas concept, which states that only parts of the watershed contribute overland flow to a storm hydrograph. Hewlett and Hibbert took this concept even further, and in 1967 they proposed that as well as partial area response of a catchment, the response of the catchment is variable in both space *and* time. This is referred to as the variable source areas concept and is considered to be the most accurate one in terms of describing stormflow processes (Davie, 2008:81). Nowadays aspects of both Horton's and Hewlett and Hibbert's hypotheses are accepted. Both types of overland flow generation can occur, however infiltration-excess overland flow is often more important where human modification has reduced the infiltrability of the soil or for impermeable areas (Dingman, 2015:481), whilst saturated overland flow occurs where the infiltrating water is hindered by a water table, an underlying impervious layer or a decrease in hydraulic conductivity (Dingman, 2015:483). In relation to the two properties being assessed, both types of overland flow might be relevant, as reduced infiltrability due to human modification is likely, as well as the possibility of underlying parking garages acting as underlying impermeable layers.

3.2.3 Slope and roughness

Slope is one of the factors often mentioned as having an influence on the runoff coefficient. However, there appears to be no exact agreement of what this effect is or its magnitude. In the paper written by Huang, Wu and Zhao (2013), literature on the topic was reviewed, and the conclusion was that there is no strong consensus regarding the effects of slope on runoff. Numerous articles were considered, some finding a positive correlation between slope gradient and runoff, some finding a negative correlation, and some finding no correlation at all. An argument for the negative correlation was that a higher slope gradient yielded less clogging because of the lower kinetic energy per unit surface area being hit by rain, thus more easily allowing for infiltration into the ground. Arguments for a positive correlation were for example decrease in depth of overland flow, reduced surface storage with increasing slope gradient, or less time for infiltration to occur because of higher flow velocities. Despite the uncertainty presented in this article though, in Dingman (2015:358) it is stated that overland flow increases with increasing slope, and no uncertainty about this is mentioned.

In contrast to its positive relationship with slope gradient, runoff generation *decreases* with increasing surface roughness (Dingman, 2015:358). In likeness to slope, the roughness of the surface influences the speed of overland flow, which in turn affects the amount of water that can infiltrate into the soil. The smoother the surface, the faster the runoff can flow, allowing less time for infiltration. As well as affecting the runoff velocity and infiltration, roughness and slope also affect the depression storage of an area (Skotnicki & Sowinski, 2013). Terrain irregularities such as small pits and depressions will collect and retain water, preventing it from becoming overland flow, but instead retaining it until it can infiltrate or become evapotranspiration. Hence, depression storage implies water on the surface, but less overland flow.

3.2.4 Temporal and spatial variability

As mentioned above, it is accepted that the overland flow generation of a catchment is variable in both space and time. In Dingman (2015:375) there is a short review of work done in the field of testing spatial variability of infiltration. The conclusion is that:

> *(1) infiltration varies greatly over short (1- to 20-m) distances, and (2) the variations are often not related to soil textures but are instead determined by plant and animal activity and by small scale topographic variations.*

This great spatial variability is significant to consider in relation to catchments characterised by high slope gradients, which allow for water to travel from one section of the catchment to another. This is because, if the terrain slopes, overland flow generated in one section will flow onto a different section. Due to the possibility of high spatial variability of infiltration rates, the section receiving the run-on might not yet be producing overland flow and might thus be capable of infiltrating the received run-on. In this situation, all the precipitation might ultimately end up being infiltrated, despite the production of runoff in one section of the catchment. Unfortunately, sufficient measurements to account for spatial variability is rarely available, and therefore, catchments are often divided into large homogenous subareas to compute area averages, despite this not being a reliable option (Dingman, 2015:379). This is what was done by Sweco in their dimensioning.

As well as great spatial variability of the runoff coefficient, its value might also vary over time for a given location. This applies both in shorter terms, e.g. throughout the duration of a rainfall event, or in longer terms, such as antecedent conditions and seasonal variability. The rate at which water infiltrates into the soil changes over the course of a rainfall event (Davie, 2008:59). It usually starts out high and then decreases until it steadies out at the infiltration capacity of the soil, i.e. the rate at which the water infiltrates when the soil is fully saturated. A visual representation of how infiltration rate varies over time is shown in Figure 3.1 below. For shorter or smaller storms, a larger percentage of the total rainfall amount will be infiltrated, due to a higher average infiltration rate, whilst for a longer or larger storm, a smaller percentage will be infiltrated, as the infiltration rate has time to reach a lower value. Therefore, when dimensioning for larger events, it can be advantageous to use a slightly higher runoff coefficient to account for the average infiltration rate being lower. Lack of consideration for these temporal variations could results in erroneous runoff predictions.

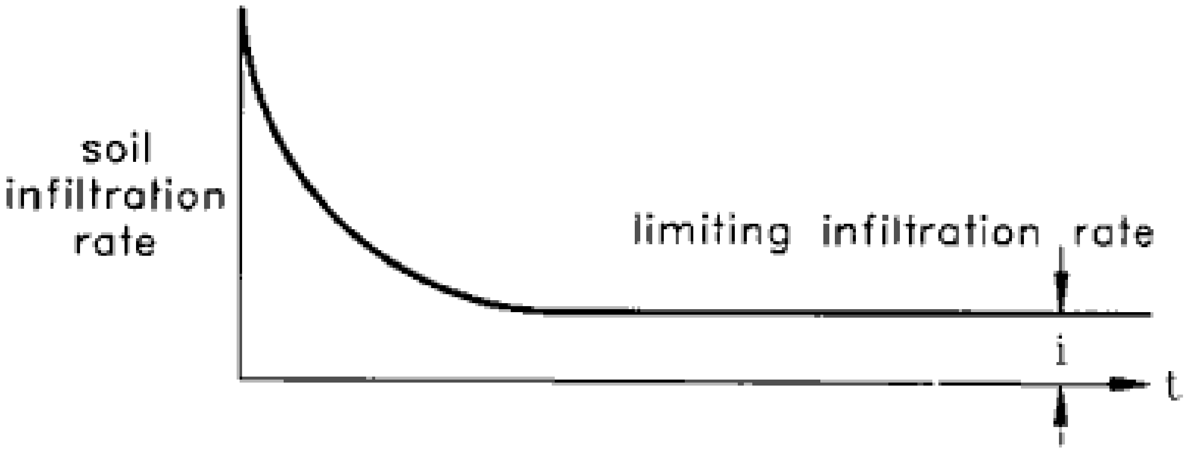


Figure 3.1 Visual representation of how infiltration rate changes over time (Stanger, 1994).

The runoff coefficient for a catchment can vary from one rainfall event to another, due to the antecedent moisture conditions of the soil (Dingman, 2015:514). Antecedent conditions affect the initial infiltration rate at the onset of a rainfall event, and thus influences the amount of water than can be infiltrated. If a large rainfall event takes place after a preceding event, runoff will more quickly be generated because of wetter antecedent conditions, and the runoff coefficient will be larger. More severe and less frequent storms tend to have wetter antecedent moisture conditions (Viessmann & Lewis, 2003), which is an important fact to consider in relation to the topic of this thesis. In terms of the rational equation, the commonly suggested runoff coefficients assume antecedent moisture conditions for frequent storms in the range of 2- to 10-year return period. Because of this, Viessmann & Lewis (2003) provide a list of suggested multipliers for less frequent storms to account for different antecedent moisture conditions. These can be viewed in Table 3.1.

Table 3.1 Suggested multipliers for the runoff coefficient for less frequent storm. The purpose of the multipliers is to account for antecedent moisture conditions. (Viessman & Lewis, 2003).

Antecedent moisture condition multipliers	
Return period [Years]	**Multiplier**
2-10	1.0
25	1.1
50	1.2
100	1.25

3.3 Vegetation

There are a few ways in which vegetation influences the runoff generation of an area, thus the runoff coefficient. Two of these factors have already been discussed earlier, namely by (1) changing the properties of the soil, which increases the rate of infiltration, and by (2) protecting the soil surface against the compaction/clogging from heavy raindrops. Additionally, vegetation reduces the amount of runoff by intercepting and retaining rain on the plant foliage, which is promptly evaporated. The interception loss depends on the type, stage of development, and density of the vegetation, in addition to characteristics of the rainfall (Dingman, 2015:283). A fourth way in which vegetation reduces runoff is by decelerating the runoff on gentle slopes, thus allowing more time to infiltrate into the ground (Critchley et al., 1991).

3.4 Snow

Snow and sub-zero temperatures can contribute towards increased runoff in at least two ways, (1) as direct input through snowmelt, and (2) by creating “concrete frost”. Concrete frost occurs when a soil with high water content freezes during an intense cold period. This reduces the permeability of the soil considerably, effectively increasing the runoff generated from rainfall (Shanley & Chalmers, 1999:1844). However, despite the contributions of snowmelt and freezing, these are not deemed important factor in this thesis, and will thus not be discussed more in detail. The reason for this is that this thesis is more concerned with large, short-term rainfall event. That being said, the largest rainfall events in Oslo usually occur in the summer and fall months, June to November (Foss, 2014), whilst snow melt and sub-zero temperatures are very rarely factors in Oslo during this time.

3.5 Evaporation

As is evident when looking at the water balance equation, evaporation is a hydrological process influencing the amount of water available to become surface runoff, and as was seen in section 2.2, permeable surfaces have higher evaporation rates than impermeable surfaces. However, since the rainfall events that are of interest in this thesis are high intensity, short duration, we can assume that evaporation will not be a significant loss throughout the duration of these events, due to the air being partially saturated. Therefore, no further literature on evaporation will be reviewed.

3.6 Runoff coefficients

After reviewing literature on hydrology, we will once again bring the topic back to runoff coefficients. Having obtained a better understanding of how hydrological processes influence the runoff coefficient, it is easy to understand why determining correct coefficients is a complex task. Despite many guidelines and suggestions for this selection, the runoff coefficient will ultimately depend on the characteristics of the specific area, and the guideline values might not always be correct. For instance, an area might be characterised by a steep slope gradient, indicating a runoff coefficient in the higher range of suggested values. But how do we determine just how much higher the value should be? And if we choose a large runoff coefficient to account for a steep slope gradient, should we still multiply it with a factor to account for antecedent moisture conditions, even if this means that it exceeds all guideline values for this surface type? These are just some of the questions we might ask when selecting runoff coefficients, demonstrating the difficulty involved in the selection.

In this thesis, the runoff coefficients will be selected based on a combination of guideline values and considerations for the hydrology reviewed. The guideline tables will be used to select an initial range of runoff coefficients, whilst the hydrology will aid in determining what value in this range that is most proper for the area being assessed. However, when basing the selection on guideline tables, the predicament is which guideline tables to use. In a publication by the Norwegian Environment Agency (NEA), runoff coefficients and selection guidelines were assessed (Magnussen, 2015). In this publication they presented three different tables of surface types and corresponding suggested runoff coefficient ranges, made by Norwegian Water (Norsk Vann)(NW), the Norwegian Public Roads Administration (NPRA) and the Swedish Water & Wastewater Association (SWWA). These tables can be viewed below, and as one can see, the suggested values vary between the three; sometimes considerably so. Note for example the surface type gravel road, which has a runoff coefficient of 0.4-0.6 for NW, 0.3-0.7 for NPRA and 0.2-0.4 for SWWA, or lawns/park, which has a suggested runoff coefficient of 0.05-0.1, 0.2-0.4, and 0.1 for NW, NPRA, and SWWA, respectively. NEA also point out that the reasoning behind the suggested values is rarely described, which adds to the problematic nature of determining runoff coefficients, as we do not know what consideration have already been taken when determining the tabulated values.

Table 3.2 Guidelines for selection of runoff coefficients depending on surface type, as given by Norwegian Water (Magnussen, 2014).

Norwegian Water – Suggested runoff coefficients	
Surface type	φ
Rooftops	0.8-0.9
Asphalt roads and streets	0.7-0.8
Gravel roads	0.4-0.6
Lawn	0.05-0.1

Table 3.3 Guidelines for selection of runoff coefficients depending on surface type, as given by the Norwegian Public Roads Administration (Magnussen, 2014).

Norwegian Public Roads Administration – Suggested runoff coefficients	
Surface type	φ
Concrete, asphalt, bare rock	0.6-0.9
Gravel roads	0.3-0.7
Park area or cropland	0.2-0.4
Forest	0.2-0.5

Table 3.4. Guidelines for selection of runoff coefficients depending on surface type, as given by the Swedish Water & Wastewater Association. Note, some of the surface types originally mentioned in this table that are considered less relevant for this paper were left out, in order to shorten the table (Magnussen, 2014).

Swedish Water & Wastewater Association – Suggested runoff coefficients	
Surface type	φ
Rooftops	0.9
Concrete, asphalt, bare rock with steep slope	0.8
Stone-embedded surfaces with gravel joints	0.7
Gravel roads, mountainous park with steep slope and little vegetation	0.4
Gravel site and gravel path, undeveloped plot	0.2
Park with rich vegetation	0.1
Flat dense forest	0-0.1

As mentioned, in forthcoming work, the runoff coefficients will be based on both guidelines tabulated above and hydrological understanding. Due to difficulties in choosing correct values, the considerations taken for each sub-area will be outlined when the choice is made, so that any potential error in judgement is transparent. The author expects and acknowledges that the values might not be completely accurate, though this is likely the case in most such assessments.

4.Methodology

In the specialisation project, the author found a disparity between observed volume and the volume that was to be expected based on the dimensioning method, and therefore concluded that the detention systems were either under- or over-dimensioned. Now, the aim is to evaluate this topic further, and to try to determine what might be the main causes of Sweco's inaccurate volume estimates. The primary focus will be on evaluating whether the runoff contributing area used by Sweco was reasonable, and to consider the choice of runoff coefficients more in detail. This will be done with the aid of SCALGO. Lastly, the newfound contributing areas will be modelled in PCSWMM to obtain a more accurate view on the runoff process on the terrain. How this work will be completed will now be presented more in detail.

4.1 SCALGO

The computer tool SCALGO has been presented as a tool which can be helpful in determining waterways, and to better understand the conveyance of water on the surface. By using this information, we can determine the area that contributes runoff to one specific location, which in this case is the detention systems. Hence, SCALGO will be used to determine the runoff contributing area (RCA) for each detention system. The assumption is that the information given in SCALGO is accurate, as an in-depth analysis of SCALGO's accuracy is beyond the scope of this thesis. The different functions/tools in SCALGO, the procedure for obtaining the RCA, and potential issues and uncertainties will be now be outlined.

4.1.1 Features and tools

To better understand how SCALGO will be used, it is helpful to be familiar with some of its basic features. Therefore, the functions that will be used in this thesis are briefly described below. In SCALGO, information is obtained by regarding a map and clicking on points of interest. For this work, a basic map depicting different surface types and human made structures is used. Topographic contour lines are depicted as orange lines.

Flow Accumulation –

By activating flow accumulation, the pathways of accumulated runoff on the surface are depicted on the map as blue lines. The thicker the line, the larger the upstream area to that flow path. The minimum upstream area required for a blue line to appear is 20 m^2.

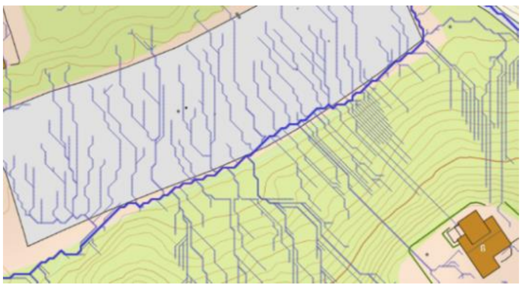


Figure 4.1 Example of the flow accumulation tool in SCALGO.

Flooded areas –

When activated, this function depicts areas on the surface that will be flooded (marked in blue) for a given amount of water depth. If there is no water, there is no flooding. It is also possible to activate and view the flow pathways that lead to the flooded areas.

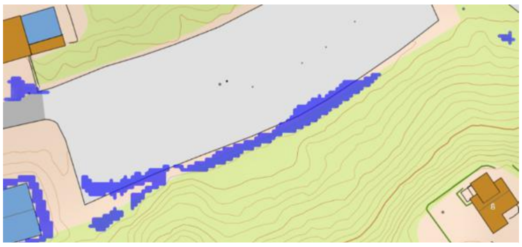


Figure 4.2 Example of the flooded areas function in SCALGO.

In most of the work completed in SCALGO, both "flow accumulation" and "flooded areas" will be activated. They will for the most part be used together with the watershed tool.

Watershed tool –

The watershed tool allows us to click anywhere on the terrain, and then shows the upstream area contributing runoff to that specific point (area marked in green). The size of the contributing area is stated on the map. The watershed tool can show either depression-free flow or flash flood mapping.

Figure 4.3 Example of depression-free flow in SCALGO.

If **depression-free flow** is activated, the map also shows the downstream pathway of the runoff from the point of interest (path in red). Runoff accumulated in depressions is not accounted for here and does not affect the flow of water. Depression free flow is depicted in the top figure.

Figure 4.4 Example of flash-flood mapping with a water depth of 0 mm in SCALGO.

If **flash-flood mapping** is activated, the upstream area contributing runoff to a selected point is shown, but as opposed to depression-free flow, runoff accumulation in depressions is considered. This entails that if the point of interest is in a flooded area, the contributing area will be depicted as the entire upstream area contributing runoff to the flooded area, instead of just runoff specifically flowing through the point of interest. Because of this, flash-flood mapping requires a water depth input, as this affects the size of the flooded area. The middle figure shows flash-flood mapping where there is no water on the surface, and hence, no flooded areas. The bottom figure shows flash-flood mapping with 6mm water on the surface, and therefore, flooding at the point of interest. Since the point of interest is in the flooded area, the entire upstream area contributing to the flooded area is marked in green.

Figure 4.5 Example of flash-flood mapping with a water depth of 6 mm in SCALGO.

Workspace –
A workspace can be created by selecting the area we want to work with. It is then possible to edit the terrain and evaluate the effects on the flood risk. For this thesis, the workspace tool will mainly be used to determine the size of an area of interest. The black shape on the righthand figure has an area of 817 m^2, as determined by the workspace tool.

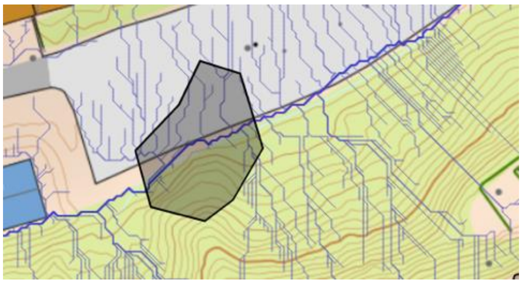


Figure 4.6 Example of the creation of a workspace in SCALGO.

4.1.2 The procedure

The first task towards determining the RCA is to collect information about the drainage system on the given property, as well as drainage systems of upstream areas. This information is imperative for the work in SCALGO, as it is needed to estimate what areas do or do not contribute runoff to the detention system. The information can be obtained either from Sweco or from Oslo Municipality's databases. Once all available and relevant information is gathered, the task of determining the RCA in SCALGO commences.

The first task in SCALGO is to determine the area that drains into each storm drain that is connected to the detention system. This is done by using the depression-free flow function and clicking on the location of an existing storm drain. The result will be the upstream watershed to this point, marked in green. This procedure is repeated for all drains, and once the task is completed, we know the area that could possibly drain into the detention system. However, there might be sections of this newfound area that never contribute water to the detention system, either due to the runoff being captured by another drainage system, or due to other aspects hindering the runoff from reaching the detention system's drainage system. Therefore, the next task is to uncover and subtract these areas from our area. This is done in the same manner as for the storm drains, by using the depression-free flow function and clicking on locations of interest, e.g. by a storm drain connected to a different drainage system. When all relevant watersheds have been identified, the final RCA can be determined by adding and subtracting contributing and non-contributing areas.

Once the detention system's RCA has been determined, we must assign runoff coefficients to the different sub-areas. Although simply dividing the catchment into homogenous sub-areas is not a particularly precise option due to great spatial and temporal variation, this is what must be done in order to model the catchment in PCSWMM. Therefore, the RCA is divided into fitting sub-areas based on surface types, topography and other relevant characteristics, and the unique characteristics of each sub-area are tabulated. Thereafter, a runoff coefficient is assigned based on considerations discussed in Section 3.6, i.e. tabulated guidelines and hydrology. After each sub-area and its associated runoff coefficient has been established, one area weighted average runoff coefficient will be determined for the entire RCA. This coefficient, referred to as $\varphi_{tot,Nicoline}$, along with the size of the RCA, $A_{Nicoline}$, will be used in Sweco's Excel template for computing necessary detention system volume. The volume yielded will then be compared to the volume determined by Sweco. This will give an indication as to how significant area selection and runoff coefficients could be for the final volume results. It will also give an indication as to whether the selection of area and runoff coefficients could have been a significant source of error in Sweco's dimensioning.

To get a better understanding of the procedure that has been outlined on the previous page, the first case introduced will be presented with a high level of detail and several figures. This is to help explain what has been done and why. For the latter case, the procedure is assumed to be familiar enough to not have to include the same level of explanation, though there will be several figures presented here as well.

4.1.3 Issues and uncertainties

As stated previously, in order to view the areas that will be flooded, there is a need to input a water depth, denoted "rain" in SCALGO. However, calling it *rain* is somewhat misleading, as it is more precisely the water depth that is "placed onto" the surface to see where there is depression storage. Changing the value for *rain* changes the extent of flooded areas, and thus, the flash-flood mapping results. However, the input of *rain* is not required when using depression-free flow, and since this is the function we will mainly be using when determining the RCAs, the error associated with selecting an incorrect value for *rain* is therefore not extremely significant. Nonetheless, although the flash-flood mapping is a secondary tool, it is still of interest, as it provides certain information that the depression-free flow tool does not. When flash-flood mapping is activated, it detects potential areas of depression that collect and store water. Thus, it locates areas that do not contribute runoff to the detention system, despite the depression-free flow tool indicating that it would. Hence, we are still required to select a value to use for *rain*, and the uncertainty associated with this selection must therefore be evaluated.

Since the parameter *rain* is not actually rain, it is uncertain how to determine the proper value to use in this project, where the goal is to dimension for a 20-year rainfall event. Therefore, a somewhat arbitrary value of 34.7 mm has been chosen. This is the rainfall magnitude for an event with a 20-year return period and duration of 60 minutes at Blindern in Oslo. The value is a great overestimation, as this amount of rain will never be present on the surface for the given rainfall events, due to the water either infiltrating, evaporating or being transported away as runoff. Hence, the value is knowingly incorrect, though accepted. This is because changing the rain value does not have a significant impact on the extent of the flooded areas or overland flow on the property. An example is given in Figure 4.7 below, where the size of the watershed and the extent of flooding is shown for a *rain* input of (a) 19.1 mm, and (b) 40.3 mm rain. These are the intensities for 20-year rainfall events at Blindern, with respectively 15- and 180-minutes durations. As one can see, the difference is hardly noticeable from the map. On this property, we only notice a slight change when the *rain* value is set to (c) 82 mm, which corresponds to the rainfall magnitude for a 200-year return period event with a duration of 1440 minutes at Blindern. Thus, the uncertainty associated with an incorrect *rain* value is considered to minimal.

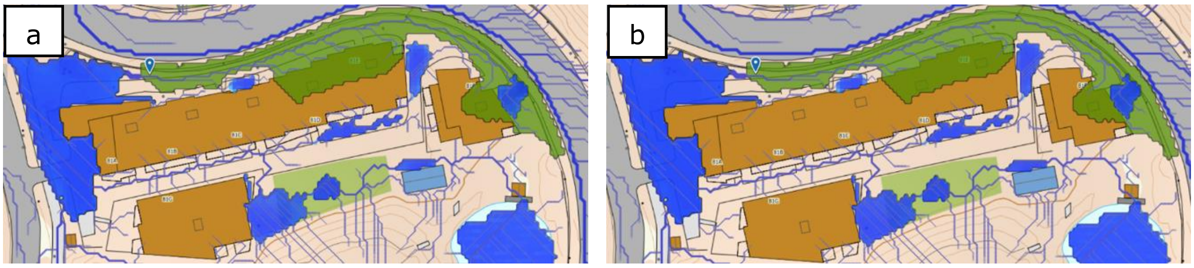


Figure 4.7 Watershed for given point (green) and flooded area on property (blue).

a) 19.1. mm rain
b) 40.3 mm rain
c) 81.0 mm rain

By using the arbitrary *rain* value of 34.7 mm we can obtain a qualitative assessment of depression storage and the subsequent retention on the properties. We know that unless a storm drain is located beneath a flooded area, water will be retained. However, due to the uncertainty of the *rain* value, we are prevented from using the quantitative information provided in SCALGO. With the presence of 34.7 mm of water on the surface, the depression storage to the right of the largest building can retain as much as 3.19 m^3. However, since the *rain* input is uncertain, this quantitative output cannot be directly applied to any runoff volume computations. Due to this, there is little use of SCALGO's quantitative output, and the depression storage seen in SCALGO will only be used qualitatively, as an aid in determining the ponding depth for selected sub-areas when modelling in PCSWMM.

The first step towards determining the RCA was stated as being to collect information about the drainage systems upstream the detention system. This information is later used to assess what areas contribute water to the detention system. However, erroneous results will occur if this task is not adequately completed and significant drainage systems are not discovered. This could lead to exaggerated area assessments, and thus incorrect volume estimations. There is no absolute guarantee that all the drainage systems have been unearthed in the upcoming cases, and the results could therefore be inaccurate.

4.2 PCSWMM

4.2.1 PCSWMM

PCSWMM is a computer software that computes dynamic rainfall-runoff quantity and quality from developed urban or rural areas, and it is stated in the manual that one of the typical uses of SWMM is to size detention facilities (James et al., 2010). In this thesis, the aim is to estimate the rainfall-runoff quantities from two different urban areas to evaluate whether two already existing detention facilities have been adequately sized. Thus, PCSWMM is regarded as a perfect tool to reach a reasonable conclusion to this inquiry. If the results obtained in PCWMM seem reasonable compared to previous observations from the specialisation project, and the procedure in PCSWMM is considered reasonably time-consuming, Sweco should consider a shifted focus towards a more software-based design method, such as this.

The advantages of using PCSWMM are many, as there are many more considerations taken in the model than what is done in simpler models, such as the one utilised by Sweco. For example, PCSWMM accounts for several hydrological processes related to runoff, such as dynamic rainfall patterns, temporal variations in infiltration, retention in depression storage, and many more. These factors are considered individually instead of lumping them all together in a single runoff coefficient, thus allowing for a more precise consideration of their impact on the runoff process. The PCSWMM model also considers runoff accumulation and flow time on the surface of each sub-area, and flow time and storage in the drainage system. This results in more realistic inflow values to the detention system. Outflow can also be modelled more realistically when using PCSWMM by including a head-discharge curve out of the storage facility, based on the desired relationship, e.g. a vertical vortex valve curve.

4.2.2 The procedure

It is common to calibrate a model against known values. This could appear to be a likely course of action in this thesis, as measurements were done in the specialisation project, thus resulting in data available for calibration. However, by remembering the purpose of the thesis, namely to evaluate how Sweco can improve upon their dimensioning practice, creating calibrated models has been deemed inaccurate. This is because when Sweco dimension, they do not have pre-existing data to use for model calibration, and thus, they must rely only on guideline values and user-experience when modelling. Therefore, in this thesis, it has been determined to mimic the procedure that Sweco would likely have to follow, by choosing values that they would likely pick. Results obtained from the models will be evaluated to see if the values yielded seem more reliable than the ones obtained from Sweco's pre-existing Excel template method.

The work in PCSWMM starts by drawing the different sub-catchments that make up the total RCA. Each sub-catchment is modelled as a rectangle in PCSWMM, and the shape that is drawn in the model is thus not important. For each sub-catchment, a range of different parameters must be assigned a value. The area size, area width and slope of each sub-catchment is estimated using SCALGO, and percentage of impervious surfaces is estimated based on maps and photos. The Manning's number for overland flow on impervious and pervious surfaces, as well as the depth of depression on impervious and pervious surfaces is determined based on guidelines values in the SWMM manual for most sub-catchments. These guideline values can be viewed in the tables below. Where it is deemed proper, the values used in PCSWMM might stray from the guidelines, and this choice will be reasoned for. The choice of infiltration model and infiltration input values will be discussed more extensively in the next sub-section.

Table 4.1 Guideline values for the selection of Manning's n to use for different surface types when modelling in PCSWMM. Source: James, Rossman and James (2010).

Manning's n – Overland flow	
Surface type	**n [-]**
Smooth Asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Short grass, prairie	0.15
Dense grass	0.24

Table 4.2 Guideline values for depression storage depths to use for different surface types when modelling in PCSWMM. Source: James, Rossman and James (2010).

Depression storage	
Surface type	**Depth [mm]**
Impervious surfaces	1.27-2.54
Lawns	2.54-5.08
Pasture	5.08

Once all sub-catchments have been created, junctions representing the storm drains and manholes are entered into the model. In PCSWMM, these are modelled as small storage units to account for the fact that storm drains and manholes have volumes that can be filled. Elevations are set based on information given in documents obtained from Sweco. Storm drains deemed insignificant or redundant for the modelling are excluded. This could for example apply when two storm drains are located within close proximity to one another. Once all junctions are in place, conduits are entered as connections between the junctions. Lengths are estimated using SCALGO, whilst geometry is obtained from documentation from Sweco. Conduit roughness is based on guideline values from the SWMM manual, and these guidelines are reiterated in Table 4.3 below.

Table 4.3 Guideline values for the selection of Manning's n to use for different conduit materials when modelling in PCSWMM. Source: James, Rossman and James (2010).

Manning's n – Closed conduits	
Conduit material	**n [-]**
Concrete – smooth forms	0.012-0.014
Plastic	0.011-0.015

Lastly, the detention system must be established in the model, either as storage units for geocellular detention systems, or as conduits for concrete pipe detention systems. The volume of the storage unit is described by a function representing surface area versus depth. This area-depth relationship, as well as information about invert and outlet elevations of the detention system, is obtained from documentation from Sweco. The outflow from the detention system is regulated by adding what is referred to in PCSWMM as an *outlet* to the system, and this allows for the consideration of temporal variation of outflow. The input is a head-discharge curve that is specific to the vertical vortex valve at each detention system. The curves for *Christinedal* and *Siemens* were obtained from the manufacturers during the work with the specialisation project, and they will be entered into PCSWMM.

Once all elements have been entered into the model, each sub-catchment must be assigned an outlet junction to where the runoff will enter the drainage system. The correct outlet for each sub-catchment is known based on knowledge of flow direction viewed in SCALGO. Each sub-catchment must also be assigned to a rain gauge, which determines the rain that falls upon the area. More detailed information about rain gauges and rainfall events will follow shortly.

4.2.3 Infiltration model

It has been determined to use the Horton model for infiltration. The primary reason is the limited number of input parameters required, i.e. minimum and maximum infiltration rates, decay constant and drying time. The inclusion of more parameters could potentially lead to more accurate results, however, due to the lack of on-site measurements in this thesis, and thus lack of knowledge of the parameter values, a model with fewer parameter inputs is considered a good thing. Selecting correct parameter values for the infiltration model is difficult, and for the discussion on this, an article pertaining to infiltration rates and infiltration capacities in soils in urban Oslo will be referenced and used to support the selection of parameter values in this thesis.

The initial plan was to use the Geological Survey of Norway's (NGU) soil map to determine the soil type on the *Christinedal* and *Siemens* properties, and to base the infiltration values on literature values for the given soil type. However, upon further investigation, an article pertaining specifically to infiltration rates in urban soils in Oslo was discovered, and this was then used as the primary source for determining infiltration rates. For six different locations in Oslo, Solheim et al. (2017) measured the infiltration capacity on urban soils with varying clay content, using both a Modified Phillip-Dunne Infiltrometer and Double Ring Infiltrometer. They experienced large variability in infiltration rates, despite the measuring sites being located within the same plot and being classified as the same soil type. The infiltration rate was measured in the range of 1-89.5 cm/hr. The most conservative values measured were a minimum and maximum infiltration rate of 0.5 and 20.2 cm/hr, respectively, and these were measured for soils characterised as silty clay. Due to the large variation in measured infiltration rates, Solheim et al. considered the use of NGU's soil maps to be unsuitable for determining infiltration rates on urban plots in Oslo, as urban soils often contain old filling masses and cracks with good infiltration potential. These characteristics, and other characteristics that affect infiltration rates, are not apparent on NGU's maps. Solheim et al. also pointed out that there is a disparity between literature values and measured values for infiltration rates on soils containing clay, and that measured values are often higher than what is found in literature.

As is understandable based on the information reviewed above, Solheim et al. expressed the importance of conducting multiple on-site measurements to obtain more reliable infiltration rates for the urban soils in question. The main reasons stated were large variance from one site to another and disparity between literature values and measured values. However, even with the use of on-site testing, obtaining infiltration values that reliably describe entire areas is usually impossible, due to large spatial variation. Anyhow, under the current circumstances, on-site measurements are not possible, and estimates must therefore be made relying on available information. Based on the reviewed article, it has been decided to use values found by Solheim et al., rather than other literature values. It has also been determined to use conservative values for infiltration, as the author considers under-dimensioning of detention systems to be more detrimental than over-dimensioning. Therefore, the lowest infiltration rates found by Solheim et al. will be used as the basis for input into the Horton infiltration model. This means a minimum infiltration rate of 5 mm/hr, and a maximum infiltration rate of 202 mm/hr, i.e. the measured infiltration rates for silty clay. If certain characteristics of the sub-catchments suggest the need for either higher or lower values than these, other infiltration rates will be argued for when relevant.

4.2.4 Rainfall events

As mentioned, to model runoff events in PCSWMM, rain gauges must be assigned to each sub-catchment. Due to both a small area and short time-frame for the simulations, all sub-catchments will be connected to the same rain gauge for each simulation, as they will likely experience the same rain input. Simulations will be completed for several different rainfall events to account for the difference in runoff response to both variable rainfall magnitude and pattern. Despite all rainfall events being defined as approximately 20-year events, the maximum volume observed in the detention systems might differ significantly due to this variability. Since dimensioning of detention systems should focus on the worst-case scenario to prevent flooding and property damage, it is important to simulate several different rainfalls in order to identify what this scenario is. The rainfall events that have been chosen for the modelling will be presented more in detail shortly. Five of the events have been based on real historical rainfall events, whilst the remaining three are constructed symmetrical hyetograms based on IDF-values from Blindern for a 20-year return period. Time series with data points for precipitation were downloaded from *Regnbyge.no* with a spatial and temporal resolution of 0.1 millimetres and 1 minute, respectively.

What is a 20-year rainfall event? In this thesis, we refer to a rainfall event of such a magnitude that at least one time interval has 20-year return period, i.e. a 5% chance of occurring. The largest return period for any time interval is the defining return period for that event. Hence, although Sweco dimension for a 20-year return period, the return period does not need to be 20 years for each time interval, as that is practically impossible for a real-life rainfall event. For example, an event could have a return period of 20 years for the durations of 10, 15 and 20 minutes, whilst the return period for the durations of 30, 45 and 60 minutes could be 5 years or 50 years. This is the case for most of the rainfall events presented. However, despite this issue, using real-life events has been considered to yield more reliable results than only relying on constructed symmetrical hyetograms, as they more realistically represent variations in rainfall patterns.

An additional complication with the events found from historical data is that they have a return period larger than 20 years for several time intervals, and this means that they are larger than what Sweco aimed to dimension *Christinedal* and *Siemens* for. Because of this, there is a need for downscaling the time series to make them fit the definition of a 20-year rainfall event. This is done by multiplying every data point in each time series with a scaling factor. The desirable scaling factor is the one that results in the rainfall event complying with the definition of a 20-year event. This work is completed by first importing the data into Excel and multiplying with the scaling factor. For each time interval, the maximum consecutive precipitation value, i.e. maximum intensity, is computed from the scaled data points. This intensity is then compared to IDF-values from Blindern to determine the return period of the given intensity and duration. In this thesis, a more precise return period is estimated than what is normally done in IDF-curves. A better precision is obtained by using the logarithmic relationship between return period and intensity found from Blindern's IDF-curves to create an IDF-table with a resolution of one-year. The results from each scaling procedure is an IDF-table for the event being processed, as well as the scaled time series. The time series is later transferred to PCSWMM and assigned to rain gauges. The scaling procedure described is shown in Figure 4.8 to Figure 4.14 with screen captures from Excel.

Observed	Example			
Max intensity	2.2	4	5.6	7.6
Time interval	1	2	3	5
0.2	0.2	0	0	0
0.6	0.6	0.8	0	0
0	0	0.6	0.8	0
0.8	0.8	0.8	1.4	0
2.2	2.2	3	3	3.8
1.8	1.8	4	4.8	5.4
1.6	1.6	3.4	5.6	6.4
1.2	1.2	2.8	4.6	7.6
0.8	0.8	2	3.6	7.6

Scaled	Scaling factor:		0.94	
Maks	2.068	3.76	5.264	7.144
Time series	1	2	3	5
0.188	0.188	0	0	0
0.564	0.564	0.752	0	0
0	0	0.564	0.752	0
0.752	0.752	0.752	1.316	0
2.068	2.068	2.82	2.82	3.572
1.692	1.692	3.76	4.512	5.076
1.504	1.504	3.196	5.264	6.016
1.128	1.128	2.632	4.324	7.144
0.752	0.752	1.88	3.384	7.144

Scaled	Scaling factor:		0.94		
Maks	2.068	3.76	5.264	7.144	15.98
Time series	1	2	3	5	10
0.188	0.188	0	0	0	0
0.564	0.564	0.752	0	0	0
0	0	0.564	0.752	0	0
0.752	0.752	0.752	1.316	0	0
2.068	2.068	2.82	2.82	3.572	0
1.692	1.692	3.76	4.512	5.076	0
1.504	1.504	3.196	5.264	6.016	0
1.128	1.128	2.632	4.324	7.144	0
0.752	0.752	1.88	3.384	=SUMMER(R8:R12)	

Figure 4.8 Scaling procedure, input (left). The blue field shows the input area for precipitation data obtained from Regnbyge.no.

Figure 4.9 Scaling procedure, scaling (middle). The data points in the blue input field in Figure 4.8 are multiplied with the scaling factor, which is specified in the orange field in the first row. The resulting data points are shown in the blue field in Figure 4.9.

Figure 4.10 Scaling procedure, finding maximum intensity (right). For each time interval, the maximum observed intensity is determined by summing the last x data points for time interval x. In this figure, the maximum intensity of the 5-minute time interval has been determined by continuously summarising the 5 last scaled data points (highlighted in yellow and blue). The maximum intensity for each time interval is computed and stated in the green row up above.

IDF - From Blindern														
Time interval (min)	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return period (year)	Intensity (mm)													
2	1.8	3.0	4.0	5.6	8.4	10.3	11.8	14.0	16.3	17.7	18.5	20.3	23.3	27.0
5	2.2	3.9	5.3	7.5	11.3	14.1	16.4	19.6	23.1	25.1	25.2	27.3	30.8	35.4
10	2.6	4.4	6.1	8.8	13.2	16.7	19.5	23.2	27.7	30.0		31.9	35.6	40.8
20	2.9	5.0	6.9	10.0	15.0	19.1	22.4	26.7	32.0	34.7		36.3	40.3	46.0
25	3.0	5.2	7.1	10.4	15.6	19.9	23.3	27.8	33.4	36.1	-	37.7	41.8	47.7
50	3.2	5.7	7.9	11.5	17.3	22.3	26.2	31.3	37.7	40.8	-	42.0	46.3	52.9
100	3.5	6.3	8.6	12.7	19.1	24.7	29.0	34.7	41.9	45.3	-	46.3	51.0	58.1
200	3.8	6.8	9.4	13.9	20.9	27.0	31.8	38.1	46.1	49.9	-	50.6	55.5	63.1

Figure 4.11 IDF-table from Blindern.

IDF - From Blindern	
Time interval (min)	1
Return period (year)	
2	1.8
5	2.2
10	2.6
20	2.9
25	3.0
50	3.2
100	3.5
200	3.8

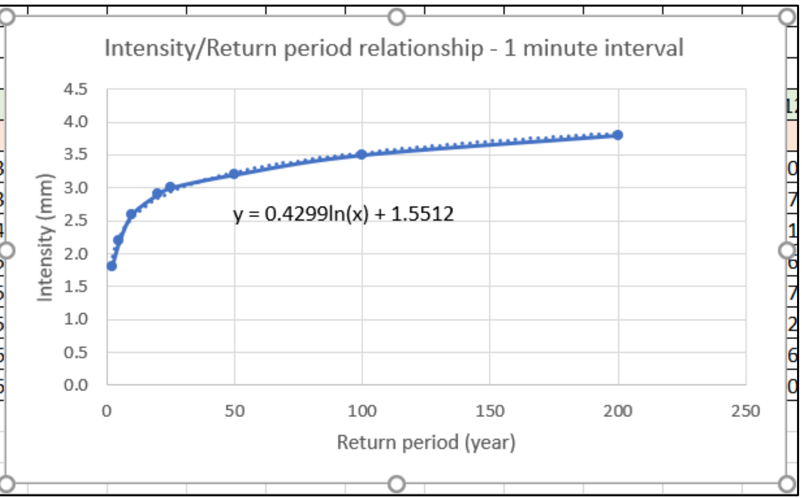


Figure 4.12 Logarithmic relationship between return period and intensity for 1-minute time interval. This mathematical relationship is determined for each time interval based on the IDF-table seen in Figure 4.11 above.

Time interval (min)	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return period (year)	Intensity (mm)													
1	1.6	2.5	3.4	4.6	6.9	8.2	9.3	11.0	12.6	13.7	15.5	16.5	19.3	22.5
2	1.8	3.1	4.2	5.8	8.7	10.7	12.3	14.6	17.0	18.5	20.2	21.0	24.1	27.9
3	2.0	3.4	4.6	6.5	9.8	12.1	14.0	16.7	19.6	21.3	22.9	23.7	26.9	31.0
4	2.1	3.7	5.0	7.0	10.6	13.2	15.3	18.2	21.4	23.3	24.8	25.5	28.9	33.3
5	2.2	3.8	5.2	7.4	11.2	14.0	16.2	19.3	22.9	24.8	26.3	27.0	30.4	35.0
6	2.3	4.0	5.4	7.8	11.7	14.6	17.0	20.3	24.0	26.1	27.5	28.2	31.7	36.4
7	2.4	4.1	5.6	8.0	12.1	15.2	17.7	21.1	25.0	27.1	28.5	29.2	32.7	37.6
8	2.4	4.2	5.8	8.3	12.4	15.7	18.3	21.8	25.9	28.0	29.4	30.1	33.7	38.6
9	2.5	4.3	5.9	8.5	12.7	16.1	18.8	22.4	26.6	28.9	30.2	30.8	34.5	39.5
10	2.5	4.4	6.0	8.7	13.0	16.5	19.2	22.9	27.3	29.6	30.9	31.5	35.2	40.4
11	2.6	4.5	6.1	8.8	13.3	16.8	19.6	23.4	27.9	30.2	31.5	32.1	35.9	41.1
12	2.6	4.6	6.2	9.0	13.5	17.1	20.0	23.9	28.5	30.8	32.1	32.7	36.5	41.8
13	2.7	4.6	6.3	9.1	13.7	17.4	20.3	24.3	29.0	31.4	32.7	33.2	37.0	42.4
14	2.7	4.7	6.4	9.3	13.9	17.7	20.7	24.6	29.5	31.9	33.1	33.7	37.5	43.0
15	2.7	4.7	6.5	9.4	14.1	17.9	21.0	25.0	29.9	32.4	33.6	34.1	38.0	43.5
16	2.7	4.8	6.6	9.5	14.3	18.2	21.2	25.3	30.3	32.8	34.0	34.6	38.5	44.0
17	2.8	4.8	6.6	9.6	14.4	18.4	21.5	25.7	30.7	33.2	34.4	35.0	38.9	44.5
18	2.8	4.9	6.7	9.7	14.6	18.6	21.7	25.9	31.1	33.6	34.8	35.3	39.3	44.9
19	2.8	4.9	6.8	9.8	14.7	18.8	22.0	26.2	31.4	34.0	35.2	35.7	39.6	45.3
20	2.8	5.0	6.8	9.9	14.9	19.0	22.2	26.5	31.7	34.4	35.5	36.0	40.0	45.7
21	2.9	5.0	6.9	10.0	15.0	19.1	22.4	26.7	32.1	34.7	35.9	36.3	40.3	46.1
22	2.9	5.0	6.9	10.1	15.1	19.3	22.6	27.0	32.3	35.0	36.2	36.6	40.7	46.5
23	2.9	5.1	7.0	10.1	15.3	19.5	22.8	27.2	32.6	35.3	36.5	36.9	41.0	46.8
24	2.9	5.1	7.0	10.2	15.4	19.6	23.0	27.4	32.9	35.6	36.7	37.2	41.3	47.1
25	2.9	5.2	7.1	10.3	15.5	19.8	23.1	27.6	33.2	35.9	37.0	37.5	41.5	47.5

Figure 4.13 IDF-table with 1-year resolution for return period. This table was made based on the logarithmic relationship between return period and intensity for each time interval as shown above. The maximum intensity found for each time interval in Figure 4.10 is looked up in this table. As we can see from the values highlighted in yellow, the intensity for the 5-minute interval from the example in Figure 4.10 has a return period of 4-5 years.

IDF Table														
Time interval (min)	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return period (years)	3	4	5	4	30	62	72	117	85	60	137	190	93	37

Figure 4.14 Example of resulting IDF-table from the scaling procedure. The table shows the return period and time interval for the maximum intensities found after scaling the data points. This table was created automatically by looking up values in the previous table.

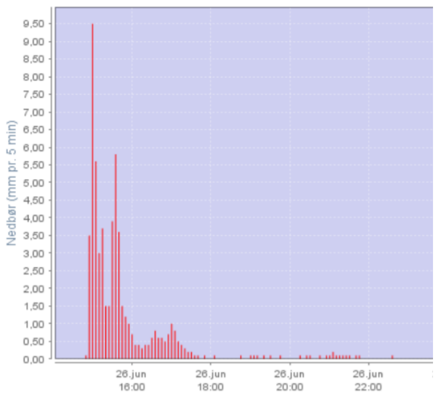
Presented below are the rainfall events that will be modelled in PCSWMM. It has been determined to scale each time series twice, using two dissimilar scaling factors. The first set of data series is multiplied with a scaling factor that yields a return period no higher than 22 years for any time interval, whilst the second set is multiplied by a scaling factor that yields a return period of 18 years or above for four different time intervals. The rules for determining scaling factors have been chosen somewhat arbitrarily, though the reasoning behind the allowance of slightly higher return periods than 20 years is the importance of being conservative when modelling. The second set of scaling factors is approximately 5-7% larger than set one. We could think of this difference as a climate factor added to the first set of time series. Both *Christinedal* and *Siemens* were dimensioned with a climate factor of 10%. Hence, simulating rainfall events slightly larger than 20-year events would be in line with Sweco's dimensioning goals. The second set also allows for evaluation of the significance of the event's magnitude on the results. Additionally, the author thinks it wise to simulate rainfalls where more than one single time interval reaches above 20 years, so that the rainfall is well within the margins of what constitutes a 20-year rainfall event.

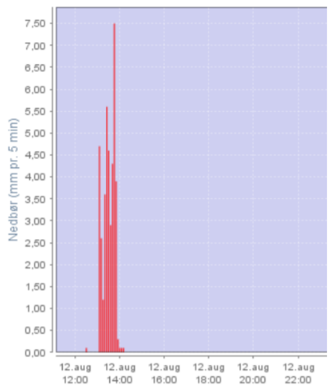
Details about the rainfall events will now be presented briefly, followed by Table 4.4, which summarises the scaling factors for each event.

Blindern 2014 – Figure 4.15 shows the rainfall pattern and magnitude of the event recorded at Blindern in 2014. Due to several time intervals having a return period greater than 20 years, the time series had to be downscaled before being simulated in PCSWMM.

Sandaker 12.08.13 – The event that occurred at Sandaker in 2013 was a short duration, high intensity rainfall event, as can be seen from the middle figure below. The different time intervals had a return period ranging from two to one hundred years. Thus, the event was larger than what Sweco normally dimension for, and the time series had to be downscaled.

Blindern 2008 – The Blindern event in 2008 was yet another short duration, high intensity rainfall event, as can be seen in Figure 4.17. This was the historical event closest to a 20-year rainfall event, though it had to be downscaled slightly.





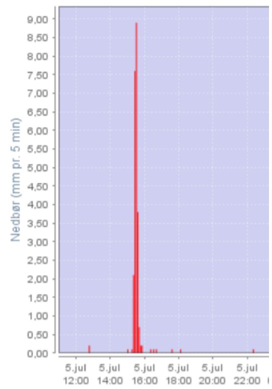


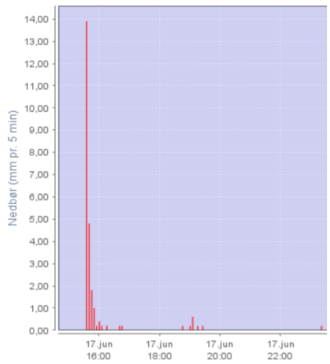
Figure 4.15 (Left) Rainfall data for event at Blindern in 2014. Data before scaling.

Figure 4.16 (Middle) Rainfall data for event at Sandaker in 2013. Data before scaling.

Figure 4.17 (Right) Rainfall data for event at Blindern in 2008. Data before scaling.

Blindern 17.06.80 – There were two large rainfall events recorded at Blindern in the year 1980. The first one occurred on June 17th. The rainfall data for this event can be viewed in the first figure below.

Blindern 06.08.80 – Rainfall data for the second event of 1980 can be seen in the middle figure below.



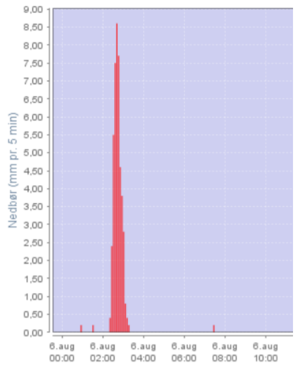
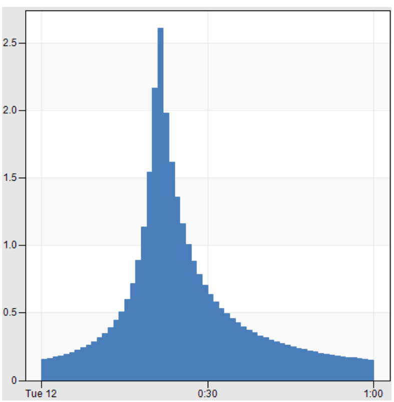
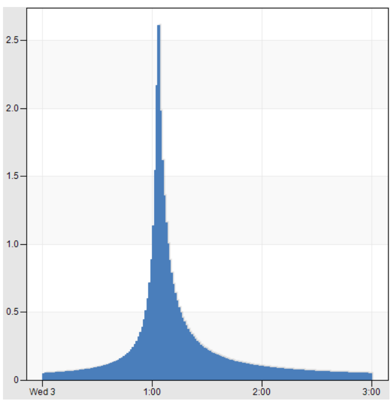


Figure 4.18 (Left) Rainfall data for event at Blindern 17.06.1980. Data before scaling.

Figure 4.19 (Right) Rainfall data for event at Blindern 06.08.1980. Data before scaling.

Constructed symmetrical hyetogram – The last data series to be presented are the constructed symmetrical hyetograms based on IDF values from Blindern. The hyetograms were constructed automatically in PCSWMM by selecting the intensities for a 20-year return period from the IDF-table, as well as choosing a duration for each event. Despite the same return period and intensities, the runoff results will differ depending on event duration. Therefore, three different event durations will be simulated, i.e. one hour, three hours, and 24 hours. These durations have been selected to portray a range of different durations, though other durations could have been chosen instead. When dimensioning detention systems, the selection of event duration will depend on the desired dimensioning specifications of the project. Longer durations yield larger runoff volumes.





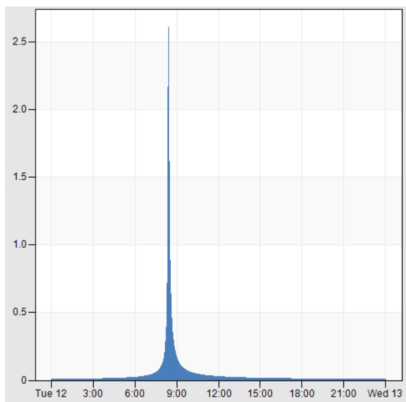


Figure 4.20 (Left) Constructed symmetrical hyetogram. 1-hour duration, 20-year return period, intensities from Blindern.

Figure 4.21 (Middle) Constructed symmetrical hyetogram. 3-hour duration, 20-year return period, intensities from Blindern.

Figure 4.22 (Right) Constructed symmetrical hyetogram. 24-hour duration, 20-year return period, intensities from Blindern.

Table 4.4 shows the two sets of scaling factors used to downscale the precipitation data for the recorded historical rainfall events. The symmetrical hyetograms do not need to be scaled, as they are constructed specifically for a 20-year return period. The IDF-tables showing the resulting return periods for each time interval for each rainfall event is included in Appendix 1.

Table 4.4 Scaling factors used to downscale precipitation data for the selected rainfall events.

Scaling factors		
Event	**Scaling factor 1**	**Scaling factor 2**
Blindern 2014	0.695	0.73
Sandaker 2013	0.85	0.85
Blindern 2008	0.9	0.962
Blindern 17.06.80	0.646	0.682
Blindern 06.08.80	0.715	0.753

4.2.5 Evaporation

Evaporation can be included in the PCSWMM model either based on climatic conditions, e.g. monthly temperature averages or temperature data series, or by stating a constant daily value. However, in this thesis, evaporation is thought to be negligible. This is because during the times of interest, i.e. in the middle of high intensity, short duration rainfall events, the air is assumed to be partially saturated, thus reducing the evaporation rate significantly. This is supported in the SWMM manual, where it is stated that single event simulations are usually insensitive to the evaporation rate and that evaporation is typically neglected when a single rainfall event or a synthetic storm is simulated (James et al., 2010: 778). To further support or disprove the assumption that evaporation is insignificant to the final detention system volume, it will be included as a parameter in the sensitivity analysis, which will be conducted after the primary modelling. Evaporation will then be included as a constant daily value.

4.2.6 Issues and uncertainties

As any other method, PCSWMM has some simplification, and as follows, uncertainties. Therefore, when working in PCSWMM, it is wise to be aware of these uncertainties, so that they can be considered when evaluating the final results. The importance of presenting model uncertainty is also emphasised in the SWMM manual. Here it is stated that the sensitivity and uncertainty linked to the use of arbitrary judgments about parameter selection and estimation, as well as use of deficient data, is critical to end-users, but rarely reported (James et al., 2010:10). This is the reason why the uncertainty will be discussed now and in following sections. It is also justification for the completion of the soon-mentioned sensitivity analysis.

Uncertainty can occur due to simplified model parameters or deficient or uncertain input data. Examples of the former are sub-catchment slope and shape. In PCSWMM, the slope that is entered into the modelled is averaged for the entire sub-catchment, and instead of modelling different shapes, all sub-catchments are modelled as rectangles. Thus, the heterogenous nature of most sub-catchments is not accounted for, as sub-catchment contours and topography are simplified. This is however a source of error that the user has little control over, except for ascertaining that the slope, size and width input are as precise as possible. The latter source of uncertainty, namely deficient input data, is most obvious when it comes to parameters such as Manning's number, depression storage depth, climatology, and infiltration model parameters, amongst others. Obtaining good data for these parameters requires extensive on-site testing, which is oftentimes not achievable due to reasons related to e.g. time or finances. Additionally, input data for drainage system design will likely be deficient when dimensioning detention systems, as this is often determined *after* determining detention system volume.

Yet another potential source of uncertainty when modelling is human error, e.g. due to lack of experience with the software or hasty and careless modelling. This could for example be in the form of wrongful input data, wrongful use of functions and tools, negligence of important requirements, misinterpretation of results, or as simple as misplacing a comma. These errors could propagate through the model and be detrimental to the final results, though the severity of the issue will depend on the type of error, as is the case with other errors as well.

As has been outlined, there are many potential sources of error and uncertainty in PCSWMM. Therefore, the model creator should strive to obtain satisfactory data, perform a sensitivity analysis to determine the significance of potentially deficient input data, and acknowledge and discuss the reasons for, and the implications of, the simplifications and uncertainties in the model. If the uncertainties are considered too great, other methods for obtaining the desired results should be contemplated. Some of the uncertainties could oftentimes be reduced by calibrating the model against recorded data, to make sure that the model simulations resemble real-life events. However, data for calibration is not always available, and even when it is, the user must be certain that also this data is reliable, or the calibration would be pointless.

4.2.7 Calibrated model

Despite earlier statements about the decision not to calibrate the model against measurements from the specialisation project, the initial plan was to create both a model based on guideline values *and* a calibrated model, and to then compare the results. However, as the modelling will prove, a calibrated and accurate model is difficult to create. The author has no basis for deciding which parameters should be edited, and to what value they should be modified to. Additionally, the value changes needed to create adequate similarity between the measured and simulated values are quite drastic, resulting in parameter values far from what one might find in guidelines. Due to this reasoning, creating a calibrated model, even if only as a secondary model, has once again been deemed unproductive. Therefore, the focus will be on creating the model based on guidelines values, and on conducting a sensitivity analysis for this model.

4.2.8 Parameter sensitivity analysis

The parameter inputs to the PCSWMM model are uncertain and based on guideline values rather than on-site measurements. Therefore, it has been deemed purposeful to conduct a sensitivity analysis to see how much the different parameters influence the final detention system volume. The analysis will not be conducted on parameters that are based on maps and which are therefore fairly certain, such as slope, area size, area width and impervious percent, but rather for parameters such as Manning's number, evaporation, infiltration rates and depression storage depths. The values will not be changed drastically, but to similar values that might also be deemed somewhat realistic according to guidelines. Due to restraints on time, the sensitivity analysis will be conducted by changing the parameter values for all sub-catchment simultaneously, as changing individual parameters to dissimilar values would be too time-consuming. Additionally, the analysis will only be conducted for the two rainfall events that produce that largest detention system volumes, due to time restraints. The author acknowledges that this is a limited and simplified parameter analysis but believes that the scope of the thesis neither allows for nor requires a more extensive analysis.

5.Case I: Christinedal

5.1 Assessing runoff contributing area and runoff coefficients

The first case being assessed is the detention system *Christinedal*, and the objective is to find the best estimate for the RCA using SCALGO. By using SCALGO's depression-free flow function, we can see that the area potentially contributing runoff to the *Christinedal* property is quite large. The area, which is highlighted in green in Figure 5.1, has an upstream area of 8.19 hectare. However, as we will soon discover, most of this area does not actually contribute runoff to the detention system. Based on the placement of storm drains on the *Christinedal* property, drainage systems on neighbouring properties, and flow pathways, a more accurate RCA will be argued for, and large parts of the area seen in the figure below will be excluded. The choices made will be explained in detail, so that potential errors are openly presented. Once the RCA has been determined, it will be divided into smaller sub-areas, which will be assigned appropriate runoff coefficients.

Figure 5.1 Watershed potentially contributing runoff to the detention system.

5.1.1 Determining runoff contributing area

On Figure 5.2 we can see some key features of the *Christinedal* property. The red circles mark the locations of storm drains connected to the detention system, and the blue line represents a small open drain which leads runoff to an open detention system, which is represented by the green square on the left. This detention system has a volume of approximately 0.73 m^3, and once its capacity is surpassed, the water will run onto the ground below and into the storm drain on the left-hand side. The blue circles also represent storm drains; however, these will only be utilised when the amount of runoff exceeds the capacity of the open drain. Stormwater enters the detention system from either one of the storm drains on the property, or directly from the rooftops. Knowing this, we can use

SCALGO to determine what areas contribute specifically to these drains. If the water does not reach any one of the drains, we can assume that it does not reach the detention system at all. The *Christinedal* detention system is in the upper left-hand corner of the map, marked by a green hexagon.

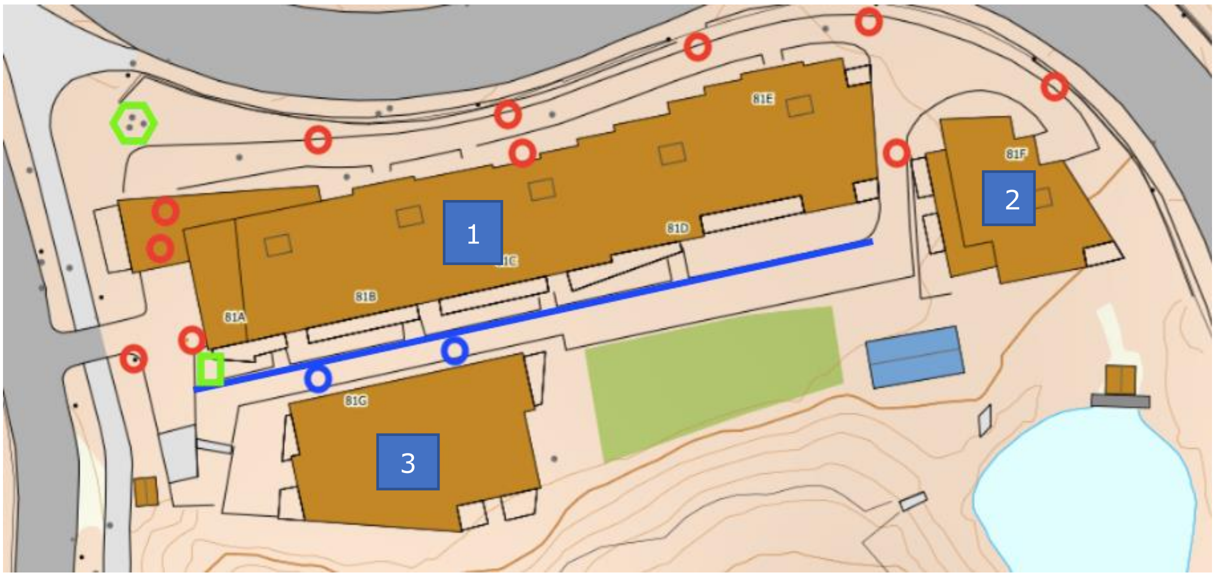
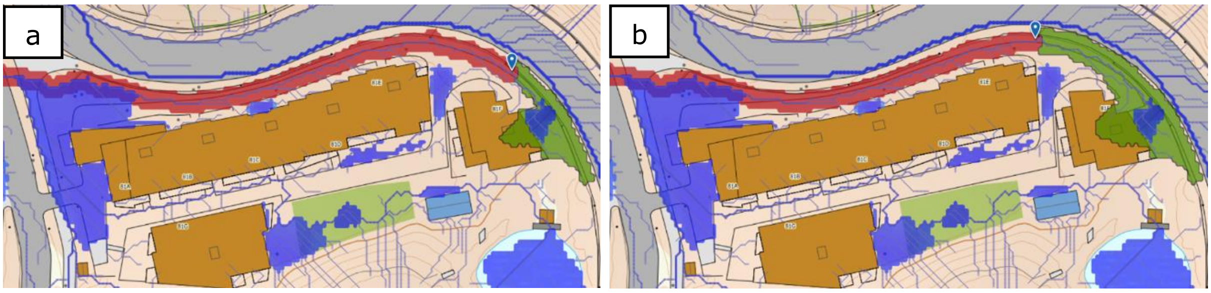


Figure 5.2 Location of storm drains on the Christinedal property. Primary storm drains marked with red circles, and secondary storm drains marked with blue circles. The blue line marks the location of an open drain, and the green square marks the location of a small open detention system. The green hexagon marks the location of the primary detention system, Christinedal.

The figures below show the storm drains on the northern side of the property and their associated watersheds (marked in green). This area will henceforth be referred to as the Northern area. The stormwater travels from the eastern part of the watershed towards the location of the detention system. The accumulated size of the Northern area is approximately 1540 m^2 and is represented in whole in Figure 5.3e. For storm drains b-e, the entire green watershed depicted in the figures will likely not drain into that specific drain, as much of the runoff will drain into an earlier storm drain instead. However, it is also possible for the water to flow past all the storm drains and to remain on the surface.



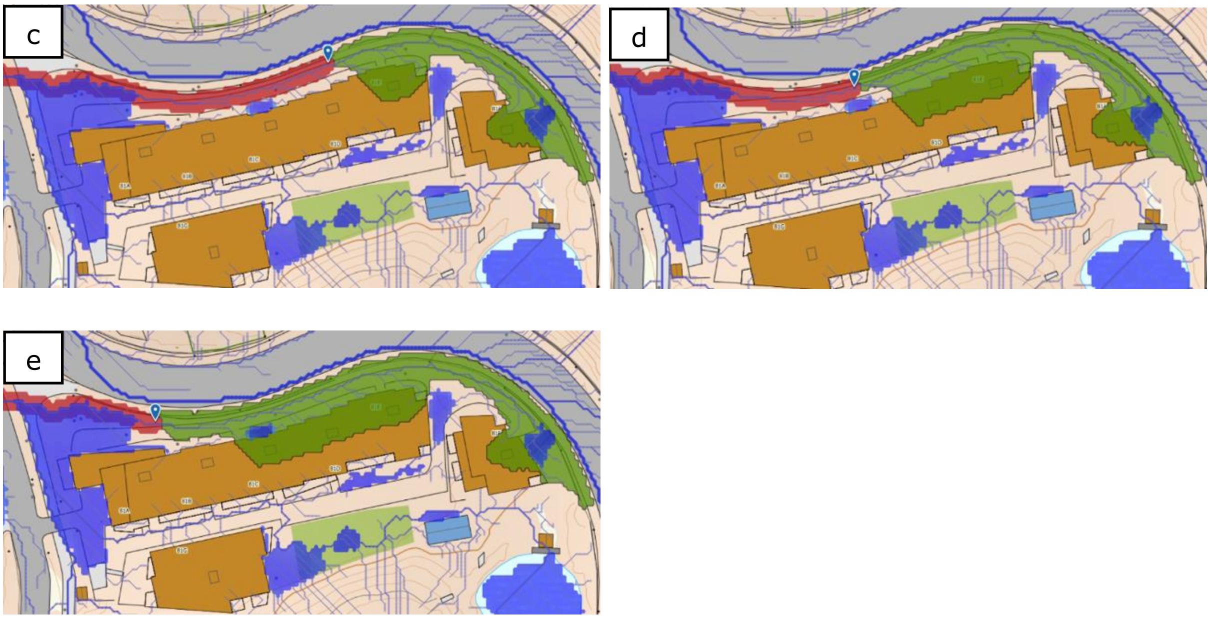


Figure 5.3 Areas that will in theory contribute runoff towards the stormwater drain at the most western point of the green shapes, i.e. where there is a small blue marker indicating the point of interest. Not all the water from the green shape in figure e will contribute towards this storm drain, as some of the water will likely drain into earlier drains or flow past the drain.

As we can see from the figures above, some of the watersheds encompass parts of the property buildings. However, the runoff from these buildings does not flow onto the ground below but is instead collected and transported directly to the detention system in a separate pipe system. Therefore, the fraction of the rooftops included in the figures above will be subtracted from the Northern area, so that the rooftops can be assessed as a separate sub-area. SCALGO's workspace tool is used to approximate the rooftop areas included above. Screen captures from this procedure are shown in Figure 5.4 below. The fraction of rooftop 1 is found to be approximately 383 m^2, and the fraction of rooftop 2 is approximately 90 m^2. This gives a new total contributing northern area of 1067 m^2.

$$A_N = 1540m^2 - 383m^2 - 90m^2 = 1067m^2$$

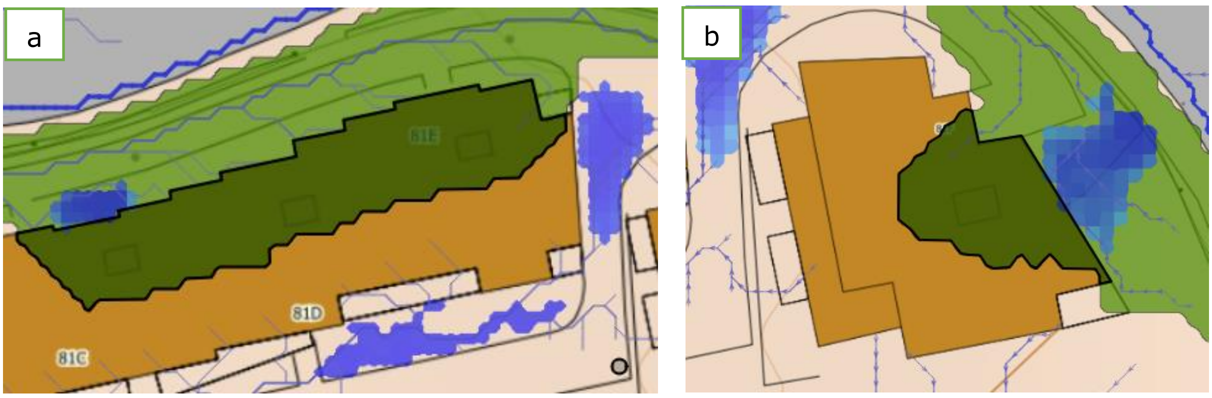


Figure 5.4. Identification of rooftop area size included in the watersheds connected to the storm drains on the Northern area. (a) Rooftop 1 has a green area of 265 m^2, and (b) rooftop 2 has a green area of 90 m^2.

By utilising the flash-flood mapping function and a rain input value of 34.7 mm, a fraction of the Northern area has been computed not to contribute to the watershed seen in Figure 5.3e, due to the water being retained in a depressed area. This appears in SCALGO as the yellow section in Figure 5.5 below. However, seeing as there is a storm drain located in the depression storage, this watershed will indeed contribute stormwater to the detention system, and will therefore be computed as its own sub-area (the rooftop area excluded).

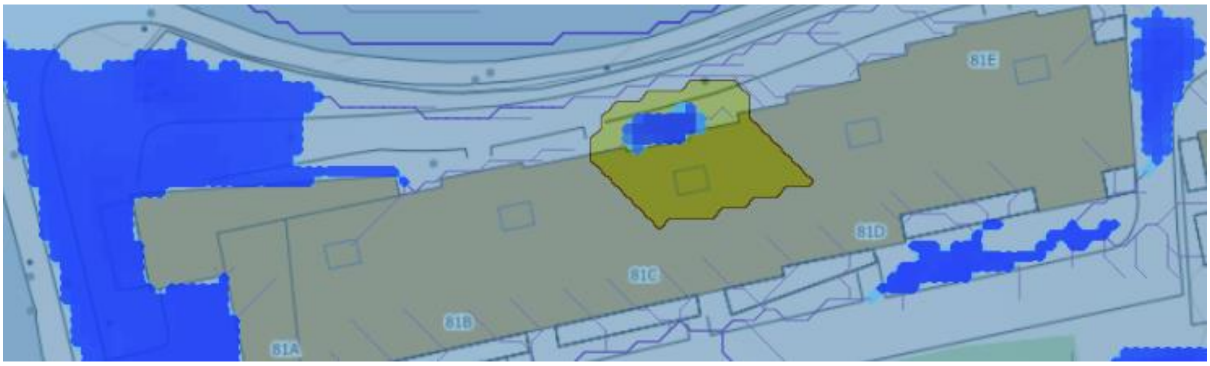


Figure 5.5 Small watershed (yellow) that will be modelled as its own sub-area (rooftop not included). For the given rainfall amount of 34.7 mm, the water in this area does not travel in the western direction, due to being retained in a section of depression storage, without any pathways out. The water is however drained by a storm drain present on the sub-area.

Next, we look at the South-Eastern area. As mentioned, alongside the southern face of building 1 there is an open drain leading stormwater in the direction of the detention system. The water from the open drain is first led to a small detention system, and then into a storm drain. The watershed that seemingly contributes runoff to the small detention system is shown in Figure 5.6. However, a part of this area does not drain into the given point. It so happens that Oslo municipality has stormwater pipes connected to the outlet of the pond located on the south-east side of the property. The consequence of this is that none of the area contributing runoff to this pond will drain onto the *Christinedal* property or into the detention system. The area connected to this pond is shown in Figure 5.7, and will be excluded from the final RCA.

Figure 5.6 (Left) Watershed (in green) on the south-east side of the property that contributes runoff to the small detention system, i.e. where the blue marker is placed.

Figure 5.7 (Right) Watershed connected to the outlet of the pond. The pond is connected to municipal stormwater drainage systems and can therefore be excluded from the final contributing area to Christinedal*.*

As we can see from the figures on the previous page, it appears as if a portion of the neighbouring property to the south contributes runoff to the *Christinedal* property. Assuming there is no drainage system inlet on the sloped hill between the properties, this area will likely provide run-on to *Christinedal*, and will therefore be included in the final RCA. This is a sub-area that was not included in Sweco's dimensioning area.

The sizes of the watersheds in Figure 5.6 and Figure 5.7 are approximately 9500 m^2 and 4500 m^2, respectively. If we subtract the latter from the former, we are left with 5000 m^2. If we additionally subtract the rooftop areas included in the first watershed, i.e. 592 m^2, 230 m^2, and 272 m^2 for buildings 1, 2, and 3, respectively, the final size of the South-Eastern area is 3906 m^2. The portion of rooftop area being subtracted can be viewed in Figure 5.8 below, along with the area size computation for the South-Eastern area.

$$A_{SE} = 9500m^2 - 4500m^2 - 592m^2 - 230m^2 - 272m^2 = 3906m^2$$

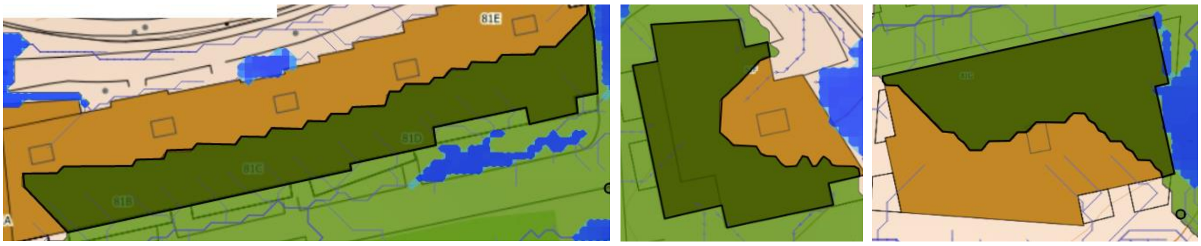


Figure 5.8 Identification of rooftop area included in the watersheds connected to the open drain on the South-Eastern area. Rooftop 1 (top) has a green area of 592 m^2, rooftop 2 (left) has a green area of 230 m^2 and rooftop 3 (right) has a green area of 272 m^2.

Next, we look at the South-Western area. As we can recall from Figure 5.1, it appears as if a large upstream area south-west of *Christinedal* contributes stormwater to the detention system. However, by looking more closely at flow pathways and the placement of storm drains, we can observe that runoff from the south-west flows past the detention system's storm drains. This is also the case for smaller parts of the *Christinedal* property which were included in Sweco's dimensioning area. To understand this better, we can regard Figure 5.9 and Figure 5.10 below. The first figure is zoomed out to give an idea of the extent of the watershed. The second image zooms in on the area of interest, and here we can see that the water from the south-west never flows onto the *Christinedal* property, and thus, never crosses any of the detention system's storm drains. It makes sense that the runoff follows this pathway instead of entering the *Christinedal* property, as the sidewalk it follows has a built-up curb on the right-hand side, thus hindering the water from flowing onto the property. Since these areas do not contribute to the detention system, they will be excluded from the final RCA.

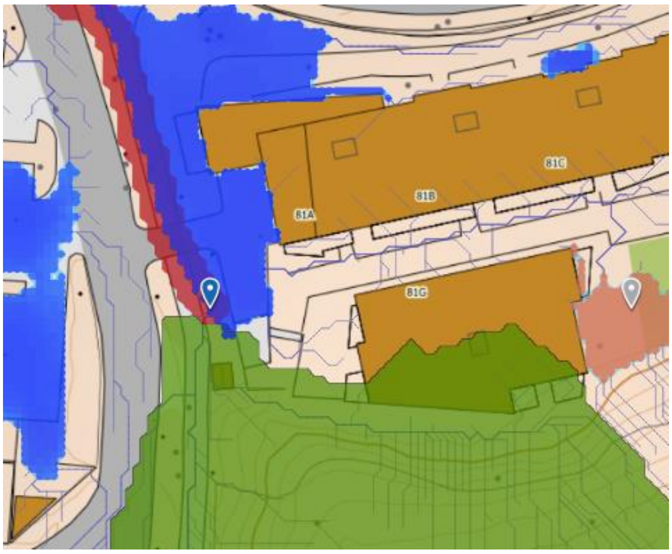


Figure 5.9 (Left) Watershed (in green) on the Western side of the property that appears to contribute runoff to the detention system Christinedal*.*

Figure 5.10 (Right) A zoomed in image of the Western area entering the Christinedal property. Here we can see that the pathway of the runoff (marked in red) does not cross any of the storm drains connected to the detention system. The water is hindered from reaching the property by a built-up curb.

As of now, there are a few sections of the property not yet accounted for; one being the small area to the left of building 3. According to SCALGO, this area contributes runoff to a storm drain connected to the detention system, and it will therefore be included in the RCA. It can be seen in Figure 5.11 and is approximately 127 m^2 when the rooftop section is not included. There are other such small contributing areas on the north-western side of the property, and these will be included in the final RCA as well, due to their accessibility to a storm drain. However, these areas will not be presented with figures, such as the area in Figure 5.11 was. Instead, they will appear on the figure showing the final runoff contributing area as the section marked in blue. These areas make up approximately 887 m^2. Despite the lack of a detailed explanation regarding the inclusion of each tiny area, an evaluation has been completed where topography, surface, type, flow path, and configuration of the surroundings has been contemplated before including the area.

Figure 5.11 Runoff contributing watershed (in green) wedged between the Western and South-Eastern watersheds. Runoff from this area flows close by a storm drain, and therefore contributes runoff to the detention system.

Lastly, before presenting the final RCA, the buildings located on the property will be presented. There are three main buildings on the property, which have formerly been referred to as buildings 1, 2 and 3. If including the balconies, they have area sizes of approximately 1362 m^2, 348 m^2 and 553 m^2, respectively, and they all have flat rooftops. We can assume that these buildings contribute a large percentage of stormwater to the detention system, as the water is led directly from the rooftops and into drainage pipes connected to the detention system. Buildings 2 and 3 only have one drainage point, whilst building 1 has five different drainage points. In addition to the main buildings, there is also a smaller building on the property, named the yellow house, which has an area of approximately 65 m^2. An additional fifth building included in the RCA is a fraction of a house on the neighbouring property to the south, with a contributing area of approximately 167 m^2. The two smaller buildings both have slanted rooftops, and the runoff will therefore run onto the ground below, where it will be subject to hydrological processes before it potentially reaches the detention system. All five buildings can be viewed in Figure 5.12 below.

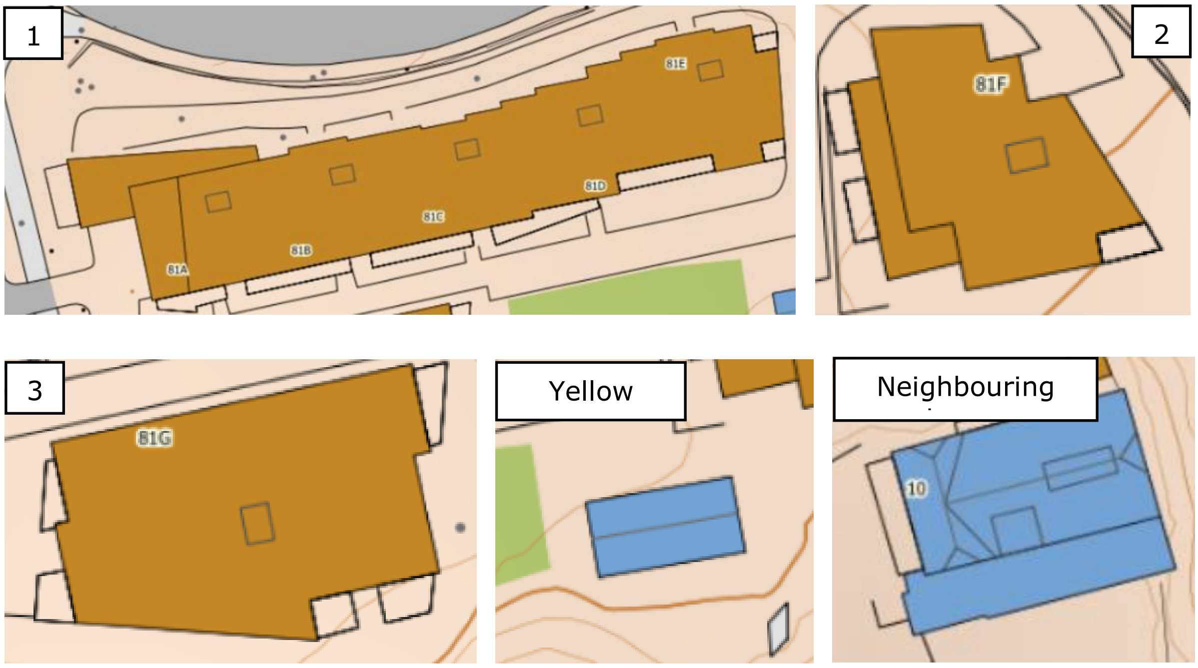


Figure 5.12 Buildings contributing runoff to the Christinedal *detention system. Building one (top left) has an area of 1460 m^2, building two (top right) has an area of 325 m^2, building three (bottom left) has an area of 510 m^2, the yellow house (bottom middle) has an area of 65 m^2, and the neighbouring building (bottom right) has a contributing area of 167 m^2.*

Based on the area assessment in this section, page 42 summarises the sub-areas included in the final RCA, as well as their sizes. All of the area shapes and sizes are estimations and add up to an area of approximately 8207 m^2. This is larger than the area used by Sweco in their dimensioning, but only around a 7% increase. The final estimate for the RCA is shown in the last figure on the indicated page. Green marks areas found directly in SCALGO, whilst blue indicates areas that were included based on the author's judgement. The orange buildings are also included in the RCA. The exact size of the RCA is unknown, as the watershed tool in SCALGO has a precision of 0.01 hectares for watersheds above 0.1 hectares, though this error is considered negligible.

Northern Area
$+1540\ m^2$

Figure 5.13 Northern area as seen in SCALGO.

Northern rooftop sections
$-(383 + 90)\ m^2$

Figure 5.14 Northern rooftop sections estimated using SCALGO.

South-Eastern Area
$+9500\ m^2$

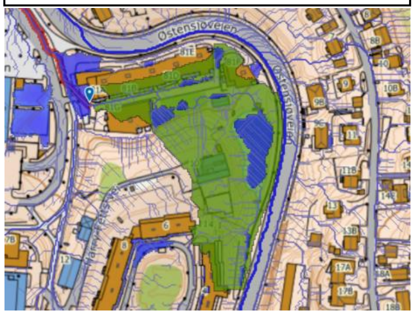


Figure 5.15 South-Eastern area as seen in SCALGO.

Pond Area
$-4500\ m^2$

Figure 5.16 Pond area as seen in SCALGO.

South-Eastern Rooftop
$-(592 + 230 + 272)\ m^2$

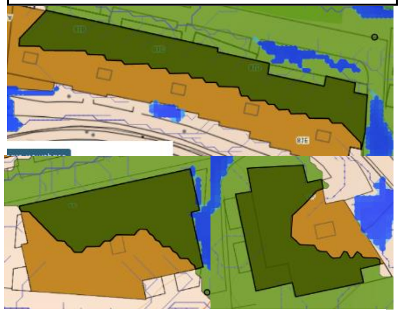


Figure 5.17 South-eastern rooftop sections estimated

Small Area
$+127\ m^2$

Figure 5.18 Small sandwiched area as seen in SCALGO.

Additional contributing area
$+844\ m^2$

Figure 5.19 Additional contributing area estimated by the author.

Main buildings
$+(1362 + 348 + 553)\ m^2$

Figure 5.20 Main buildings on property.

Final RCA
$\approx 8207\ m^2$

Figure 5.21 Final runoff contributing area estimate.

$$A \approx A_N + A_{SE} + A_{Small} + A_{Additional} + A_{Buildings}$$

$$A \approx 1067\ m^2 + 3906 + 127\ m^2 + 844 m^2 + 1362\ m^2 + 348\ m^2 + 553\ m^2 = \mathbf{8207\ m^2}$$

Figure 5.22 below shows the final RCA in a bigger format, with the addition of storm drain locations marked. The figure is repeated due to its importance for this thesis. This is the area that will be used in further computations and modelling in PCSWMM.

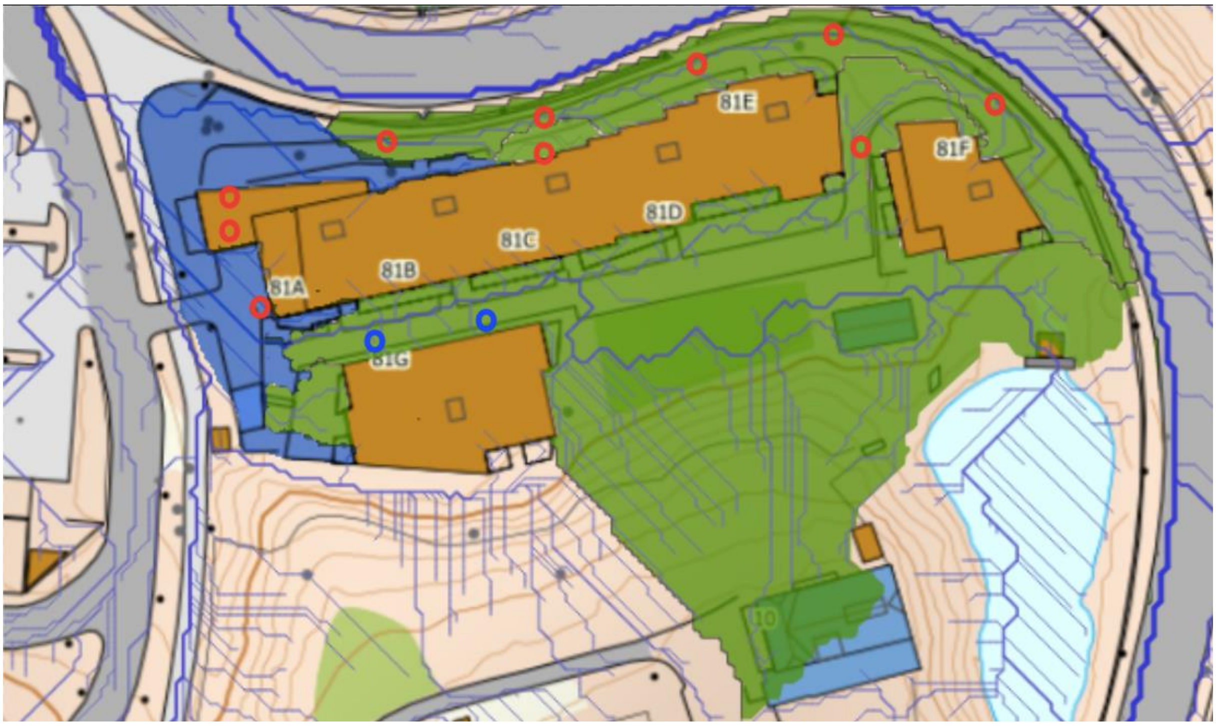


Figure 5.22 Map of the estimate for the total runoff contributing area. The area marked in green was found directly using SCALGO's watershed tool, whilst the area marked in blue was selected based on judgement from the author. Red and blue circles mark storm drains.

5.1.2 Assigning runoff coefficients

Now that the RCA has been determined, the work towards dividing the area into different sub-sections and assigning runoff coefficients can begin. Figure 5.23 below shows a detailed division of the RCA into different surface types. Each sub-area is outlined by a bolded black line and is distinguishable from the neighbouring area by a different coloured pattern. A summary of the different surface types and approximations of their sizes is shown in Table 5.1. In the table, there is also a column for commenting on other aspects of the surface types that might have an influence on the runoff coefficient. However, the level of detail seen in Figure 5.23 will not be modelled in PCSWMM, as it would be too complicated and time-consuming. Therefore, based on the detailed knowledge of the area, we must make a simplified division of the RCA, with fewer sub-areas. First though, we will try to determine what runoff coefficients we should use for each surface type mentioned in the table below.

Figure 5.23 Detailed division of the RCA into sub-areas with different surface types.

Table 5.1. A summary of the different surface types observed on the Christinedal property, and approximate sizes for each surface type. The third column lists characteristics of the sub-areas/surface types that might affect the runoff coefficient. Permeable surfaces equal approximately 3570 m^3 and impermeable surfaces approximately 4637 m^3.

Area division by surface type		
Surface type	**≈Area [m^2]**	**Comment**
Rooftop and balcony directly linked to detention system	2263	Flat surface
Rooftop not directly linked to detention system	232	Sloped roof, leading to grass below
Balcony not directly linked to detention system	228	Water from the balcony runs onto short grass below
Asphalt	1374	≈50% flat ≈50% gently sloped
Paving stone	325	≈Flat Parking garage below
Concrete	40	Stairs = steep slope
Water/stream	70	Rocky stream bank Underlying impermeable mat
Gravel	105	≈Flat Above steep hill towards property
Bushes	183	Flat area Parking garage below
Suburban lawn – short grass, bark, scarce bushes	1002	Mostly flat, but some portions on slopes ≈30% above parking garage
Short grass area with some trees	600	≈Flat
Taller grass	1400	Steep slope towards property
Playground – sand and grass	385	≈Flat Parking garage below

The surface types mentioned in Table 5.1 will be assigned a runoff coefficient based on surface type, topography, slope, and other characteristics commented on in the table. The coefficients will be given for a 20-year rainfall event, and because of this we assume higher values to account for saturation of the ground and temporal variation. In line with what was stated earlier, the selected runoff coefficients will primarily be based on tabulated guidelines from Section 3, whilst hydrological understanding will be used to determine where in the suggested value range we should select the coefficients. For some of the surface types, additional sources will be referenced. Given that there are quite a few surface types listed in Table 5.1, not all of them will be discussed separately, but rather merged together with a similar surface type.

Before commencing the selection process of runoff coefficients, it should be noted that parts of the RCA have an underlying parking garage. In areas where this is the case, the runoff coefficient is assumed to be higher. This is because the parking garage will act as an underlying impervious layer which can cause saturation from below and thus, saturated overland flow, in addition to infiltration-excess flow. This will affect several of the sub-areas listed. As for the antecedent moisture condition multipliers suggested by Viessmann & Lewis, (2003), they will be included only for the surface types that are somewhat permeable, as they are not relevant for impermeable surface types that do not have any infiltration. The runoff coefficients selected in the tables below will be applicable for those specific areas and are not a generalisation for all areas of similar characteristic.

Table 5.2 Estimation of runoff coefficient for the surface type "rooftop and balcony, directly linked to detention system" with the characteristics specified in the table.

Rooftop and balcony directly linked to detention system	
φ - NW	0.8-0.9
φ – NPRA	-
φ - SWWA	0.9
Characteristic	Consequence
Flat roof	As documented in the journal article by Farreny et al. (2011), flat roofs tend to have lower runoff coefficients than slanted roofs. Their findings indicated a runoff coefficient range of 0.7-0.85 for flat roofs, the value depending on material selection. A flat roof would also indicate more time until flow begins because it takes longer to accumulate enough water to produce flow. This could allow for more time to evaporate.
Directly linked to detention system	Since the roof is directly linked to the detention system, we can assume that most of the water will reach the detention system, which would indicate a high runoff coefficient. Some of the losses will likely be evaporation and surface wetting but these are assumed not to be extremely significant.
Concluding φ	Comment
0.85	Due to the roof being directly linked to the detention system, a runoff coefficient in the higher range of the values listed in Farreny et al. (2011) has been selected, as this was considered to be the most important characteristic. However, given that the roof is flat, the highest value of 0.9, as seen in both NW and SWWA, has not been selected. The balconies that are directly connected to the detention system are also given this same value, as they are also flat and impervious.

Table 5.3 Estimation of runoff coefficient for the surface type "rooftop, not directly linked to detention system" with the characteristics specified in the table.

Rooftop *not* directly linked to detention system	
***φ* - NW**	0.8-0.9
***φ* – NPRA**	-
***φ* - SWWA**	0.9
Characteristic	Consequence
Slanted roof	According to Farreny et al., slanted roofs have higher runoff coefficients, in the range of 0.7-0.95 depending on the material. The higher the slope gradient, the quicker the water flows off the rooftop. This would thus indicate a runoff coefficient in the higher range.
Not directly linked to detention system	Since the roof is not directly linked to the detention system, we can assume that most of the water will be led onto the ground below. Once on the ground, the water might be infiltrated, though the hydrological processes occurring *after* the water has left the rooftop will not be considered in the runoff coefficient for the rooftop itself.
Concluding ***φ***	Comment
0.95	Due to their slanting, the rooftops are given a higher runoff coefficient than the flat rooftops, i.e. 0.95, which is the highest value in the guideline values stated in Farreny et al..

Table 5.4 Estimation of runoff coefficient for the surface type "asphalt and concrete"

Asphalt and concrete	
***φ* - NW**	0.7-0.8
***φ* – NPRA**	0.6-0.9
***φ* - SWWA**	0.8
Characteristic	Consequence
≈50% flat	A flat surface would indicate a runoff coefficient in the lower range, due to the water not being transported away as quickly. This could allow for more evaporation and infiltration. However, considering that there is not much infiltration with this surface type, the coefficient is still considered to be quite high.
≈50% gently sloped	Sloped terrain would result in more rapid movement of water. This would indicate a higher runoff coefficient, as the water reaches the detention system more easily, and does not have much time to be subjugated to evaporation and/or infiltration.
Stairs = steep slope	Concrete stairs with a high slope gradient would indicate a runoff coefficient higher in the range. However, due to the small size of the affected area, this area will be lumped together with the gently sloped asphalt in terms of establishing a runoff coefficient.
Concluding ***φ***	Comment
0.75 for flat 0.85 for sloped	The influence of slope on the runoff coefficient has been considered significant enough to provide two different runoff coefficients; 0.75 for flat areas and 0.85 for sloped areas. The values are based on the guidelines and influenced by the stated characteristic.

Table 5.5 Estimation of runoff coefficient for the surface type "paving stones" with the characteristics specified in the table.

Paving stones	
***φ* - NW**	-
***φ* – NPRA**	-
***φ* - SWWA**	0.7
Characteristic	Consequence
≈Flat	The flat surface will allow the water more time to seep in between the paving stones and infiltrate, thus indicating a lower runoff coefficient.
Underlying parking garage	The underlying parking garage can impede further infiltration and cause saturation from below, thus indicating a higher coefficient.
Antecedent moisture conditions	Antecedent moisture conditions could be significant in terms of how much water can infiltrate into the ground below the paving stones. Therefore, the runoff coefficient will be multiplied with 1.1, in accordance with Viessmann & Lewis (2003), as asserted in Section 3.
Concluding ***φ***	Comment
0.75	Since there is only one guideline value for this surface type, we will rely on this value as our basis. The underlying parking garage indicates a higher runoff coefficient, whilst the flat surface indicates a lower coefficient, and the guideline value is therefore chosen. However, multiplying by 1.1 as indicated, results in a runoff coefficient of 0.77, which has been rounded down to 0.75, since the multiplier of 1.1 is meant for a return period of 25 years, as opposed to 20 years.

Table 5.6 Estimation of runoff coefficient for the surface type "gravel" with the characteristics specified in the table.

Gravel	
***φ* - NW**	0.4-0.6
***φ* – NPRA**	0.3-0.7
***φ* - SWWA**	0.2-0.4
Characteristic	Consequence
≈Flat	The flat surface will allow the water more time to infiltrate and/or evaporate.
Location	The gravel is located in an area where people will often reside and walk, and therefore, we can expect the gravel to be compacted, resulting in a higher runoff coefficient.
Antecedent moisture conditions	In accordance with the table by Viessmann & Lewis (2003), the runoff coefficient will be multiplied with 1.1 to account for antecedent moisture conditions for a rainfall event with a 25-year return period.
Concluding ***φ***	Comment
0.6	Since there is a great disparity between the guideline values for gravel, the selection process is based on much uncertainty. However, due to the expected compactness of the gravel, the decision has fallen upon a coefficient value in the higher suggested range, i.e. 0.55. Due to the flatness of the area, the highest value was not chosen. Multiplying this with the Viessmann & Lewis coefficient of 1.1, the result is a runoff coefficient of approximately 0.6 for gravel.

Table 5.7 Estimation of runoff coefficient for the surface type "suburban lawn – short grass, bark, scarce bushes" with the characteristics specified in the table.

Suburban lawn – short grass, bark, scarce bushes	
φ - NW	0.05-0.1
φ – NPRA	0.2-0.4
φ - SWWA	0.1-04
Characteristic	Consequence
Vegetation	This area is vegetated with short grass (≈5cm), bark and scarce bushes. This will increase infiltration to the ground, as outlined in section 3. Additionally, the vegetation will likely intercept rain and cause evapotranspiration, though not with the same magnitude as taller and denser vegetation. Since these are areas people might typically walk on, we can expect the ground to be somewhat compacted, reducing the infiltrability.
Mostly flat	Flat terrain will allow for more time for evaporation and infiltration into the ground, and thus results in less runoff production.
≈30% above parking garage	The underlying parking garage might reduce the infiltration capacity of the soil, thus yielding a higher runoff coefficient.
Antecedent moisture conditions	In accordance with the table by Viessmann & Lewis (2003), the runoff coefficient that is determined based on the area's characteristics is multiplied with 1.1 to account for antecedent moisture conditions.
Concluding **φ**	Comment
0.33 with garage 0.22 without garage	Based on the characteristics outlined above, an initial runoff coefficient of 0.3 is given for the area with an underlying garage and 0.2 for the area without an underlying garage. Multiplying with 1.1 due to antecedent conditions results in concluding runoff coefficients seen in the cell on the left.

Table 5.8 Estimation of runoff coefficient for the surface type "bushes, short grass area with some trees" with the characteristics specified in the table.

Bushes, short grass area with some trees	
φ - NW	0.05-0.1
φ – NPRA	0.2-0.4
φ - SWWA	0.1-04
Characteristic	Consequence
Vegetation	Although this area is similar to the previous one, it is believed that the inclusion of trees and bushes will decrease the runoff coefficient slightly. This is due to the soil likely having a higher infiltration rate, in addition to a higher rate of interception.
≈Flat	The flat terrain will allow for more time for evaporation and infiltration into the ground, and thus less runoff production.
Parking garage below bushes	The underlying parking garage might reduce the infiltration capacity, thus yielding a higher runoff coefficient.
Antecedent moisture conditions	In accordance with the table by Viessmann & Lewis (2003), the runoff coefficient that is determined based on the area's characteristics is multiplied with 1.1 to account for antecedent moisture conditions for a rainfall event with a 25-year return period.
Concluding φ	Comment
0.22 with garage 0.16 without garage	The characteristics of this area type are similar to those for the preceding area type, however, due to the addition of bushes and trees it is logical this area is assigned a smaller runoff coefficient. Due to the bushes having an underlying parking garage, the initial runoff coefficient is set to 0.2, which becomes 0.22 after multiplying by 1.1. For the areas that do not have an underlying parking garage, the runoff coefficient is set to 0.15, which becomes 0.16 after multiplying with 1.1 and rounding down.

Table 5.9 Estimation of runoff coefficient for the surface type "tall and dense grass cover" with the characteristics specified in the table.

Tall and dense grass cover	
***φ* - NW**	0.05-0.1
***φ* – NPRA**	0.2-0.4
***φ* - SWWA**	0.1-04
Characteristic	Consequence
Vegetation	This are type is covered by tall, dense grass (≈15cm). This results in a large portion of water lost to infiltration, retention and evapotranspiration, and the runoff coefficient will therefore be quite low.
Slope	The area is characterised by a steep slope gradient towards the property. This could reduce the amount of water lost to infiltration, thus resulting in a slightly higher runoff coefficient.
Antecedent moisture conditions	In accordance with the table by Viessmann & Lewis (2003), the runoff coefficient that is determined based on the area's characteristics is multiplied with 1.1 to account for antecedent moisture conditions for a rainfall event with a 25-year return period.
Concluding ***φ***	Comment
0.06	As discussed, the area is vegetated by tall and dense grass and will therefore be in the lower range of the guideline values, possibly around 0.05. Multiplying with 1.1 to account for antecedent conditions and rounding up due to the steep slope gradient, we get 0.06.

Table 5.10 Estimation of runoff coefficient for the surface type "water/stream with rocky stream bank" with the characteristics specified in the table.

Water/stream with rocky stream bank	
***φ* - NW**	-
***φ* – NPRA**	0.6-0.9 (bare rock)
***φ* - SWWA**	0.8 (bare rock with steep slope)
Characteristic	Consequence
Water	Water has a runoff coefficient of 1, as it does not remove any water from the runoff situation.
Stream bank	The rocky stream bank reduces the total runoff coefficient slightly due to more wetting surface and lowering of the flow velocity. This effect is not considered extremely significant though, since rock also has a high runoff coefficient.
Underlying impermeable mat	Beneath the stream and rocky bank there is an impermeable mat, which will hinder infiltration into the ground, thus resulting in a high runoff coefficient.
Concluding ***φ***	Comment
0.95	The runoff coefficient for the stream is considered to be quite high, due to the combination of water, rock and the impermeable mat. Therefore, the runoff coefficient is set near to its maximum value, i.e. 0.95.

Table 5.11 Estimation of runoff coefficient for the surface type "playground" with the characteristics specified in the table.

Playground/social area – sand, short grass and gravel	
φ - NW	-
φ – NPRA	-
φ - SWWA	-
Characteristic	Consequence
Sand	As well as good infiltration rates, sand in a playground could mean greater depths of depression storage, as children might dig and play in the area. This would indicate a lower runoff coefficient.
Grass	As had been determined earlier, grass has a runoff coefficient varying between 0.05 and 0.4 depending on grass type, density and underlying characteristics. Due to the location of an underlying parking garage, and somewhat tall grass, a runoff coefficient of approximately 0.16 is deemed sufficient for this area.
Gravel	The sand box on the playground is surrounded by a sizeable area of gravel, which has a higher runoff coefficient than sand and grass, i.e. in the range of 0.2-0.7. Therefore, the presence of gravel will increase the total runoff coefficient.
Antecedent moisture conditions	In accordance with the table by Viessmann & Lewis (2003), the runoff coefficient that is determined based on the area's characteristics is multiplied with 1.1 to account for antecedent moisture conditions for a rainfall event with a 25-year return period.
Concluding φ	Comment
0.27	Determining a reliable runoff coefficient for the playground is deemed somewhat difficult, as there are no guideline values, and the area has a variable surface type composition. However, based on the comments above, a runoff coefficient of 0.25 has been decided upon due to the good infiltration potential of the grass and sand, but also the presence of less permeable gravel. Multiplying with 1.1, the runoff coefficient is 0.27.

For each surface type in the presented tables, the runoff coefficient has been based solely on the characteristics of that specific area, isolated from neighbouring areas. However, as mentioned earlier, to model the RCA in PCSWMM, the watershed must be simplified by reducing the number of sub-areas, and this is done by merging some of the many smaller areas seen in Figure 5.23. By merging and creating new sub-areas, there is an opportunity for evaluating how the different surface types interact with one another, and how this affects the runoff coefficient for the new sub-area. Therefore, when assigning runoff coefficient to the sub-areas, area weighted average will act as the primary determinant, with surface type interaction influencing the final choice. This is expected to reduce error compared to only looking at the sub-areas as averaged homogenous areas, as run-on from impervious onto pervious surfaces is considered to some extent. Thus, the runoff coefficient describing the entire catchment will likely also be lower than what it would be by only using area averages.

In Figure 5.24 below, we can see the new sub-areas that will be used in the forthcoming modelling, followed by justification for the runoff coefficient selections. The concluded runoff coefficients might not fit the actual definition of the runoff coefficient, i.e.

precipitation received to runoff generated, but rather act as a representation of precipitation received to runoff generated *and transported to the detention system*. For any given sub-area, if runoff is expected to be hindered from reaching the detention system, the runoff coefficient will be lowered accordingly. For example, an area might be cut off from a storm drain by a tall stone curb, thus lowering the runoff contribution to the detention system and subsequently lowering the runoff coefficient for the area. Thus, despite the area characteristics suggesting a higher runoff coefficient, the coefficient will be set lower to account for the runoff being prevented from reaching the detention system. In PCSWMM, this will be considered by increasing the depression storage depth.

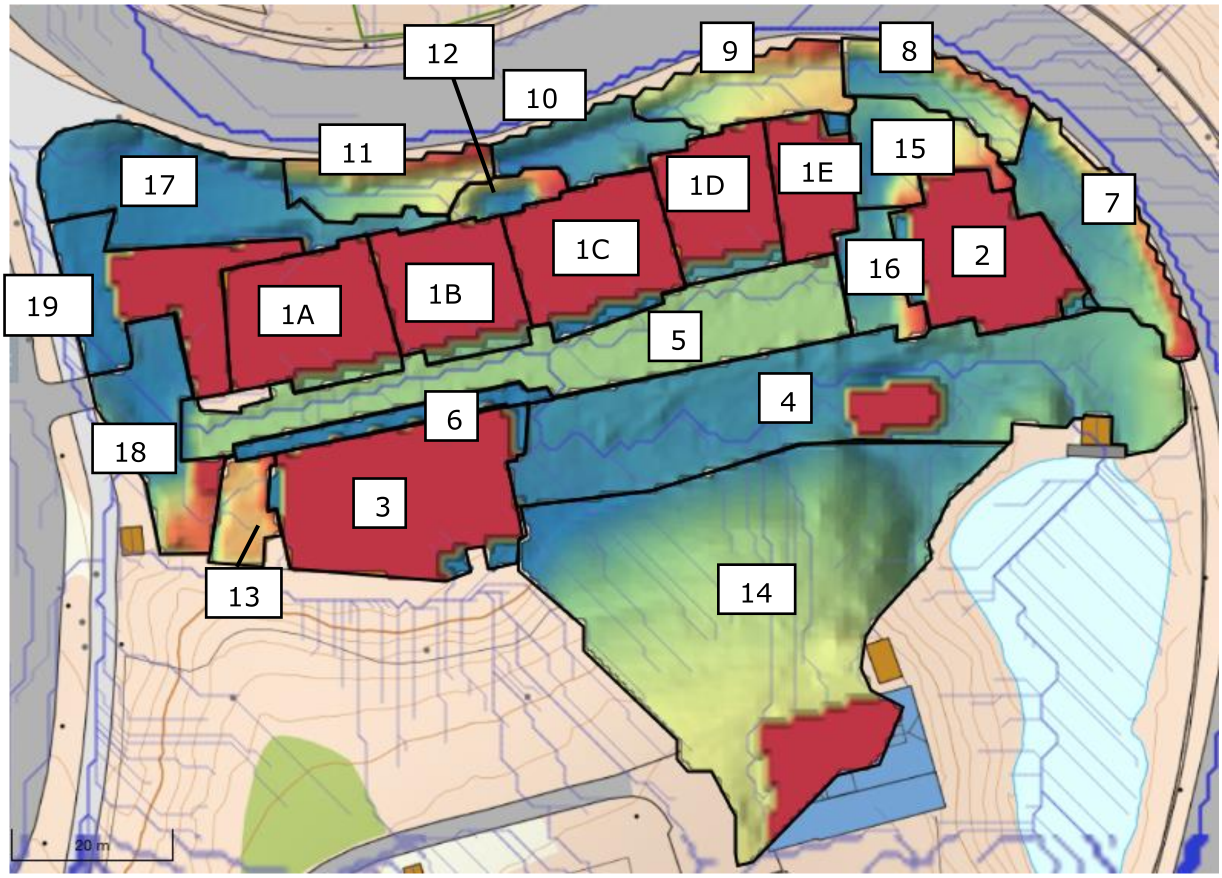


Figure 5.24 Final division into sub-areas. These sub-areas will be modelled as separate sub-catchments in PCSWMM.

Table 5.12 Justification for selection of runoff coefficient for areas 1A, 1B, 1C, 1D, 1E, 2 and 3.

Justification of runoff coefficient selection	
Area(s)	1A, 1B, 1C,1D, 1E, 2, 3
Size	$333 + 279 + 331 + 246 + 173 + 348 + 553 = 2263\ m^2$
Runoff coefficient, φ	0.85
Justification for φ	All these sub-areas consist of flat rooftops directly linked to the detention system; a surface type that was determined to have a runoff coefficient of 0.85 in Table 5.2.

Table 5.13 Justification for selection of runoff coefficient for area 4.

Justification of runoff coefficient selection			
Area(s)	4		
Accumulated size	$1120\ m^2$		
Runoff coefficient, φ	0.28		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	65	Slanted rooftop	0.95
	70	Stream/stream bank	0.95
	385	Playground	0.27
	300	Short grass, some trees, underlying parking garage	0.22
	300	Short grass, some trees	0.16
	$\varphi_{avg} = \frac{65*0.95+70*0.95+385*0.27+300*0.22+300*0.16}{65+70+385+300+300} = 0.309$ We can expect some of the runoff from the rooftop to be infiltrated into the ground below, thus resulting in a reduced runoff coefficient. By assuming that 50% of the runoff from the rooftop is infiltrated, we get a new runoff coefficient of 0.28.		

Table 5.14 Justification for selection of runoff coefficient for area 5.

Justification of runoff coefficient selection			
Area(s)	5		
Accumulated size	$596\ m^2$		
Runoff coefficient, φ	0.54		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	80	Flat asphalt	0.75
	325	Paving stones	0.75
	191	Short grass, underlying parking garage	0.33
	$\varphi_{avg} = \frac{80*0.75+325*0.75+191*0.33}{80+325+191} = 0.615$ The area weighted average runoff coefficient for this area is 0.615. However, it is believed that not all of the runoff produced on the grass areas will reach the detention system due to being bordered by a stone curb. This will prevent a large portion of the water from reaching the drainage system. Therefore, approximately 70% of the runoff produced from the grass area is excluded, and the runoff coefficient is set to 0.54.		

Table 5.15 Justification for selection of runoff coefficient for area 6.

Justification of runoff coefficient selection	
Area(s)	6
Accumulated size	$82\ m^2$
Runoff coefficient, φ	0.05
Justification for φ	This is a homogenous area that is covered by bushes and has an underlying parking garage, thus indicating a runoff coefficient of 0.16 according to Table 5.8. However, since the area is bordered by a relatively tall stone curb, easy access to the detention system is prevented, and water will pond on the surface. Therefore, the runoff coefficient will be set ≈70% lower than initially indicated, i.e. to 0.05.

Table 5.16 Justification for selection of runoff coefficient for areas 7, 8, 9, 10 and 11.

<table>
<tr><th colspan="4">Justification of runoff coefficient selection</th></tr>
<tr><td>Area(s)</td><td colspan="3">7, 8, 9, 10, 11</td></tr>
<tr><td>Accumulated size</td><td colspan="3">$287 + 164 + 209 + 163 + 170 = 993\ m^2$</td></tr>
<tr><td>Runoff coefficient, φ</td><td colspan="3">0.66</td></tr>
<tr><td rowspan="6">Justification for φ</td><td colspan="3">Sub-area composition</td></tr>
<tr><td>≈Area [m^2]</td><td>Surface type</td><td>φ</td></tr>
<tr><td>250</td><td>Sloped short grass</td><td>0.33</td></tr>
<tr><td>100</td><td>Sloped bark and bushes</td><td>0.22</td></tr>
<tr><td>643</td><td>Sloped asphalt</td><td>0.85</td></tr>
<tr><td colspan="3">All of the included areas have a slight slope, though this is not accounted for in the previously established runoff coefficients. Therefore, the runoff coefficients that are used for similar surface types, but with underlying parking garage will be used instead, to account for a larger runoff coefficient due to sloping. This results in coefficients of 0.33 and 0.22 for short grass and bark/bushes, respectively.

$$\varphi_{avg} = \frac{250 * 0.33 + 100 * 0.22 + 643 * 0.85}{250 + 100 + 643} = 0.656$$</td></tr>
</table>

Table 5.17 Justification for selection of runoff coefficient for area 12.

Justification of runoff coefficient selection	
Area(s)	12
Accumulated size	$61\ m^2$
Runoff coefficient, φ	0.85
Justification for φ	This area consists mainly of concrete and asphalt with easy access to a storm drain. Most of the water will likely reach the storm drain, as the whole area is depressed, with the storm drain being located on the lowest point of the area. Therefore, the runoff coefficient for sloped asphalt/concrete is used.

Table 5.18 Justification for selection of runoff coefficient for area 13.

Justification of runoff coefficient selection	
Area(s)	13
Accumulated size	$91\ m^2$
Runoff coefficient, φ	0.1
Justification for φ	The surface type of this area is short grass with an underlying parking garage, indicating a runoff coefficient of 0.33. However, like area 6, this area is not directly connected to a storm drain and is additionally bordered by a stone curb. This will prevent easy access toward the detention system and increase ponding depth on the area. Therefore, the runoff coefficient will be set lower than initially indicated, i.e. to 0.1.

Table 5.19 Justification for selection of runoff coefficient for area 14.

Justification of runoff coefficient selection			
Area(s)	14		
Accumulated size	$1672\ m^2$		
Runoff coefficient, φ	0.14		
Justification for φ	Sub-area composition		
	≈Area [m^2]	**Surface type**	**φ**
	167	Slanted rooftop	0.95
	105	Gravel	0.6
	1400	Tall/dense grass	0.06
	$\varphi_{avg} = \frac{167 * 0.95 + 105 * 0.6 + 1400 * 0.06}{167 + 105 + 1400} = 0.181$ The area weighted average runoff coefficient for this area is 0.181. However, in likeness to area 4, we can expect some of the runoff from the rooftop and the gravelled area to run onto the vegetated hill below and be infiltrated into the ground, thus resulting in a reduced runoff coefficient. By assuming that 30% of the runoff from the rooftop and gravelled area is infiltrated, we get a new runoff coefficient of 0.14.		

Table 5.20 Justification for selection of runoff coefficient for areas 15 and 16.

Justification of runoff coefficient selection			
Area(s)	15, 16		
Accumulated size	$184 + 123 = 307\ m^2$		
Runoff coefficient, φ	0.61		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	65	Short grass, parking garage	0.33
	31	Short grass	0.22
	211	Flat asphalt	0.75
	$\varphi_{avg} = \frac{65 * 0.33 + 31 * 0.22 + 211 * 0.75}{65 + 31 + 211} = 0.607$		

Table 5.21 Justification for selection of runoff coefficient for area 17.

Justification of runoff coefficient selection			
Area(s)	17		
Accumulated size	$432\ m^2$		
Runoff coefficient, φ	0.44		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	250	Short grass, parking garage	0.22
	182	Flat asphalt	0.75
	$\varphi_{avg} = \frac{250 * 0.22 + 182 * 0.75}{250 + 182} = 0.443$		

Table 5.22 Justification for selection of runoff coefficient for area 18.

Justification of runoff coefficient selection			
Area(s)	18		
Accumulated size	$258\ m^2$		
Runoff coefficient, φ	0.80		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	20	Short grass, parking garage	0.22
	238	Sloped asphalt	0.85
	$\varphi_{avg} = \frac{20 * 0.22 + 238 * 0.85}{20 + 238} = 0.795$		

Table 5.23 Justification for selection of runoff coefficient for area 19.

<table>
<tr><td colspan="4">Justification of runoff coefficient selection</td></tr>
<tr><td>Area(s)</td><td colspan="3">19</td></tr>
<tr><td>Accumulated size</td><td colspan="3">$332\ m^2$</td></tr>
<tr><td>Runoff coefficient, φ</td><td colspan="3">0.51</td></tr>
<tr><td rowspan="5">Justification for φ</td><td colspan="3">Sub-area composition</td></tr>
<tr><td>≈Area $[m^2]$</td><td>Surface type</td><td>φ</td></tr>
<tr><td>228</td><td>Balcony</td><td>0.85</td></tr>
<tr><td>104</td><td>Short grass</td><td>0.22</td></tr>
<tr><td colspan="3">$$\varphi_{avg} = \frac{228 * 0.85 + 104 * 0.22}{228 + 104} = 0.653$$
A portion of the balcony in this sub-section is connected directly to the detention system, whilst the rest is led to a grassy area below. Unfortunately, it has not been possible to determine the size of each of these portions, and we will thus assume a 50/50 distribution. For the balcony area that contributes runoff to the ground, the runoff coefficient will be lower, due to some of the water infiltrating. Additionally, the location at which the water is led is bordered by a stone curb, which prevents the water from reaching a storm drain. Thus, it has been determined that the balcony area not directly connected to the detention system will have a runoff coefficient reduced by 50%, yielding a new total runoff coefficient of 0.51.</td></tr>
</table>

5.1.3 New $\varphi * A$ and Sweco's template

The new RCA found in this project is somewhat larger than the one used by Sweco. This would indicate that the choice of area was not the main source of error in Sweco's dimensioning, and that other factors should considered more questioningly. Below, computations are completed to evaluate whether choice of runoff coefficients could have been a significant source of error in their dimensioning instead. First, an area weighted average runoff coefficient, $\varphi_{Nicoline}$, is determined for the RCA found earlier. It is then multiplied with the RCA size, $A_{Nicoline}$, and the resulting value is compared to Sweco's value for $\varphi_{Sweco} * A_{Sweco}$. The author's computation makes use of both the new area *and* new runoff coefficients, whilst Sweco's computations uses the values used by Sweco in their dimensioning. Hence, runoff coefficients are not evaluated individually in these computations, but rather combined with the RCA size to compare reduced runoff contributing area, $\varphi_i * A_i$.

$$\varphi_{Nicoline} = (2263 * 0.85 + 1120 * 0.28 + 596 * 0.54 + 82 * 0.05 + 993 * 0.66 + 61 * 0.85 + 91 * 0.1 + 1672 * 0.14 + 307 * 0.61 + 432 * 0.44 + 258 * 0.8 + 332 * 0.51)/(2263 + 1120 + 596 + 82 + 993 + 61 + 91 + 1672 + 307 + 432 + 258 + 332) = \mathbf{0.520}$$

$$Reduced\ RCA = \varphi_{Nicoline} * A_{Nicoline} = 0.520 * 8207 = \mathbf{4268}\ m^2$$

$$\varphi_{Sweco} = \frac{4942 * 0.9 + \frac{2690}{2} * 0.3 + \frac{2690}{2} * 0.15}{4942 + 2690} = \mathbf{0.662}$$

$$Reduced\ RCA = \varphi_{Sweco} * A_{Sweco} = 0.662 * 7632 = \mathbf{5052}\ m^2$$

$$V(\varphi_{Nicoline} * A_{Nicoline}, K_f = 1.1) = \mathbf{77}\ m^3$$

$$V(\varphi_{Sweco} * A_{Sweco}, K_f = 1.1) = \mathbf{99}\ m^3$$

As stated, despite the use of a larger area than the one used by Sweco, the author's volume is significantly smaller, due to smaller runoff coefficients. By inputting the new values for φ and A into Sweco's Excel template, the result is a maximum necessary storage volume of 77 m^3, which is 22 m^3 less than what Sweco found. This shows that the choice of runoff coefficients could have been a leading source for over-dimensioning *Christinedal*, and thus, that careful considerations should be taken when determining them. However, an issue with concluding based on these computations is that despite the careful consideration put into the coefficient selection in this thesis, there is no certainty that they are more correct than the ones used by Sweco, and they could even be more imprecise. Therefore, if regarding only these results, and not bearing in mind the results from the specialisations project, stating with certainty that the new volume is more accurate than Sweco's, is simply not true. As we can observe in Table 5.24, a slight change in average runoff coefficient results in a significant change in volume, highlighting the problematic nature of relying on runoff coefficients. The largest volume in the table, which is based on the author's area and a runoff coefficient of 0.7, is 279% larger than the volume produced for Sweco's area with a runoff coefficient 43% lower, i.e. 0.4.

Table 5.24 Necessary storage volume based on Sweco's Excel template for a range of different runoff coefficients for both the area size used by Sweco and the area size found earlier in the section. A climate factor of 1.1 has been utilised.

Computed volume in Sweco's Excel template		
$\boldsymbol{\varphi}$	$\mathbf{V(A_{Sweco=7632})}$	$\mathbf{V(A_{Nicoline=8207})}$
$\varphi = 0.4$	43	49
$\varphi = 0.5$	64	72
$\varphi = 0.6$	86	95
$\varphi = 0.7$	107	120

It was initially considered to find dimensioned volumes by only changing one of the parameters at a time to evaluate the significance of each parameter change individually. This would be done by first computing for Sweco's area and Nicoline's runoff coefficient together, and vice versa. However, this was deemed unproductive since the two areas are different not only in size, but also extent, and thus, composition of surface types. Therefore, the average runoff coefficient for one RCA would not be a correct description of the other RCA, due to dissimilar area basis. Had a new average runoff coefficient been found based on Sweco's area appraisal, it would be different than $\varphi_{Nicoline}$, despite the same considerations taken in the runoff coefficient selection as previously in this thesis. Therefore, $\varphi_{Sweco} * A_{Sweco}$ versus $\varphi_{Nicoline} * A_{Nicoline}$ has been compared, despite this resulting in a comparison of two parameters combined. However, due to the new RCA being larger than Sweco's area, we know that in this specific case, runoff coefficients are the reason for the author's volume being smaller than Sweco's volume, and not area size.

Now that we have supported the importance of runoff coefficients, the focus will turn to the method used. As was stated in the specialisation project, it is believed that the method used by Sweco is the main source of error, due to the many simplifications related to temporal and spatial variation, outlet from the detention system, consideration of rainfall pattern, and lack of storage in the drainage system, amongst others. By dimensioning the detention systems using a new method, we can evaluate how much the results differ due to the use of a simpler or more complex method. Therefore, the RCA found in SCALGO will now be modelled in PCSWMM.

5.2 PCSWMM

5.2.1 Input

The sub-areas shown in Figure 5.24 have been modelled in PCSWMM. The parameter values for sub-catchments, junctions, conduits and storage units were found following the procedure outlined in the methodology section, i.e. by using maps and documents provided by Sweco or by gathering information using SCALGO. The selected input values for percentage impervious surfaces, Manning's number and depression storage depth are tabulated below for each sub-catchment, whilst additional parameter inputs are shown in Table 5.26. The remaining input values for sub-catchments and conduits are included in the Appendix.

Table 5.25 Parameter values for each sub-catchment in the Christinedal PCSWMM-model.

Input parameters used in PCSWMM						
Sub-catchment	**Imperv. [%]**	**N imperv.**	**N perv.**	**Dstore imperv. [mm]**	**Dstore perv. [mm]**	**Zero Imperv [%]**
1A-1E, 2, 3	100	0.012	0.15	2	0	25
4	14	0.011	0.15	2.5	10	50
5	68	0.013	0.15	2.5	15	25
6	5	0.013	0.17	1.5	20	25
7	50	0.013	0.15	1.5	4.5	25
8	68	0.013	0.15	1.5	4.5	25
9	66	0.013	0.15	1.5	4.5	25
10	48	0.013	0.15	1.5	4.5	25
11	66	0.013	0.15	1.5	4.5	25
12	90	0.013	0.15	1.5	3.5	25
13	0	0.012	0.15	1.5	20	25
14	12	0.012	0.2	2	5	50
15	68	0.013	0.15	1.5	3.5	25
16	68	0.013	0.15	1.5	5	25
17	42	0.013	0.15	2	3.5	25
18	92	0.013	0.15	2	5	25
19	68	0.013	0.15	2.5	10	25

In Table 5.25 we can see that some of the parameter values differ from the guideline values tabulated in the methodology section, e.g. pervious depression storage depth. This is due to the specific characteristics of the sub-catchments in question, which were discussed extensively previously in the section. For example, if the pervious section of a sub-catchment is bordered by a stone curb, as was the case with sub-catchments 5, 6, 13 and 19, the pervious depression storage assigned in PCSWMM will be larger, to account for ponding of water caused by the hindrance of flow towards the detention system.

It has been determined to use a Manning's number of 0.012 for all PVC conduits, and 0.013 for concrete conduits. Diameters have been entered according to data obtained from Sweco, and this information has been tabulated in the Appendix. The values used in the infiltration model, as well as climatology parameters, are listed in the table below.

Table 5.26 Input parameters to the Christinedal PCSWMM-model. The values stated are used for all sub-catchments.

Input parameters used in PCSWMM	
Parameter	**Value**
Maximum infiltration rate	202 mm/hr
Minimum infiltration rate	5 mm/hr
Decay constant	4
Drying time	7 days
Evaporation rate	0 mm/day

5.2.2 Results – Detention system volume

After creating the *Christinedal* model in PCSWMM, the map of the model appears as seen in Figure 5.25 below. Each sub-catchment is bordered by a red line, the conduits are marked in yellow, and the manholes and storage units are marked as blue circles or green squares. As we can see, the sub-catchments and drainage system have been created in line with what was presented in the methodology section and case work above. If we look at the profile of the detention system, which is outlined by red in Figure 5.26, we can see that the drainage system is functioning as expected, with water running through the conduits and filling up the detention system.

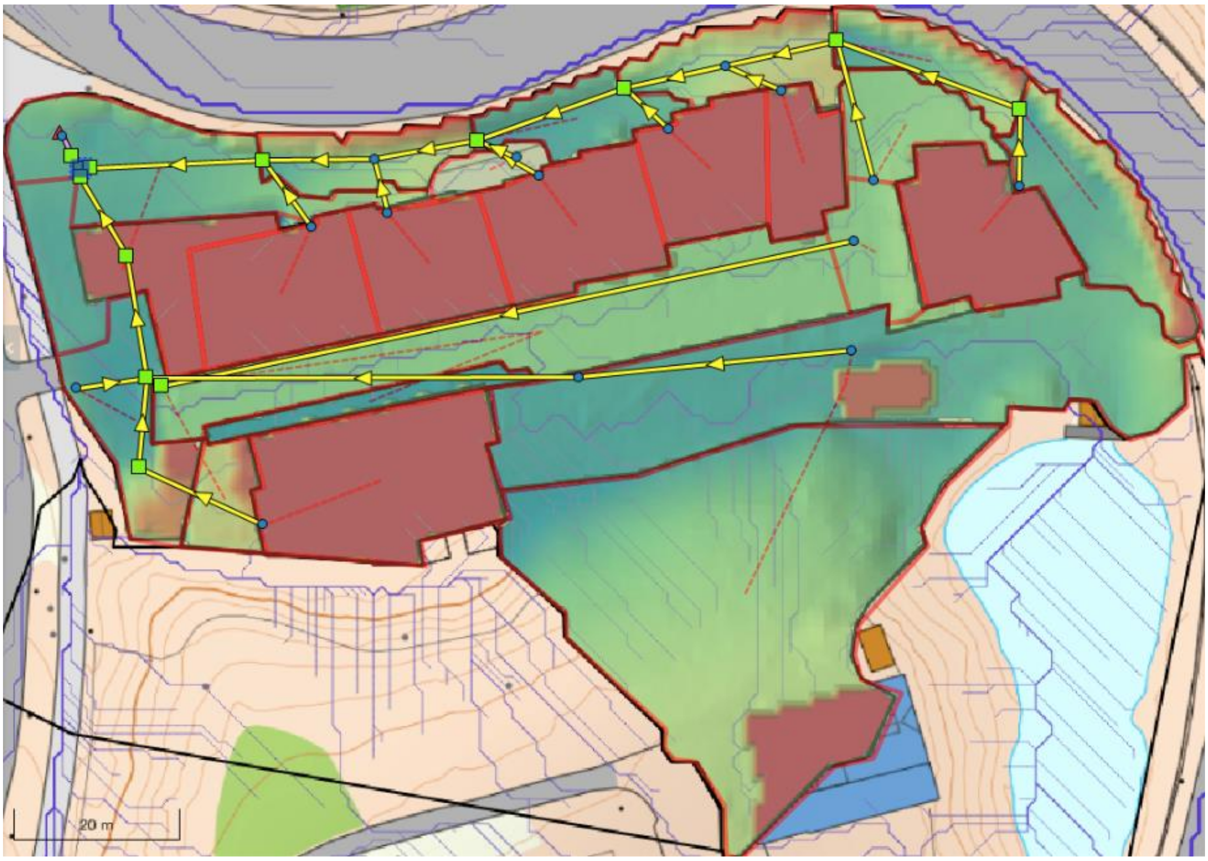


Figure 5.25 Map of Christinedal property in the PCSWMM model.

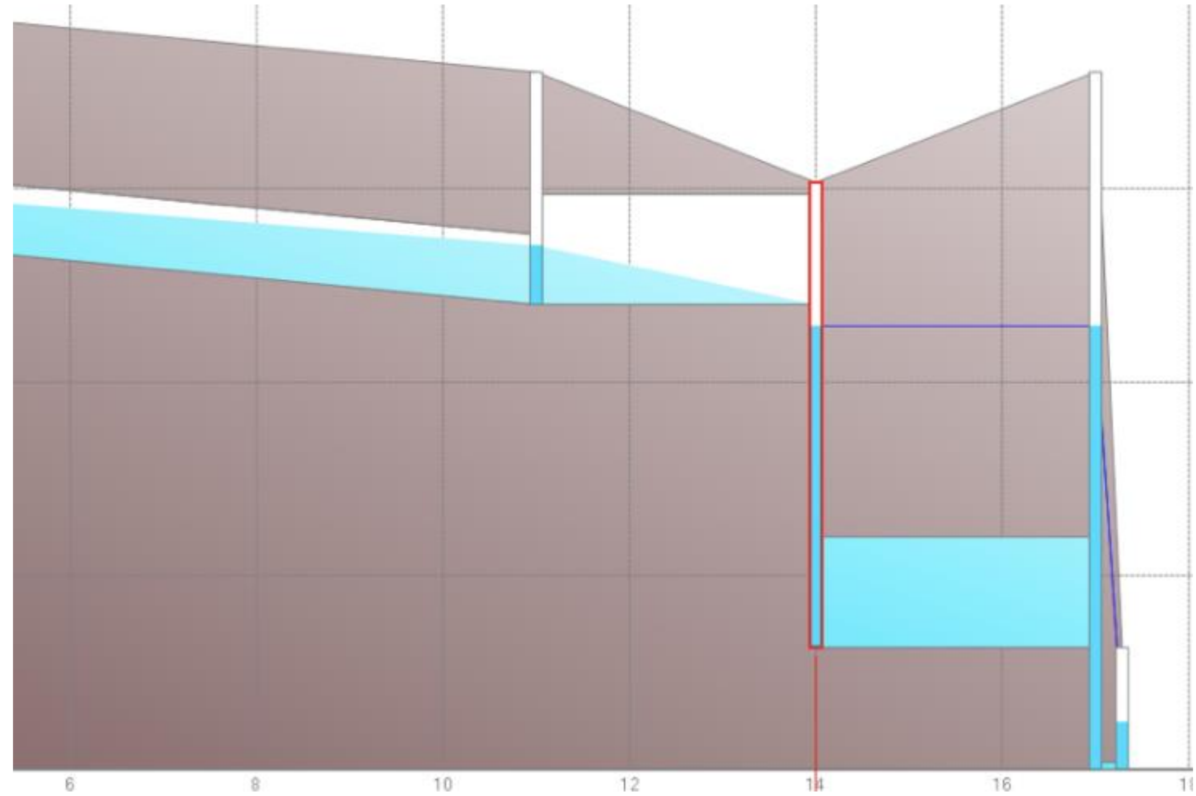


Figure 5.26 Profile of Christinedal detention system in PCSWMM model. The detention system is highlighted in red. The filling degree in this figure is taken from a random simulation.

Before simulating the rainfall events presented in the methodology, rainfall events recorded in the fall of 2018 in connection to the specialisation project were simulated. The simulated water depth in the flow regulating manhole was then compared to the observed depth. The results for four separate rainfall events can be viewed in Figure 5.27, where orange lines represent simulated depth and blue lines represent observed depth. As we can see, the simulated depth is larger than observed depth for all peak values. For the most part, the simulated and observed graphs follow a similar pattern, though the magnitude often differs. This especially holds true for the first and last event. The similarity in pattern instils some confidence in the model, though it is apparent that the model is not completely accurate, which should be considered when evaluating the results.

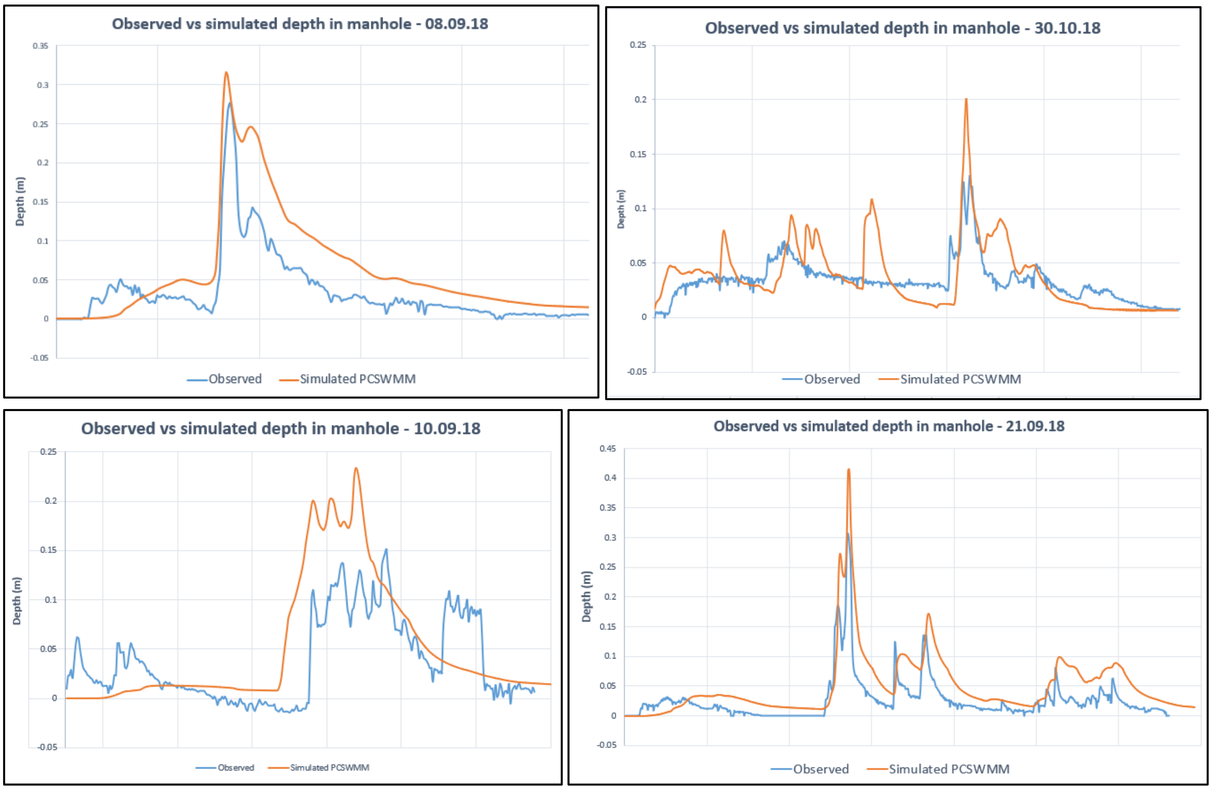


Figure 5.27 Simulated vs. observed water level depth in the flow regulating manhole for four different rainfall events recorded at Christinedal. Top left: Measured rainfall event on 08.09.18. Top right: Measured rainfall event on 30.10.18-31.10.18. Bottom left. Measured rainfall event on 10.09.18. Bottom right: Measured rainfall event on 21.09.18.

Each of the provided rainfall time series were simulated in the PCSWMM model. The maximum detention system volume observed for each simulation is tabulated below.

Table 5.27 Maximum simulated volume in the detention system Christinedal for several different rainfall time series.

Recorded rainfall events				
	Scaling factor 1		**Scaling factor 2**	
Rainfall	**Max volume simulated [m^3]**	**% of total detention system volume**	**Max volume simulated [m^3]**	**% of total detention system volume**
Blindern 2014	53.8	53.3 %	59.7	59.2 %
Sandaker 2013	73.2	72.5 %	73.2	72.5 %
Blindern 2008	43.7	43.3 %	48.8	48.4 %
Blindern 17.06.80	20.2	20.0 %	22.7	22.5 %
Blindern 06.08.80	68.1	67.5 %	73.2	72.5 %
Blindern IDF 20-year return period				
Rainfall duration	**Max volume simulated [m^3]**		**% of total detention system volume**	
1 hr	64.7		64.2 %	
3 hrs	71.5		70.9 %	
24 hrs	74.0		73.3 %	

Of all the rainfall events simulated, the largest detention system volume was $73.2\ m^3$ for the recorded events and $74.0\ m^3$ for the constructed events. This corresponds to respectively $72.5\ \%$ and $73.3\ \%$ of the dimensioned volume, thus pointing to the same conclusion as in the specialisation project and the results from section 5.1, i.e. that the detention system *Christinedal* is over-dimensioned for rainfalls with a 20-year return period. Though the simulation results and Sweco's dimensioning results differed significantly, there was similarity between the simulated volume and the volume found when using the new RCA and new runoff coefficients in the Excel template. The volumes differed with less than $5\ \%$, i.e. $74\ m^3$ versus $77\ m^3$. Thus, so far all work completed indicates that Sweco should lower the runoff coefficients they use or consider an alternative dimensioning method. However, the matter is not necessarily simple, as they must also be wary not to lower the runoff coefficients excessively, which could result in under-dimensioning of the detention system.

In Table 5.28 we see combinations of permeable and impermeable runoff coefficients that yield a detention system volume of $74\ m^3$ if used with the new RCA in Sweco's Excel template. These could potentially serve as suggested runoff coefficients for future dimensioning. For these computations, the RCA found by the author was roughly divided into permeable and impermeable surfaces, based on Table 5.1. The new RCA was used in lieu of Sweco's area appraisal because it is believed to be more accurate as it is based on careful consideration of flow pathways, and not an abstract property line. If we are to come up with suggestions for runoff coefficients to use in future dimensioning, there is no point in determining these based on an incorrect area appraisal. Since φ_i and A_i are both needed in the Excel template together, both must either be correct or incorrect simultaneously to yield the sought-out volume. Therefore, if the area appraisal is incorrect, so are the suggested runoff coefficients in the table below. Hence, the new RCA, which is believed to be more accurate, has been used in these computations.

Table 5.28 Combinations of permeable and impermeable runoff coefficients that yield a volume of 74 m^3 when using the new RCA for the Christinedal property in Sweco's Excel template.

Combinations of permeable and impermeable runoff coefficients	
Permeable runoff coefficient	**Impermeable runoff coefficient**
0	0.9
0.05	0.86
0.075	0.84
0.1	0.82
0.15	0.78
0.2	0.75

5.3.3 Results – Sensitivity analysis

The parameter sensitivity analysis will be conducted for the two rainfall events that produced the largest volumes, namely Sandaker 2013 and the 24-hr constructed event for Blindern. The modified parameter values, the new detention system volume, and the significance of the change, is seen in Table 5.29 and Table 5.30.

Table 5.29 Parameter sensitivity analysis for the PCSWMM modelling of Christinedal for the rainfall event Sandaker 2013. The maximum detention system volume for the simulation was 73.2 m^3. Due to the water level depth results having a resolution of 0.01, the volume has a resolution of 0.8, and the percentage reduction/increase below ±1.1 is unknown and could be in the range of 0 to ±1.1.

Sensitivity analysis – Sandaker 2013		
Parameter	**New maximum volume in detention system [m^3]**	**Reduction/increase [%]**
Infiltration		
Max infiltration 50 mm/hr	>101	> +38.0
Max infiltration 100 mm/hr	79.0	+7.9
Max infiltration 150 mm/hr	74.0	+1.1
Max infiltration 250 mm/hr	71.5	-2.3
Max infiltration 300 mm/hr	70.6	-3.6
Minimum infiltration 2 mm/hr	73.2	< ±1.1
Minimum infiltration 10 mm/hr	72.3	-1.2
Minimum infiltration 20 mm/hr	72.3	-1.2
Decay constant		
Decay constant = 2	70.6	-3.6
Decay constant = 6	74.0	+1.1
Drying time		-
Drying time = 6 days	73.2	< ±1.1
Drying time = 8 days	73.2	< ±1.1
Manning's n overland flow		
Impervious n=0.011	73.2	< ±1.1
Impervious n=0.014	71.5	-2.3
Pervious n=0.14	73.2	< ±1.1
Pervious n=0.16	72.3	-1.2
Evaporation		
Evaporation 0.5 mm	72.3	-1.2
Evaporation 1 mm	72.3	-1.2
Evaporation 2 mm	72.3	-1.2
Depression storage		
Impervious, all catchments 1.5 mm	73.2	< ±1.1
Impervious, all catchments 2.5 mm	72.3	-1.2
Pervious, all catchments 2.5 mm	73.2	< ±1.1
Pervious, all catchments 5 mm	73.2	< ±1.1
Pervious, all catchments 10 mm	73.2	< ±1.1
Zero Impervious		
10 % for all catchments	72.3	-1.2
40 % for all catchments	73.2	< ±1.1
Manning's n, pipe flow		
n=0.011	72.3	-1.2
n=0.013	73.2	< ±1.1
Pipe diameter		
All pipes one size smaller (if possible)	74.0	+1.1
All pipes one size larger (if possible)	72.3	-1.2

Table 5.30 Parameter sensitivity analysis for the PCSWMM modelling of Christinedal for the rainfall event Blindern 24hrs. The maximum detention system volume for the simulation was 74.0 m^3. Due to the water level depth results having a resolution of 0.01, the volume has a resolution of 0.8, and the percentage reduction/increase below ±1.1 is unknown and could be in the range of 0 to ±1.1.

Sensitivity analysis – Blindern 24 hrs		
Parameter	**New maximum volume in detention system [m^3]**	**Reduction/increase [%]**
Infiltration		
Max infiltration 50 mm/hr	>101	> +36.5
Max infiltration 100 mm/hr	94.2	+27.3
Max infiltration 150 mm/hr	75.7	+2.3
Max infiltration 250 mm/hr	73.2	-1.1
Max infiltration 300 mm/hr	72.3	-2.3
Minimum infiltration 2 mm/hr	74.0	< ±1.1
Minimum infiltration 10 mm/hr	74.0	< ±1.1
Minimum infiltration 20 mm/hr	73.2	-1.1
Decay constant		
Decay constant = 2	71.5	-3.4
Decay constant = 6	76.5	+3.4
Drying time		
Drying time = 6 days	74.0	< ±1.1
Drying time = 8 days	74.0	< ±1.1
Manning's n overland flow		
Impervious n=0.011	74.8	+1.1
Impervious n=0.014	73.2	-1.1
Pervious n=0.14	74.0	< ±1.1
Pervious n=0.16	74.0	< ±1.1
Evaporation		
Evaporation 0.5 mm	74.0	< ±1.1
Evaporation 1 mm	74.0	< ±1.1
Evaporation 2 mm	74.0	< ±1.1
Depression storage		
Impervious, all catchments 1.5 mm	74.0	< ±1.1
Impervious, all catchments 2.5 mm	74.0	< ±1.1
Pervious, all catchments 2.5 mm	74.8	
Pervious, all catchments 5 mm	74.8	+1.1
Pervious, all catchments 7 mm	74.0	+1.1
Zero Impervious		< ±1.1
10 % for all catchments	74.0	
40 % for all catchments	74.0	< ±1.1
Manning's n, pipe flow		
n=0.011	74.0	< ±1.1
n=0.013	74.0	< ±1.1
Pipe diameter		
All pipes one size smaller (if possible)	75.7	+1.9
All pipes one size larger (if possible)	73.2	-1.1

The most significant impact on the resulting volume is when the maximum infiltration capacity is reduced to 50 mm/hr. However, this parameter change is considered to be so drastic that it is deemed unrealistic. As stated previously, the infiltration rate of 202 mm/hr was set as a conservative value based on Solheim et al. (2017), and as such, an on-site infiltration rate beyond 202 mm/hr is deemed more likely than 50 mm/hr. Thus, the sensitivity to higher infiltration rates is of greater concern than small infiltration rates, and fortunately, the sensitivity to this change is not extremely significant.

The second most sensitive parameter is decay constant. Therefore, more work should be done to obtain a reliable decay constant to use in the model. The other sensitivities observed in the analysis are deemed small enough to be within an acceptable margin of error in this thesis. Considering the great uncertainty in such dimensioning, the observed sensitivity will likely have little impact on the final volume that is chosen for the detention system.

6.Case II: Siemens

The second case being assessed is the detention system *Siemens.* As with the former case, the objectives are to find the best estimate for the RCA using SCALGO, to complete an in-depth evaluation of runoff coefficients, and finally, to model the new RCA in PCSWMM to find a fitting detention system volume for the property. The work begins with determining the RCA and assigning runoff coefficients.

6.1 Assessing runoff contributing area and runoff coefficients

Uncertainties and shortcomings of SCALGO were discussed in the methodology and when assessing Case I, so to avoid repetition, more discussion on this will be limited when assessing *Siemens*. The same applies to detailed explanations of the procedure in and functions of SCALGO, and therefore, the amount of details given for this case will reduced in comparison to the *Christinedal* case. However, in likeness to the former case, placement of storm drains on the property, other drainage systems, and flow pathways, will be used to determine the RCA to the detention system, and all decisions and assumptions will be presented clearly. In the figures below, we see two depictions of the area used by Sweco when dimensioning; one is illustrated by a simple map, and the other by aerial photos. However, as we will soon see, this is not an accurate assessment of the area contributing runoff to the detention system.

Figure 6.1 Left: Map depicting the area used by Sweco to dimension the Siemens detention system. Right: Aerial photo depicting the Siemens property.

6.1.1 Determining runoff contributing area

On Figure 6.2 below, key features of the drainage system on the property have been highlighted. The red and purple circles indicate the locations of storm drains, the blue line represents an open drain on the plateau above the detention system, and the detention system is marked by a green rectangle in the lower right corner. The storm drains have been marked in different colours, since the runoff is collected and transported in two seperate pipe systems. Runoff entering the red storm drains is transported around the building on the lefthand side, whilst runoff entering the purple storm drains is transported on the righthand side of the building. The open drain collects water in front of the building's main entrance and transports it to the storm drain below. By posessing this information, we can now use SCALGO to estimate the area that contributes runoff to the drainage system connected to the detention system.

Figure 6.2 Location of drainage system features on the Siemens property. Storm drains are marked by red or purple circles, the location of an open drain is marked by a blue line, and the detention system is marked by a green rectangle.

We start by looking at the north-eastern part of the property. When using SCALGO's watershed tool, it would appear as if a large area north of the *Siemens* property contributes flow towards the storm drains marked in purple. This can be observed in the first figure below. However, due to the existence of a private drainage system that collects runoff produced on the above-lying property, as can be seen from Figure 6.4, only around half of this watershed contributes runoff to the detention system. Hence, a portion of this area will be excluded from the final RCA. The blue rooftop area covered by the watershed is not included either, due to the building having its own separate drainage system.

Figure 6.3 (Left) Area contributing runoff to the purple storm drains according to SCALGO.

Figure 6.4 (Right) Private stormwater drainage system north of the Siemens property.

For the storm drains north-west of the building, the ones marked in red, each separate watershed will not be depicted, but rather the accummulated area found when using SCALGO. The water flows in the south-western direction. The green area in Figure 6.5 is approximately 3279 m^2, however, 370 m^2 of this is rooftop, which is part of a separate water contributing entity. This results in a north-western area of approximately 2909 m^2.

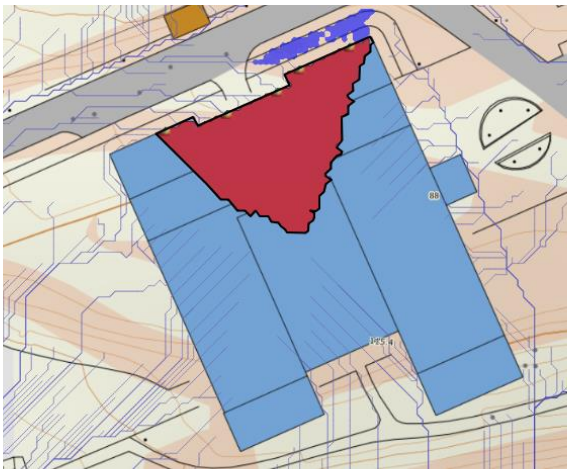


Figure 6.5 (Left) Watershed contributing runoff to the storm drains located in the northern area.

Figure 6.6 (Right) Rooftop being excluded from the northern area, due to the rooftop being computed as a separate entity.

The area on the righthand side of the *Siemens* building also contributes runoff to the detention system. This area, hereby referred to as the central area, can be viewed in Figure 6.7 below. First, the runoff collects in the open drain that was marked on Figure 6.2. It is thereby transported to the storm drain located on the southernmost point of the green watershed in Figure 6.7. From here, the water is transported into the same pipe system as the other purple storm drains. The central area is approximately 748 m^2.

The last storm drain so far not appraised is the one located directly to the right of the detention system. According to SCALGO, it captures water from a small area north-east of its location, seen in Figure 6.8, and the area size is approximately 249 m^2.

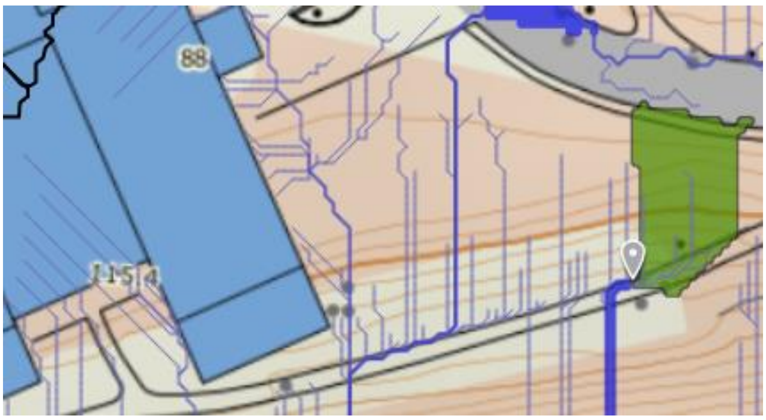


Figure 6.7 (Left) Watershed contributing runoff to the storm drain located in the central area.

Figure 6.8 (Right) Small watershed connected to the storm drain located close to the detention system in the southern part of the property.

As is apparent from Figure 6.2, the only storm drain south of the building is located on the far-right side of the property, and as we just saw, this storm drain only captures runoff from a small area located in its vicinity. This means that all other areas south of the highlighted storm drains do not contribute runoff to the detention system, as the runoff has no way of entering the system. This excludes a large part of the area used by Sweco in their dimensioning, and in fact, excludes large parts of the *Siemens* property. However, as we have also seen, areas north of the property are included in the new RCA, which was not the case for Sweco's area appraisal.

There is only one large building located on the property that contributes to the detention system. In likeness to the main buildings by *Christinedal*, the rooftop is flat, and the runoff is collected and transported directly to the detention system. The rooftop area is approximately 2970 m^2. There is also one smaller buliding on the property, seen as the orange square north of the main bulding. This building has a flat rooftop as well, and an area of approximately 32 m^2. Runoff from this building will run onto the surface below.

Figure 6.9 The two buildings that contribute runoff to the Siemens *detention system. The main building in the centre of the map (blue) has an area of approximately 2970* m^2*, and the small orange building north of the main building has an area of approximately 32* m^2*.*

On the following page, we can view the different sub-areas that are added and subtracted to form the final RCA, which can be viewed in both Figure 6.18 and Figure 6.19. This area is approximately 11'996 m^2 and is an estimate based on work in SCALGO. The size corresponds to approximately 104% of the area used by Sweco in their dimensioning, indicating nearly identical area sizes. Despite the similarity in size though, the placement of the area appraisal borders are significantly dissimilar. Sweco's area appraisal includes areas in the vicinity of the detention system, which the author's RCA does not. On the other hand, the author's RCA includes a large area north of the property, which was not included in Sweco's dimensioning area. This promotes the idea that it might be coincidental that the area sizes are of such similarity. It is believed that the RCA found by utilising SALGO is more accurate than the one used by Sweco, as the assessment considers topography and flow direction on the surface, contrary to just an abstract property line. It is obvious that the areas south of the main building, which were included in Sweco's appraisal, do not contribute to the detention system, as there is no drainage system located there. Therefore, the new RCA is deemed more precise than Sweco's area.

North-east area
+1.17 ha

Figure 6.10 North-eastern watershed as seen in SCALGO.

Private property
-0.61ha

Figure 6.11 Privately drained area as seen in SCALGO.

Rooftop
-480 m^2

Figure 6.12 Rooftop area estimated using workspace tool.

North area
+3279 m^2

Figure 6.13 Northern watershed as seen in SCALGO.

Rooftop
-370 m^2

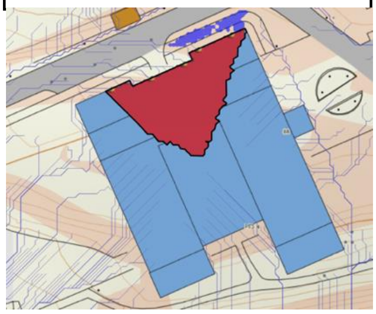


Figure 6.14 Rooftop area estimated using workspace

South area
+249 m^2

Figure 6.15 Southern watershed as seen in

Central area
+748 m^2

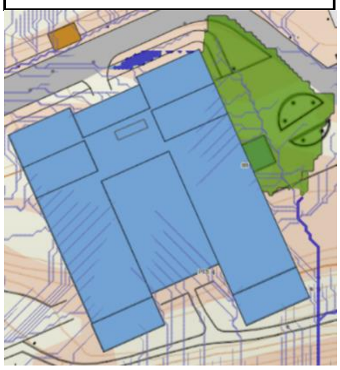


Figure 6.16 Central watershed as seen in

Rooftop
+2970 m^2

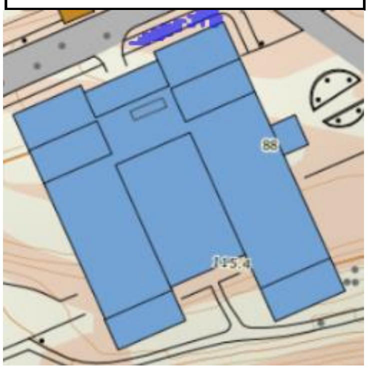


Figure 6.17 Rooftop area.

Total area
11'996 m^2

Figure 6.18 Total runoff contributing area marked in green.

$$A = 11'700m^2 - 6100m^2 - 480m^2 + 3279m^2 - 370m^2 + 249m^2 + 748 + 2970 = \mathbf{11'996}\ m^2$$

Figure 6.19 Final runoff contributing area marked in green. The runoff area also includes the main building in the lower left part of the figure.

6.1.2 Assigning runoff coefficients

Now that the RCA has been determined, the work towards dividing the area into different sub-sections and assigning runoff coefficients can begin. The *Siemens* property is less complex than *Christinedal* when it comes to variety of surface types, and as such, the number of surface-types in need of a runoff coefficient will be smaller. The number of sub-areas to be modelled in PCSWMM will also be smaller. The different surface types and the characteristics of the sub-areas will be assessed in the tables below, in the same manner as for *Christinedal*. Figure 6.20 shows the division of the RCA into different surface types.

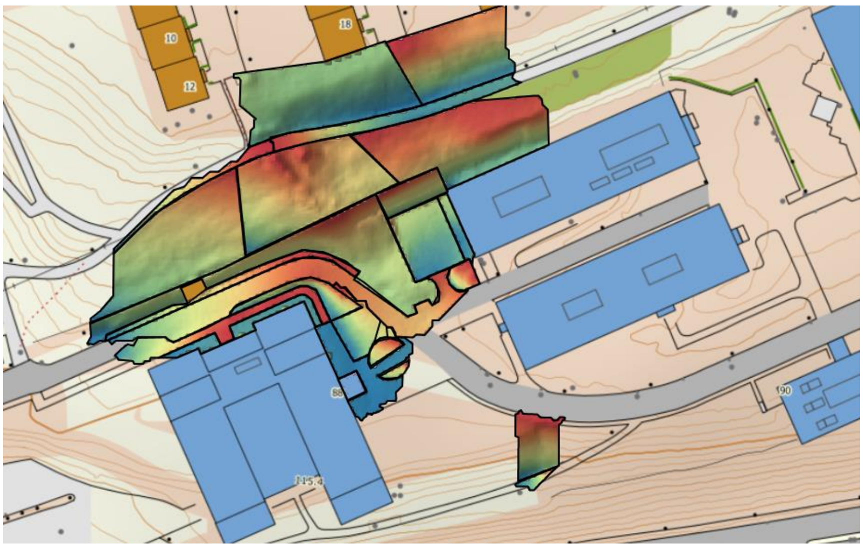


Figure 6.20 Detailed division of the RCA into sub-areas with different surface types.

Table 6.1 A summary of the different surface types observed on the Siemens property, and approximate sizes for each surface type. The third column lists characteristics of the sub-areas/surface types that might affect the runoff coefficient. Permeable surfaces equal approximately 6634 m^3 and impermeable surfaces approximately 5362 m^3.

Area division by surface type		
Surface type	**≈Area $[m^2]$**	**Comment**
Rooftop directly linked to detention system	2970	Flat surface
Balcony and rooftop not linked to detention system	76	Flat surface
Asphalt	2074	Some flat Some gently sloped
Large Paving stones	242	≈Flat
Gravel	27	≈Gently sloped
Bushes and stones	155	Surrounded by impervious surface areas
Short grass	950	Mostly flat
Tall and dense grass	5502	Steep slope

For each different surface type listed in the table above, a runoff coefficient will be determined. The selection will primarily be based on guideline values from section 3 and secondarily on other area characteristics and understanding of hydrological processes. The runoff coefficients will be given for a 20-year rainfall event.

Table 6.2 Estimation of runoff coefficient for the surface type "rooftop, directly linked to detention system" with the characteristics specified in the table.

Rooftop directly linked to detention system	
φ - NW	0.8-0.9
φ – NPRA	-
φ - SWWA	0.9
Characteristic	Consequence
Flat roof	See Table 5.2, "Characteristic: Flat roof"
Directly linked to detention system	See Table 5.2, "Characteristic: Directly linked to detention system"
Concluding φ	Comment
0.85	The main building on the Siemens property will be given the same runoff coefficient as the main buildings on the *Christinedal* property, due to similar characteristics. Arguments for the choice of runoff coefficient can therefore be regarded in Table 5.2.

Table 6.3 Estimation of runoff coefficient for the surface type "rooftop, not directly linked to detention system" with the characteristics specified in the table.

Rooftop and balcony *not* directly linked to detention system	
***φ* - NW**	0.8-0.9
***φ* – NPRA**	-
***φ* - SWWA**	0.9
Characteristic	Consequence
Flat roof	See Table 5.2, "Characteristic: Flat roof"
Not directly linked to detention system	See Table 5.3, "Characteristic: Not directly linked to detention system"
Concluding ***φ***	Comment
0.9	Both the characteristics "flat rooftop" and "not directly connected to detention system" would indicate a lower runoff coefficient. Therefore, this area will be given a slightly lower coefficient than the one used for the surface type "slanted and not connected" from the *Christinedal* case.

Table 6.4 Estimation of runoff coefficient for the surface type "asphalt" with the characteristics specified in the table.

Asphalt	
***φ* - NW**	0.7-0.8
***φ* – NPRA**	0.6-0.9
***φ* - SWWA**	0.8
Characteristic	Consequence
Gently sloped	See Table 5.4, "Characteristic: ≈50% gently sloped towards the detention system"
Very gently sloped	A part of the asphalted area has a *very* slight slope towards the storm drains. This slope is considered steep enough for the water to easily flow towards the storm drains, but not enough to increase the velocity of the runoff significantly. Thus, the runoff coefficient is slightly higher than for a completely flat area, but not as high as for a more sloped surface.
Concluding ***φ***	Comment
0.85 for gently sloped 0.8 for *very* gently sloped	The influence of slope on the runoff coefficient has been considered significant enough to provide two different runoff coefficients; 0.85 for the sloped area and 0.8 for the *very* gently sloped area.

Table 6.5 Estimation of runoff coefficient for the surface type "paving stones" with the characteristics specified in the table.

Paving stones	
φ - NW	-
φ – NPRA	-
φ - SWWA	0.7
Characteristic	Consequence
≈Paving stone joints	The joints between the paving stones could allow for infiltration into the ground. However, the paving stones are large, and hence, there is little "joint area" relative to stone area. Thus, there is little opportunity for water to infiltrate, and the paving stones are considered to have a runoff coefficient only marginally smaller than concrete, which has a runoff coefficient range of 0.6-0.9 according to the sources used in section 3.
≈Flat	The flat surface will allow the water more time to seep in between the paving stone joints, in additions to allowing more time for evaporation, thus indicating a lower runoff coefficient.
Antecedent moisture conditions	Antecedent moisture conditions are not deemed significant due to the belief that very little water will infiltrate into the paving stone joints.
Concluding φ	Comment
0.8	The paving stone joints are not thought to lower the runoff coefficient significantly, and a runoff coefficient of 0.8 is therefore chosen, as this is a commonly agreed upon runoff coefficient for concrete.

Table 6.6 Estimation of runoff coefficient for the surface type "gravel" with the characteristics specified in the table.

Gravel	
φ - NW	0.4-0.6
φ – NPRA	0.3-0.7
φ - SWWA	0.2-0.4
Characteristic	Consequence
≈Gently sloped	Sloped terrain will result in more rapid movement of water. This indicates a higher runoff coefficient, as the water does not have as much time to be subjugated to evaporation and/or infiltration.
Location	The majority of the gravel is located in an area where neither people nor vehicles will often reside, and therefore, one can expect the gravel to be less compacted.
Antecedent moisture conditions	See Table 5.6, "Characteristic: Antecedent moisture conditions"
Concluding φ	Comment
0.5	Due to the assumption that the gravel is not compacted to the same degree as at *Christinedal*, a slightly lower runoff coefficient is chosen, i.e. 0.45. Multiplying this with the Viessmann & Lewis coefficient of 1.1, the result is a runoff coefficient of approximately 0.5 for gravel.

Table 6.7 Estimation of runoff coefficient for the surface type "short grass" with the characteristics specified in the table.

Short grass	
φ - NW	0.05-0.1
φ – NPRA	0.2-0.4
φ - SWWA	0.1-04
Characteristic	Consequence
Vegetation	See Table 5.7, "Characteristic: Vegetation"
Mostly flat, but some sloped sections	Flat terrain will allow more time for evaporation and infiltration into the ground, and thus less runoff production.
Geotechnical investigation	According to Sweco's documentation, a geotechnician has reported good infiltration properties on the property. This would indicate a lower runoff coefficient. However, since no more details have been specified, just *how* good the infiltration properties are is unknown.
Antecedent moisture conditions	See Table 5.7, "Characteristic: Antecedent moisture conditions"
Concluding **φ**	Comment
0.16	Based on the characteristics outlined above, an initial runoff coefficient of 0.15 was given for the short grass areas. Multiplying with 1.1 due to antecedent conditions, yields the concluding runoff coefficients of 0.16.

Table 6.8 Estimation of runoff coefficient for the surface type "bushes and tall/dense grass" with the characteristics specified in the table.

Bushes and tall/dense grass	
φ - NW	0.05-0.1
φ – NPRA	0.2-0.4
φ - SWWA	0.1-04
Characteristic	Consequence
Vegetation	See Table 5.9, "Characteristic: Vegetation"
Sloped	The sloped terrain will allow for less time for evaporation and infiltration into the ground, and thus more runoff production. Some of the tall grass areas have a slope as steep as 20%.
Antecedent moisture conditions	See Table 5.9, "Characteristic: Antecedent moisture conditions"
Geotechnical investigation	See Table 6.7, "Characteristic: Geotechnical investigation"
Concluding **φ**	Comment
0.06	Based on the information above, the initial runoff coefficient is set to 0.05, which becomes 0.06 after multiplying by 1.1.

Now that a runoff coefficient has been determined for each surface type, the RCA must be divided into sub-areas more proper for modelling in PCSWMM. Like the former case, each of these sub-areas will be given a runoff coefficient that describes the combination of surface types within the area, as well as the interaction amongst the different surface types. The division into sub-areas can be viewed in Figure 6.21, followed by tables describing the choice of runoff coefficients.

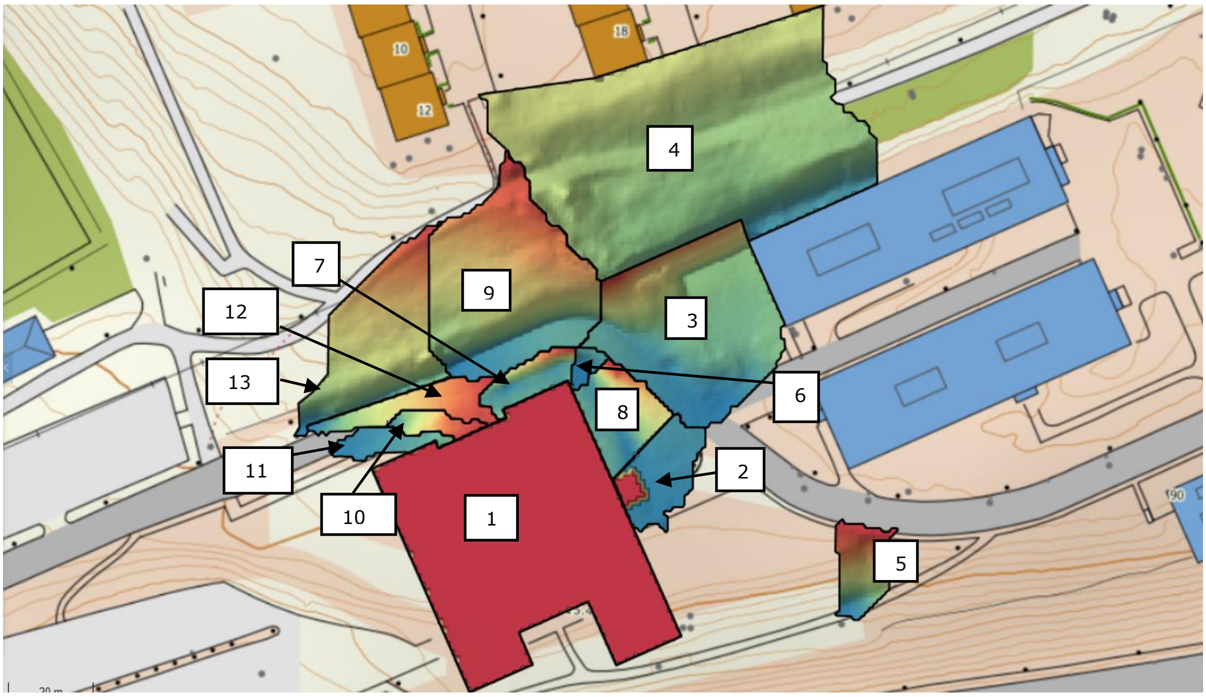


Figure 6.21 Final division into sub-areas. These sub-areas will be modelled as separate sub-catchments in PCSWMM.

Table 6.9 Justification for selection of runoff coefficient for area 1.

Justification for runoff coefficient selection	
Area	1
Size	$2970\ m^2$
Runoff coefficient, φ	0.85
Justification for φ	This area consists of flat rooftops directly linked to the detention system; a surface type that was determined to have a runoff coefficient of 0.85 in Table 6.2.

Table 6.10 Justification for selection of runoff coefficient for area 2.

<table>
<tr><td colspan="4">Justification for runoff coefficient selection</td></tr>
<tr><td>Area</td><td colspan="3">2</td></tr>
<tr><td>Accumulated size</td><td colspan="3">$352\ m^2$</td></tr>
<tr><td>Runoff coefficient, φ</td><td colspan="3">0.66</td></tr>
<tr><td rowspan="6">Justification for φ</td><td colspan="3">Sub-area composition</td></tr>
<tr><td>≈Area $[m^2]$</td><td>Surface type</td><td>φ</td></tr>
<tr><td>66</td><td>Bushes</td><td>0.06</td></tr>
<tr><td>242</td><td>Paving stones</td><td>0.8</td></tr>
<tr><td>44</td><td>Balcony</td><td>0.9</td></tr>
<tr><td colspan="3">$$\varphi_{avg} = \frac{66 * 0.06 + 242 * 0.8 + 44 * 0.9}{66 + 286} = 0.674$$
Since the bushes in this area are bordered by a metal curb, little of this water is expected to become runoff that flows towards the detention system. Therefore, if runoff contribution from the bushes is neglected, the new runoff coefficient is 0.66.</td></tr>
</table>

Table 6.11 Justification for selection of runoff coefficient for area 3.

<table>
<tr><td colspan="4">Justification for runoff coefficient selection</td></tr>
<tr><td>Area</td><td colspan="3">3</td></tr>
<tr><td>Accumulated size</td><td colspan="3">$1462\ m^2$</td></tr>
<tr><td>Runoff coefficient, φ</td><td colspan="3">0.49</td></tr>
<tr><td rowspan="5">Justification for φ</td><td colspan="3">Sub-area composition</td></tr>
<tr><td>≈Area $[m^2]$</td><td>Surface type</td><td>φ</td></tr>
<tr><td>750</td><td>Very gently sloped asphalt</td><td>0.8</td></tr>
<tr><td>712</td><td>Short grass</td><td>0.16</td></tr>
<tr><td colspan="3">$$\varphi_{avg} = \frac{750 * 0.8 + 712 * 0.16}{750 + 712} = 0.488$$</td></tr>
</table>

Table 6.12 Justification for selection of runoff coefficient for area 4.

<table>
<tr><td colspan="4">Justification for runoff coefficient selection</td></tr>
<tr><td>Area</td><td colspan="3">4</td></tr>
<tr><td>Accumulated size</td><td colspan="3">$3586\ m^2$</td></tr>
<tr><td>Runoff coefficient, φ</td><td colspan="3">0.09</td></tr>
<tr><td rowspan="5">Justification for φ</td><td colspan="3">Sub-area composition</td></tr>
<tr><td>≈Area $[m^2]$</td><td>Surface type</td><td>φ</td></tr>
<tr><td>276</td><td>Gently sloped asphalt</td><td>0.85</td></tr>
<tr><td>3310</td><td>Dense grass</td><td>0.06</td></tr>
<tr><td colspan="3">$$\varphi_{avg} = \frac{276 * 0.85 + 3310 * 0.06}{276 + 3310} = 0.121$$
The area weighted average runoff coefficient for this area is 0.121. However, we can expect some of the runoff produced on the asphalt road to be infiltrated on the permeable hill below, thus resulting in a slightly reduced runoff coefficient. Assuming that 50% of the impermeable runoff is infiltrated on the permeable areas, the final runoff coefficient is 0.09.</td></tr>
</table>

Table 6.13 Justification for selection of runoff coefficient for area 5.

<table>
<tr><td colspan="4">Justification for runoff coefficient selection</td></tr>
<tr><td>Area</td><td colspan="3">5</td></tr>
<tr><td>Accumulated size</td><td colspan="3">$249\ m^2$</td></tr>
<tr><td>Runoff coefficient, φ</td><td colspan="3">0.15</td></tr>
<tr><td rowspan="6">Justification for φ</td><td colspan="3">Sub-area composition</td></tr>
<tr><td>≈Area $[m^2]$</td><td>Surface type</td><td>φ</td></tr>
<tr><td>196</td><td>Dense grass</td><td>0.06</td></tr>
<tr><td>27</td><td>Gravel</td><td>0.5</td></tr>
<tr><td>26</td><td>Gently sloped asphalt</td><td>0.85</td></tr>
<tr><td colspan="3">$$\varphi_{avg} = \frac{196 * 0.06 + 27 * 0.5 + 26 * 0.85}{196 + 27 + 26} = 0.19$$
The area weighted average runoff coefficient for this area is 0.19. However, we can expect some of the runoff produced on the asphalt to be infiltrated on the permeable hill below, thus resulting in a slightly reduced runoff coefficient. Assuming 50% of the asphalt-runoff is infiltrated on the grass hill, the final runoff coefficient is 0.15.</td></tr>
</table>

Table 6.14 Justification for selection of runoff coefficient for areas 6 and 7.

Justification for runoff coefficient selection			
Areas	6, 7		
Accumulated size	$55 + 187 = 242\ m^2$		
Runoff coefficient, φ	0.5		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	123	Short grass	0.16
	119	Asphalt	0.85
	$\varphi_{avg} = \frac{123 * 0.16 + 119 * 0.85}{123 + 119} = 0.499$		

Table 6.15 Justification for selection of runoff coefficient for area 8.

Justification for runoff coefficient selection			
Area	8		
Accumulated size	$366\ m^2$		
Runoff coefficient, φ	0.66		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	89	Bushes	0.06
	277	Asphalt	0.85
	$\varphi_{avg} = \frac{89 * 0.06 + 277 * 0.85}{89 + 277} = 0.658$		

Table 6.16 Justification for selection of runoff coefficient for areas 10, 11 and 12.

Justification for runoff coefficient selection			
Areas	10, 11, 12		
Accumulated size	$100 + 134 + 258 = 492\ m^2$		
Runoff coefficient, φ	0.69		
Justification for φ	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	**φ**
	377	Asphalt	0.85
	115	Short grass	0.16
	$\varphi_{avg} = \frac{377 * 0.85 + 115 * 0.16}{377 + 115} = 0.689$		

Table 6.17 Justification for selection of runoff coefficient for areas 9 and 13.

Justification for runoff coefficient selection			
Areas	9, 13		
Accumulated size	$1421 + 856 = 2277\ m^2$		
Runoff coefficient, φ	0.11		
	Sub-area composition		
	≈Area $[m^2]$	**Surface type**	$\boldsymbol{\varphi}$
	1996	Dense grass	0.06
	32	Flat rooftop	0.9
	249	Asphalt	0.85
Justification for φ	$\varphi_{avg} = \frac{1996 * 0.06 + 32 * 0.9 + 249 * 0.85}{1996 + 32 + 249} = 0.158$ The area weighted average runoff coefficient for these areas is 0.158. However, if assuming that approximately 50% of the runoff produced on the asphalt is infiltrated into the permeable areas below, the new runoff coefficient becomes 0.11.		

6.1.3 New $\varphi * A$ and Sweco's template

As has been stated previously, the areas found by Sweco and by the author are nearly identical in size, although different in extent. Thus, most of the difference between Sweco's and the author's Excel template volume is caused by the choice of runoff coefficients, and not the area size. Below, we can see the computations for the area weighted average runoff coefficient for each of the area appraisals, as well as the computations for the reduced RCA, $\varphi_i * A_i$. The coefficient found by the author is approximately 35% lower than the one used by Sweco. By inputting $\varphi_i * A_i$ into the Excel template, Sweco's values yields a necessary storage volume of 223 m^3, whilst the newfound values yield a volume of 143 m^3. This is a 36% reduction, caused solely on the reduction in runoff coefficients. However, as was commented on earlier, there is no guarantee that the runoff coefficients found in this thesis are any more precise than the ones used by Sweco. Nonetheless, the results once again show that the choice of runoff coefficient is highly influential on the final volume results, and that great consideration should be taken when selecting them.

$$\varphi_{tot,Nicoline} = (2970 * 0.85 + 352 * 0.66 + 1462 * 0.49 + 3586 * 0.09 + 249 * 0.15 + 242 * 0.5 + 366 * 0.66 + 492 * 0.69 + 2277 * 0.11)/(2970 + 352 + 1462 + 3586 + 249 + 242 + 366 + 492 + 2277) = \mathbf{0.399}$$

$$Reduced\ RCA = \varphi_{tot,Nicoline} * A_{Nicoline} = 0.399 * 11996 = \mathbf{4786}\ m^2$$

$$V(\varphi_{tot,Nicoline} * A_{Nicoline}, K_f = 1.1) = \mathbf{143\ m^3}$$

$$\varphi_{tot,Sweco} = \frac{5900 * 0.9 + 5655 * 0.3}{5900 + 5655} = \mathbf{0.606}$$

$$Reduced\ RCA = \varphi_{tot,Sweco} * A_{Sweco} = 0.606 * 11555 = \mathbf{7007}\ m^2$$

$$V(\varphi_{tot,Sweco} * A_{Sweco}, K_f = 1.1) = \mathbf{223}\ m^3$$

6.2 PCSWMM

6.2.1 Input

The sub-areas shown in Figure 6.21 have been modelled in PCSWMM and the parameter input will now be presented. The parameter values for sub-catchments, junctions, conduits and storage units were found following the procedure outlined in the methodology section, i.e. by using maps and documents provided by Sweco or by information gathered using SCALGO. A few selected parameter values are shown in Table 6.18 below.

Table 6.18 Parameter values for each sub-catchment in the Siemens PCSWMM-model.

Input parameters used in PCSWMM						
Sub-catchment	**Imperv. percent [%]**	**N imperv.**	**N perv.**	**Dstore imperv. [mm]**	**Dstore perv. [mm]**	**Zero Imperv. [%]**
1	100	0.013	0	2	0	25
2	81	0.013	0.15	2	20	25
3	51	0.013	0.15	2	5	25
4	8	0.013	0.18	2	5	25
5	16	0.013	0.20	2	5	25
6	49	0.013	0.15	2	3.5	25
7	49	0.013	0.15	2	3.5	25
8	76	0.013	0.15	2	3.5	25
9	12	0.013	0.18	2	5	25
10	77	0.013	0.15	2	3.5	25
11	77	0.013	0.15	2	3.5	25
12	77	0.013	0.15	2	3.5	25
13	12	0.013	0.18	2	5	25

In the table above, we can see that one of the parameter values for sub-catchment 2 differs from the guideline values tabulated in the methodology section. The reasoning is the same as for *Christinedal*, i.e. that the permeable surface in this sub-area is bordered by a curb, which entraps the runoff, resulting in ponding. This is modelled as an increase in depression storage depth. The rest of the parameter values are within the range of suggested values.

It has been determined to use a Manning's number of 0.012 for all PVC conduits and 0.013 for concrete conduits. Diameters have been entered according to data obtained from

Sweco, and this input data can be viewed in the Appendix. Additional parameter values are listed in the table below. The infiltration rate has been set higher than what was argued for in the methodology, as documentation from Sweco shows that a geotechnician has reported good infiltration properties on the property, thus indicating a higher value than the conservative value of 202 mm/hr. However, this value still considered to be somewhat conservative compared to infiltration values measured by Solheim et al..

Table 6.19 Input parameters to the Siemens PCSWMM-model. The values stated are used for all sub-catchments.

Input parameters used in PCSWMM	
Parameter	**Value**
Maximum infiltration rate	250 mm/hr
Minimum infiltration rate	5 mm/hr
Decay constant	4
Drying time	7 days
Evaporation rate	0 mm/day

6.2.2 Results – Detention system volume

Figure 6.22 below shows the map of the *Siemens* PCSWMM model. Each sub-catchment is bordered by a black line, the conduits are marked in yellow, and the manholes are depicted as blue circles or green squares. The property has been modelled according to the description outlined in the methodology section and the current section. Figure 6.23 shows the profile of the detention system, outlined in red, for a random simulation. The detention system was modelled as a conduit instead of as a storage unit, as this was the easiest method for modelling the volume accurately.

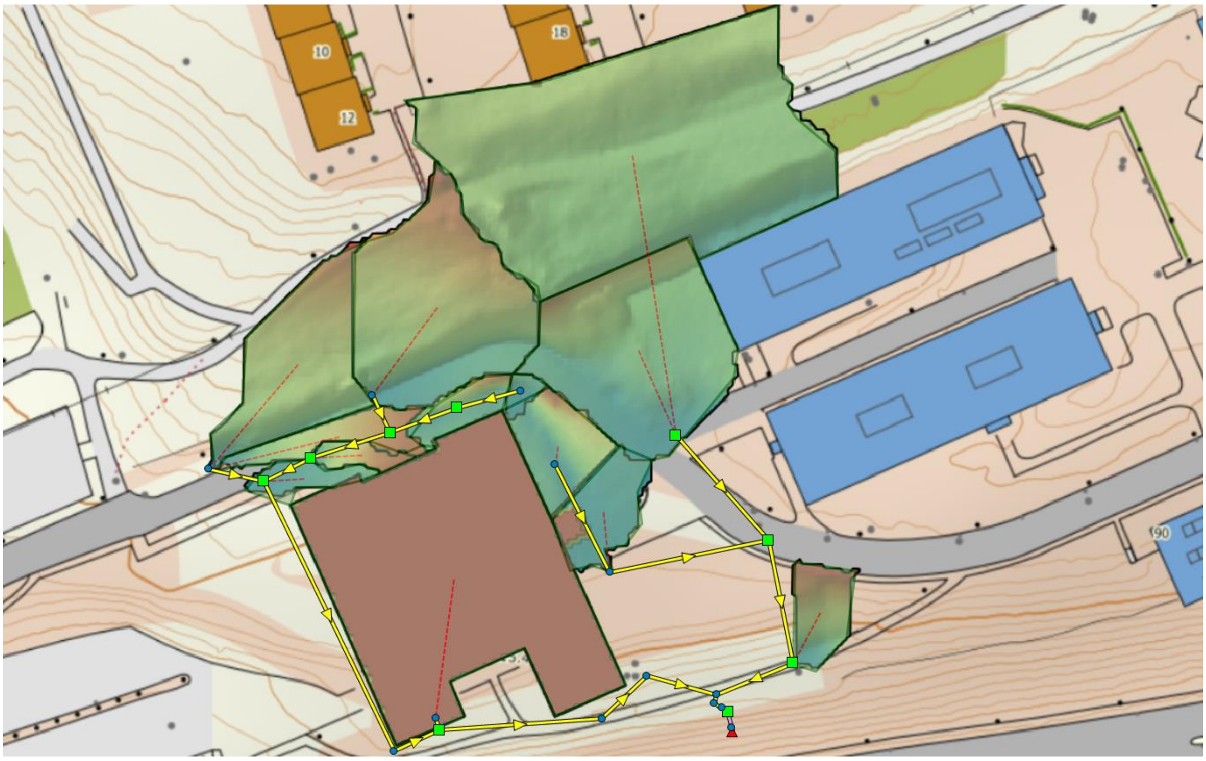


Figure 6.22 Map of Siemens property in the PCSWMM model.

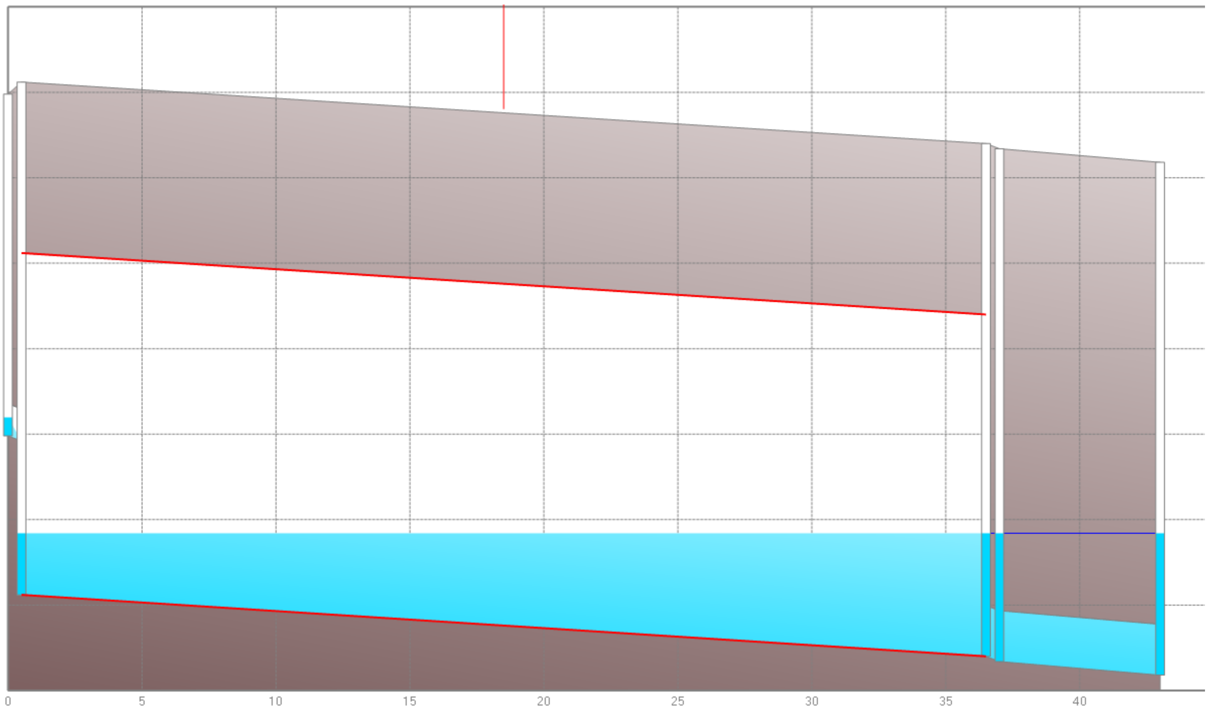


Figure 6.23 Profile of Siemens detention system in PCSWMM model. The detention system is highlighted in red. The filling degree in this figure is taken from a random simulation.

As with *Christinedal*, the first simulations completed in the *Siemens* model were for four recorded rainfall events from 2018. The simulated versus observed water depth in the flow regulating manhole can be viewed in the graphs in Figure 6.24, where orange lines represent simulated depth and blue lines represent observed depth. As we can see, the simulated depth is for the most part larger than the observed depth, and the disparity between the two lines is quite apparent. Although the model simulates a similar pattern as the observed data, the magnitude difference is significant and puts the accuracy of the model in question. However, since the simulated values are larger than the observed, the erroneous volumes yielded from the model are more likely to be too large than too small. This makes the observed error more acceptable than had it been reversed, as over-dimensioning is considered more acceptable than under-dimensioning.

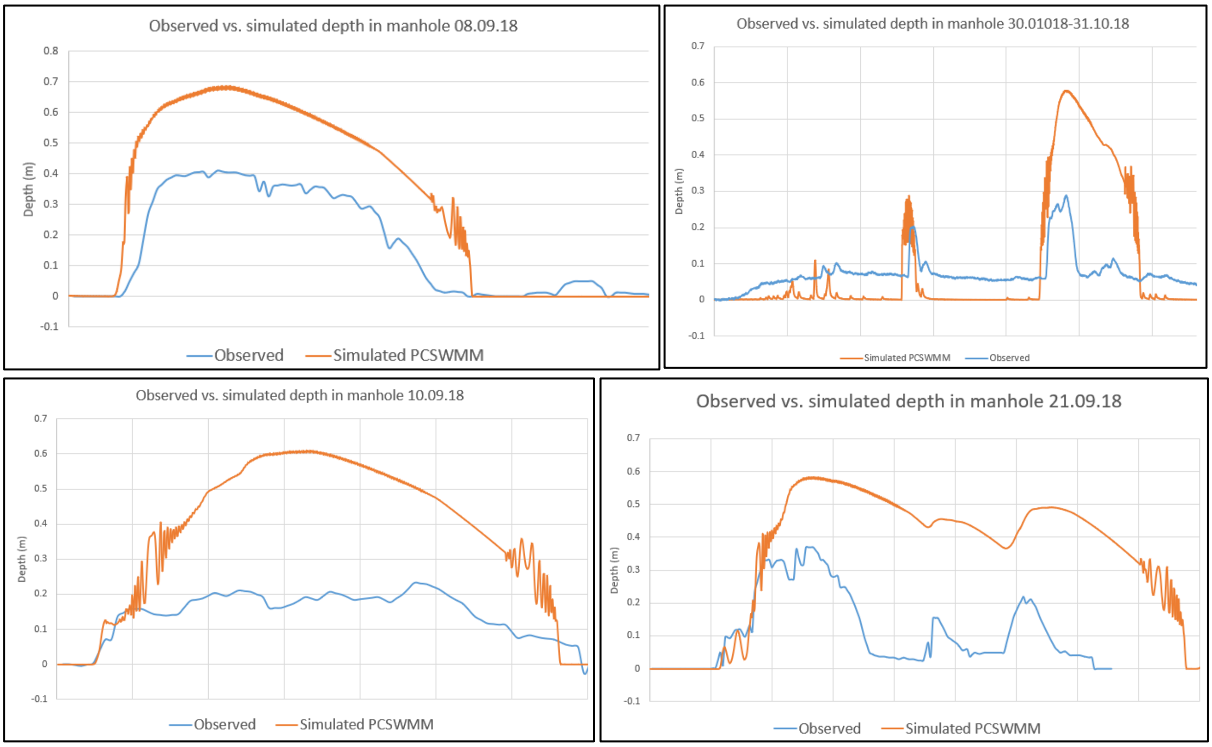


Figure 6.24 Simulated vs. observed water depth in the flow regulating manhole for four different rainfall events recorded at Siemens. Top left: Measured rainfall event on 08.09.18. Top right: Measured rainfall event on 30.10.18-31.10.18. Bottom left. Measured rainfall event on 10.09.18. Bottom right: Measured rainfall event on 21.09.18.

Each of the recorded and constructed rainfall events presented in the methodology section were simulated in the PCSWMM model. The maximum detention system volume observed during each simulation is tabulated below.

Table 6.20 Maximum simulated volume in the detention system Siemens for several different rainfall time series.

Recorded rainfall events				
	Scaling factor 1		**Scaling factor 2**	
Rainfall	**Max volume simulated [m^3]**	**% of total detention system volume**	**Max volume simulated [m^3]**	**% of total detention system volume**
Blindern 2014	136.3	61.1 %	145.0	65.0 %
Sandaker 2013	137.0	61.4 %	137.0	61.4 %
Blindern 2008	77.1	34.6 %	83.9	37.6 %
Blindern 17.06.80	45.5	20.4 %	49.2	22.1 %
Blindern 06.08.80	124.0	55.6 %	131.9	59.1 %
Blindern IDF 20-year return period				
Rainfall duration	**Max volume simulated [m^3]**		**% of total detention system volume**	
1 hr	123.3		55.3 %	
3 hrs	147.3		66.1 %	
24 hrs	154.6		69.3 %	

The largest volume simulated in the *Siemens* model for any of the recorded events was 145.0 m^3, which occurred for the data series Blindern 2014 with scaling factor 2. The largest volume simulated for the symmetrical hyetograms was 154.6 m^3, which occurred for the event with a 24-hour duration. These volumes correspond to 65.0% and 69.3%, respectively, of the constructed volume, thus indicating an over-dimensioned detention system. This is the same conclusion as in the specialisation project. Hence, the suspicion that *Siemens* is over-dimensioned has been supported by two separate methods for evaluating the volume, i.e. on-site measurements and PCSWMM modelling.

In the first two columns in Table 6.21, we can view combinations of permeable and impermeable runoff coefficients that yield 154.6 m^3 if used with the new RCA in Sweco's Excel template. The division of the RCA into permeable and impermeable surfaces was based on Table 6.1. In likeness to the former case, the computations were based on the newfound RCA as it is considered to be more accurate than Sweco's area appraisal, and since determining correct runoff coefficients is highly dependent on having an accurate RCA when only the volume is known. The third column reiterates the impermeable coefficients computed for *Christinedal*, which were tabulated in Table 5.28Table 5.1. By including these values in the table below, we can easily compare the coefficients for *Christinedal* and *Siemens* and see which permeable and impermeable combinations fit for not only one of the areas, but both.

Table 6.21 Combinations of permeable and impermeable runoff coefficients that yield a volume of 154.6 m^3 when using Sweco's area appraisal for the Siemens property in Sweco's Excel template. The far-right column shows the impermeable coefficients for Christinedal, which are the same as shown in Table 5.28.

Combinations of permeable and impermeable runoff coefficients		
Permeable runoff coefficient	**Impermeable runoff coefficient - *Siemens***	**Impermeable runoff coefficient - *Christinedal***
0	0.96	0.9
0.05	0.89	0.86
0.075	0.86	0.84
0.1	0.83	0.82
0.15	0.77	0.78
0.2	0.71	0.75

The runoff coefficients seen in the table above are considerably lower than the coefficients used by Sweco. A comparison of the *Christinedal* and *Siemens* values shows that a permeable and impermeable runoff coefficient combination of 0.1 and 0.83 or 0.15 and 0.78, respectively, yields similar PCSWMM volumes and Excel template volumes for both cases. These values fall within the guideline ranges provided by NW and SWWA. Therefore, based only on these two cases, the value combinations stated could be suggested runoff coefficients to use in future dimensioning. However, there is a significant amount of uncertainty linked to this conclusion. Firstly, it is only relevant if we assume that the PCSWMM model is accurate and reliable, which is yet to be discussed. Secondly, and more importantly, there is not enough data to support this conclusion, as more than two data points are needed. This will be discussed more extensively in the next section.

Comparing the PCSWMM results and the results obtained using the author's RCA and runoff coefficients in the Excel template, shows that the volume found in PCSWMM is larger, i.e.

154.6 m^3 versus 143 m^3. This supports what has been stated previously; that we must be wary with lowering the runoff coefficients excessively, as the result may be an under-dimensioned detention system, as is the case with the author's volume if the PCSWMM results are accurate.

6.2.3 Results – Sensitivity analysis

The parameter sensitivity analysis will be conducted for Sandaker 2013 and the 24-hrs constructed event for Blindern, which were two of the rainfall events that produced the largest volume. Sandaker 2013 was chosen as opposed to Blindern 2014 because it had the largest volume for any of the recorded events with scaling factor 1.

Table 6.22 Parameter sensitivity analysis for the PCSWMM modelling of Siemens for the rainfall event Sandaker 2013. The maximum detention system volume for the simulation was 137.0 m^3. The resolution of the volume results is 0.1.

Parameter	**New maximum volume in detention system [m^3]**	**Reduction/increase [%]**
Infiltration		
Max infiltration 50 mm/hr	>223	>+62.8
Max infiltration 100 mm/hr	163.4	+19.3
Max infiltration 150 mm/hr	137.2	+0.1
Max infiltration 200 mm/hr	137.0	0.0
Max infiltration 300 mm/hr	137.0	0.0
Minimum infiltration 2 mm/hr	137.0	0.0
Minimum infiltration 10 mm/hr	137.0	0.0
Minimum infiltration 20 mm/hr	137.0	0.0
Decay constant		
Decay constant = 2	137.0	0.0
Decay constant = 6	137.0	0.0
Drying time		
Drying time = 6 days	137.0	0.0
Drying time = 8 days	137.0	0.0
Manning's n overland flow		
Impervious n=0.012	137.7	+0.5
Impervious n=0.014	136.4	-0.4
Pervious n=0.14	137.0	0.0
Pervious n=0.16	137.0	0.0
Evaporation		
Evaporation 0.5 mm	136.9	-0.1
Evaporation 1 mm	136.8	-0.1
Evaporation 2 mm	136.4	-0.4
Depression storage		
Impervious, all catchments 1.5 mm	138.6	+1.2
Impervious, all catchments 2.5 mm	135.3	-1.2
Pervious, all catchments 2.5 mm	137.0	0.0
Pervious, all catchments 5 mm	137.0	0.0
Pervious, all catchments 10 mm	137.0	0.0
Zero Impervious		
10 % for all catchments	135.8	-0.9
40 % for all catchments	138.3	+0.9
Manning's n, pipe flow		
n=0.011	137.0	0.0
n=0.013	137.1	+0.1
Pipe diameter		
All pipes one size smaller (if possible)	137.6	+0.4
All pipes one size larger (if possible)	136.6	-0.3

Table 6.23 Parameter sensitivity analysis for the PCSWMM modelling of Siemens for the rainfall event Blindern 24hrs. The maximum detention system volume for the simulation was 154.6 m^3. The resolution of the volume results is 0.1.

Parameter	New maximum volume in detention system [m^3]	Reduction/increase [%]
Infiltration		
Max infiltration 50 mm/hr	>223	>+44.2
Max infiltration 100 mm/hr	214.4	+38.7
Max infiltration 150 mm/hr	160.7	+3.9
Max infiltration 200 mm/hr	154.6	0.0
Max infiltration 300 mm/hr	154.6	0.0
Minimum infiltration 2 mm/hr	154.6	0.0
Minimum infiltration 10 mm/hr	154.6	0.0
Minimum infiltration 20 mm/hr	154.6	0.0
Decay constant		
Decay constant = 2	154.6	0.0
Decay constant = 6	156.2	+1.0
Drying time		
Drying time = 6 days	154.6	0.0
Drying time = 8 days	154.6	0.0
Manning's n overland flow		
Impervious n=0.012	154.3	-0.2
Impervious n=0.014	154.6	0.0
Pervious n=0.14	154.6	0.0
Pervious n=0.16	154.6	0.0
Evaporation		
Evaporation 0.5 mm	154.1	-0.3
Evaporation 1 mm	153.4	-0.8
Evaporation 2 mm	152.9	-1.1
Depression storage		
Impervious, all catchments 1.5 mm	154.6	0.0
Impervious, all catchments 2.5 mm	154.5	-0.1
Pervious, all catchments 2.5 mm	154.6	0.0
Pervious, all catchments 5 mm	154.6	0.0
Pervious, all catchments 7 mm	154.6	0.0
Zero Impervious		
10 % for all catchments	154.3	-0.2
40 % for all catchments	154.4	-0.1
Manning's n, pipe flow		
n=0.011	156.2	+1.0
n=0.013	152.2	-1.6
Pipe diameter		
All pipes one size smaller (if possible)	155.7	+0.7
All pipes one size larger (if possible)	154.4	-0.1

As we can see in Table 6.22 and Table 6.23, the most drastic change to the volume occurs when the infiltration rate is lowered significantly. However, as discussed in relation to the *Christinedal* sensitivity analysis, the infiltration rate used in this thesis is considered to be conservative, and thus, more accurate than the lowered infiltration rates that cause a significant volume change in the sensitivity analysis. Infiltration rates between 200-300 mm/hr yield the same volume, which indicates that the parameter "maximum infiltration rate" is not extremely sensitive when using values within reasonable ranges. Other parameters that are somewhat sensitive ($\geq |1\%|$) are impervious depression storage, decay constant, evaporation, and Manning's n for pipe flow. However, their sensitivity is considered acceptable considering their little impact on the volume, especially when compared to the other, more significant, uncertainties in the modelling.

7.Discussion

The purpose of this thesis is to explore ways in which Sweco can improve upon their dimensioning practice of detention systems, by focusing on both the method they use and how they obtain input. This was done by reviewing relevant literature and by using the software tools SCALGO and PCSWMM. The usefulness of both tools is now to be evaluated. The focus will be on accuracy and trustworthiness of results, the ease at which the results were obtained, the time needed to obtain them, and other issues related to the method. Since more than one potential way of improving the dimensioning practice is being evaluated, the discussion will be divided into three main sections; SCALGO, PCSWMM, and runoff coefficients. This is so that all topics can be discussed in a structured and organised manner. The discussion follows the same order as the work presented in the thesis, with SCALGO being evaluated first, followed by an evaluating of PCSWMM. Runoff coefficients is the last topic to be discussed individually. However, since runoff coefficients has been a significant topic in the thesis, they might additionally be mentioned throughout the entire discussion where it is deemed relevant.

7.1 SCALGO

The potential use of SCALGO as an aid for determining detention system volumes was first proposed by Sweco. The author decided that in this thesis, the evaluation of its use would relate to overland flow on properties, and how to utilise this information to select an appropriate RCA appraisal for the subsequent dimensioning. Now, the usefulness of SCALGO as it was used in this thesis will be discussed. Since SCALGO is a relatively unfamiliar software, there is little literature about it, and therefore, most of the discussion about accuracy and potential issues will be based on the author's perception.

7.1.1 Results – Accuracy, issues, and usefulness

For the most part, the accuracy of the results obtained in SCALGO are perceived to be good. Elevation lines are depicted on SCALGO's map, and the flow direction on the surface, as well as watershed delineations, seem to coincide with these lines. However, one of the issues with SCALGO, which has been highlighted in several sections, is its lack of consideration for hydrological processes and the existence of drainage systems. Therefore, it was quickly found to be of little help in determining quantitative detention system volumes directly, but rather just the direction of flow on the properties. Hence, this limitation was an important determinant for how SCALGO would be used in the thesis. Because of this, the limitation is not considered an issue in the completed work, as this was a prerequisite for the methodology that was chosen. Neither the hydrological processes, nor the inclusion of drainage systems, are crucial for determining the general flow direction on the surface, which was the sought-after information that SCALGO provided. Therefore, this limitation will not be discussed further, as it has already been discussed previously.

Contrary to the aforementioned limitation, a significant issue when using SCALGO as an aid in dimensioning detention systems, is the disparity between the knowledge that was possessed by the author when completing the work in SCALGO, and the knowledge that *would be* possessed by Sweco, when they attempt to complete similar work. When detention systems are dimensioned, the topography and composition of the property oftentimes looks dissimilar to what it *will* look like once the area has been fully developed. Therefore, since SCALGO is a map-based tool that uses topography to determine the direction of flow, the issue is that the correct basis for determining this is usually non-existent when it is needed. However, the designer commonly has some insight into what the developed property will look like and can thus compare current and planned composition, to evaluate whether the modifications will cause a drastic change to the flow on the property. If this is the case, SCALGO will likely not be of much use. However, if the developed property's topography will resemble the old property, then one might still be able to use SCALGO for its intended purpose, i.e. to estimate the area that contributes flow to the detention system. However, this also requires that the designer has determined the approximate location of the detention system and the drainage system.

Because SCALGO's map is not updated for future topography, it cannot be used for detailed analyses as it was in the thesis. Instead of evaluating the area contributing flow into each storm drain, it can only be used to see the big picture, i.e. to estimate the larger RCA appraisal. Most likely, all "central" property areas will be connected to a drainage system and included in the RCA, as was the case for both *Christinedal* and *Siemens*. However, the accuracy of the appraisal will likely depend on how much the peripheral parts of the property are modified, as this is where the border between contributing and non-contributing areas lies. If the RCA border moves due to modification of the topography before and after development, the RCA found in SCALGO when dimensioning will be incorrect. However, oftentimes the peripheral parts of the property remain fairly unchanged, allowing for the use of SCALGO. Although there is no way of confirming this theory; by looking at old satellite images of the *Christinedal* and *Siemens* properties, it would appear that large parts of the properties' periphery were unmodified, thus indicating that the RCA appraisal found in SCALGO would have been similar both before and after the development. However, an unmodified periphery is not always the case. Additionally, some RCA borders depend on the placement of the drainage system components, such as the southern part of the *Siemens* property. Hence, SCALGO can in *some* cases help determine a better RCA appraisal, though it depends on the specifications of each case.

Now that the accuracy and limitations of SCALGO have been discussed, the important question is the necessity of the results. If a detention system is dimensioned for a property located in a highly urban area, using the property appraisal as the RCA might not be a significant misjudgement. In highly urban areas, the surrounding properties are most likely connected to their own private or municipal drainage system and it is therefore improbable that they provide a significant amount of run-on onto the property being assessed. Thus, the RCA found in SCALGO might be somewhat similar to the abstract property line that is often used as the RCA, making the work in SCALGO redundant. For both *Christinedal* and *Siemens*, there was a slight difference in what specific areas were included in the RCA found in SCALGO and the property appraisal, though their sizes were nearly the same, i.e. less than a 10% size difference for both. This was partly because neighbouring areas were drained on their own property, thus not contributing run-on. Hence, although the area extent and size will likely differ between the property appraisal and the RCA found in SCALGO, this disparity might not be significant enough for Sweco to change to a more time-consuming method that is also characterised by potentially uncertain results.

However, although it is possible that the abstract property appraisal is of similar magnitude as the actual RCA, which could be found using SCALGO, this is not a given. As it was pointed out in Section 6.1, the fact that Sweco's and the author's RCA for *Siemens* were nearly identical in size could have been a coincidence, and had the drainage system been designed differently, the sizes would likely have differed significantly also. Although urban properties are often surrounded by other drainage systems, run-on onto the assessed property is not impossible. Therefore, work in SCALGO might not be redundant anyhow, and might be quite important. A correct RCA appraisal is important independent of which method is chosen, as it influences both the Excel template method results and the PCSWMM results. Hence, the problem of having an incorrect RCA cannot be solved by choosing a different method, and it is a significant source of error. Therefore, it might be sensible to use SCALGO to obtain a better comprehension of what areas form the RCA, although this should be done without spending an excessive amount of time on the assessment, and by keeping in mind the issues and uncertainties discussed.

7.1.2 User experience: Time and simplicity

The basic features of SCALGO that were used in this thesis were easy to understand and easy to utilise. In order to obtain results that were perceived as reliable, we only had to select the function of interest and click on a position on the map. The result was a visual representation of the RCA to the specified point, and not much interpretation of the output was needed. In this way, the author found the employed software functions simple an intuitive. The results were also thought to be helpful in this thesis, as reliable and detailed RCAs were found, which were later used as input to the PCSWMM models. However, regarding the future use of SCALGO as an aid in dimensioning detention system volumes, the procedure might not be as simple. In light of the issue regarding the lack of knowledge possessed by the designer, the work in the software becomes less intuitive, as assumptions must be made about the soon-to-be developed plot. Though this is not directly related to the simplicity of SCALGO itself, it reduces the simplicity of the whole procedure, increases the time needed to obtain results, and reduces the reliability of the results. Because of this, the author becomes more ambivalent about the simplicity of the tool.

7.1.3 Suggestions

Based on the discussion above, it would be the author's advice that a simplified version of the procedure followed in this thesis should be opted when dimensioning detention systems. The knowledge obtained through SCALGO is considered necessary, though somewhat unreliable considering the information that is lacking when the procedure is to be executed. Although the utilised functions of SCALGO were found simple and speedy, the work becomes more complicated when SCALGO is not based on the correct topography, which is the case when dimensioning. This is why a *simplified* version is proposed, and only for cases where it is deemed possible. SCALGO should be used to become more familiar with how runoff flows on and around the property before development. This is easily done by spending just a few minutes clicking on the map and observing the visual representation of flow direction and flow contributing areas. This information can further be used in an attempt to predict how the development will alter flow on the property. If it appears as if the peripheral parts of the property will not be modified significantly, SCALGO can be used to determine an estimate for the RCA border upstream the detention system. This does not necessarily require detailed information about the drainage system placement, but can easily be obtained by clicking on central parts of the property that will likely be included in the RCA. Utilising SCALGO in such a casual manner will likely give more insight into the extent of the contributing area beyond just the abstract property line.

Although SCALGO has been regarded as somewhat inferior when used as outlined in this thesis, this does not signify that it does not have other appropriate uses. An alternative could be to explore the other functions of SCALGO, such as terrain editing, and how this can be used for urban planning or climate adaption, which are stated as possible uses on SCALGO's web page. Since the terrain is then being edited, the issue of future development is likely not as significant, as the development will be modelled in SCALGO. Alternatively, one could explore SCALGO's usefulness in the third step of the three-step strategy, to secure safe flood paths, since both small and large flood pathways are clearly marked on the map. On SCALGO's web page they advertise that it is possible to arrange demonstrations of the software with the company. Given the resources of large firms such as Sweco, it should therefore be possible to arrange more education on how to utilise SCALGO in a beneficial way. It is the author's opinion that these benefits should be explored. It is even possible that SCALGO is indeed appropriate for quantitatively dimensioning detention systems, but in a different way than what was attempted in this thesis.

7.2 PCSWMM

Based on the cases and results presented, a discussion is needed to evaluate whether the PCSWMM results are deemed better than the results from Sweco's method, and whether PCSWMM should be utilised by Sweco going forward. This requires a discussion on pros and cons of both the current and proposed method, as well as an evaluation of the time and skills needed to perform the required modelling.

7.2.1 Results – Accuracy, issues, and usefulness

Whether the results from PCSWMM actually *are* better than the Excel template results is impossible to know for certain without extensive on-site measurements over a long period of time, which is beyond the scope of this thesis. We can however argue for what results we *believe* are more accurate, based on available knowledge. Thus, the first thing to be discussed is the accuracy of the PCSWMM results.

Accuracy

SWMM is an extensively used software that has been utilised in many thousands of stormwater studies throughout the world, and continues to be used for planning, design and management related to stormwater runoff in urban areas (James et al., 2010:1). In the SWMM user manual, the importance of robustly reliable computer models for water system planning, design and management is emphasised, and it is stated that SWMM is based on the latest knowledge of physics. Therefore, considering the information stated in the manual, and the fact that persons much more qualified than the author in the field of stormwater management and modelling have enough confidence in the reliability of PCSWMM, the accuracy of PCSWMM will be trusted as more reliable than any other method mentioned in this thesis.

In addition to the former argument, the author independently believes that the volumes obtained from PCSWMM are more accurate and reliable than the ones produced from

Sweco's Excel method. The main reason for this stance is the additional considerations included in PCSWMM; overland flow time, volume storage in conduits, temporal variation in infiltration, depression storage, and several others, which are not considered independently in Sweco's method. However, this does not mean that the results will be trusted blindly, especially for single event simulations such as these. It is stated in the manual that for event modelling, "…every model run is governed by arbitrary assumptions of start-up conditions, which are themselves not subject to careful modelling scrutiny, such as sensitivity analysis, calibration, and error analysis", and that this can lead to unreliable results (James et al., 2010:9). This statement is highly relevant for the modelling in this thesis, as start-up conditions were not considered greatly, and parameter input was uncertain. However, although the parameter input to PCSWMM can be uncertain, so is the runoff coefficient selection for Sweco's computations. Hence, parameter input uncertainty is an issue no matter what method is chosen, and in view of this, the extra considerations taken in PCSWMM are believed to make the method more reliable than Sweco's method.

After the completion of the model simulations, a parameter sensitivity analysis was conducted. This analysis showed that the sensitivity to parameter changes was not drastic and did not have an extremely significant influence on the final volume results. The only drastic change seen was when the infiltration rate was set very low, i.e. lower than what we would expect the infiltration rate to be. Thus, this parameter sensitivity is thought to be inconsequential. Additionally, uncertainty linked to the infiltration rate can be diminished by conducting on-site measurement of infiltration rate by for example using an infiltrometer, which is considered to be simple enough to be feasible in such design projects. Therefore, though the parameter input to PCSWMM is uncertain, parameter sensitivity has been shown not to be a considerable problem and is therefore considered to be within acceptable ranges.

Calibration

As was shown in the case studies, the PCSWMM models were not calibrated very well against the measurements from 2018. For some events, the patterns describing the recorded and simulated water depth in the flow regulating manhole were similar, thus indicating that the model responded correctly to the precipitation. However, the magnitude usually differed for these events. For other events, either both or neither of the pattern or magnitude had a good fit. This reduces the trustworthiness of the PCSWMM models, as they appear not to be able to accurately mimic the real-life runoff situations and subsequent detention system response. However, as was discussed extensively in the specialisation project, the events of 2018 were very small, and due to an unusually dry summer, the soil conditions were likely different than what they are ordinarily like. It is possible that PCSWMM is better able to simulate larger events or that the models did not have adequate input to model the unusual conditions experienced in 2018. This could potentially have resulted in a larger disparity between the recorded and simulated depths for the recorded events, than what would have been the case for the simulated 20-year rainfall events, had they been recorded. However, since the response of the detention systems has not been recorded for larger events, nor in more climatically ordinary periods, there is no way of confirming nor denying this. Therefore, calibrating against the events of 2018 might have been unwise in case of transferability issues from small to large events, although this is not certain.

An additional consideration regarding model calibration is the possibility that the measurements from 2018 were imprecise, thus potentially providing erroneous basis for comparing recorded and simulated depths. The PCSWMM simulations depended on the rainfall measurements and the observed depth depended on the water level measurements. Hence, if the measurements were incorrect, calibration could lead to a more inaccurate, rather than more accurate, model. However, if calibration was to be attempted regardless, the task would prove difficult, as it was impossible to create a model that was perfectly calibrated for every event recorded simultaneously. Even if the model was to be calibrated for only *one* event, the input parameters would have to be assigned such odd values that the trustworthiness of the model would remain under question, despite the calibration. Therefore, the selection of logical and/or suggested parameter values is considered acceptable and preferred when compared to calibrated parameter values.

It is difficult to say how detrimental the lack of calibration is, and ideally the model would have been calibrated against measured values whilst simultaneously having logical parameter input. However, although a calibration has not been obtained for either of the two cases, the author finds the comparisons of simulated and measured depths satisfactory, as the simulated depths are nearly always larger than measured depths. As has been stated numerous times throughout the thesis, over-dimensioning is considered more acceptable than under-dimensioning, and larger simulated than measured depths would indicate the former. Thus, the lack of calibration reduces the confidence in the results, but not enough to deter the author from trusting them more than results obtained from Sweco's Excel template. Nevertheless, the volume obtained in PCSWMM is significantly smaller than the volumes dimensioned by Sweco, so in all likelihood, the simulated volumes are not excessive, despite the simulated depths being larger than the observed depths.

Lacking knowledge

Similar to work in SCALGO, a potentially major issue with future PCSWMM modelling is the lack of available information when the model is to be created. In this thesis, all necessary information was available; the surface's composition, topography and design, the exact location and design of the drainage system components, as well as the design of the detention system itself. However, hardly any of this information is available or even existent when Sweco must determine their detention system volume. For example, they likely do not know where there will be built-up stone curbs, which was highly influential in determining pervious depression storage depth in the *Christinedal* model. Likewise, other important features might be misrepresented or misplaced compared to what the final property and drainage system will look like. Therefore, estimations will have to be made based on experience from the designer. He or she might not know the exact design of the area and placement of storm drains and pipes, but must model the property in PCSWMM regardless, based on the approximate design, location, and size of components.

The lack of information from the designer's part will lead to much more uncertain results than what has been the case in this thesis. At this point, there is no easy way of estimating how significant the inaccuracy of having limited information will be, as this would differ from one case to another and one engineer to another, since different assumptions are made by the designer in each separate case. Therefore, if Sweco decide to proceed with PCSWMM modelling, it would be wise to compare the obtained results to results from another method, e.g. the Excel template. Additionally, after the construction of a few detention systems dimensioned using PCSWMM, the correctness of the dimensioning should be tested and reviewed, to evaluate whether the method produces adequate detention system volumes. Unfortunately, this requires a long-term plan, in addition to the risk of dimensioning inadequate detention system volumes before the accuracy of the method has been determined. However, as has been hypothesised in this thesis, the currently used method also produces inadequate detention system volumes, so trying out a new method might be worth it in the long-term.

An additional issue when modelling with limited information is the possibility that the dimensioning-procedure becomes more time-consuming compared to if all information had been known. This is because the designer will be more unsure of how to model the property, which can slow down the process. In the case where all information is known, the designer can model known components, which does not require the same level of consideration and thought, thus being quicker. However, whether this is true is uncertain, and if it is, how much more time-consuming it would be is also unsure.

Necessity

As has been argued for, modelling in PCSWMM is thought to yield more accurate runoff results than Sweco's current dimensioning practice. However, the next topic to be discussed is the necessity of switching to a new method. In the case studies it was found that using permeable and impermeable runoff coefficients of 0.1 and 0.83, respectively, in Sweco's former Excel template, yielded approximately the same volumes as PCSWMM for both cases. If this holds true for other properties/detention systems as well, modelling in PCSWMM might be unnecessary, and considering the extra time required, wasteful. It would thus be more fruitful to simply change the runoff coefficients commonly used when dimensioning, as the Excel template requires far less time and skill to use. However, as stated in the case work for *Siemens*, concluding that 0.1 and 0.83 are generally appropriate runoff coefficients would require far more data, acquired from more properties, than what is currently available. Therefore, it would be the author's opinion that PCSWMM-modelling is presently the most accurate option. However, if more research is done to compare PCSWMM results and runoff coefficients needed to produce the same volume in the Excel template, and the results point to a specific combination of permeable and impermeable runoff coefficients that apply for most areas, then the author would suggest the continued use of the Excel template method, but with the new runoff coefficients. This is due to the limited time and parameter input needed to dimension in the Excel template, compared to modelling in PCSWMM.

Sweco's method

A short remark should be made about Sweco's previous and current dimensioning method. In this thesis, all work relating to Sweco's Excel template has been based on the same template that was used to dimension *Christinedal* and *Siemens,* which utilises a constant outflow value from the detention system. Hence, the suggested runoff coefficients apply only when using this template. However, since the dimensioning of *Christinedal* and *Siemens*, a new Excel template has replaced the former. This template bases the outflow on the Aron and Kibler method, i.e. a linearly increasing outflow value. Linear outflow describes real-life events more accurately, as the outflow increases as the detention system becomes fuller, which happens as the rainfall event progresses. However, the detention system volumes produced from the Aron and Kibler method are larger than the ones produced using the method of constant outflow. For example, if using the Aron and Kibler method, the maximum volume would be 122 m^3 for *Christinedal* and 274 m^3 for *Siemens*, compared to 99 m^3 and 223 m^3, respectively. This is a 23% increase in both volumes, which is significant considering that the method of constant outflow has been found to yield excessive volumes, and that the newer method yields even *larger* volumes. Thus, the reasoning for changing methods to PCSWMM, which produces smaller volumes, might be even more justified. At the very least, the commonly used runoff coefficients should be reduced even more when using the Aron and Kibler method.

7.1.2 User experience: Time and simplicity

In addition to wondering about the quality of the results obtained through PCSWMM, a question asked in the introduction was whether the time and skills needed to model in PCSWMM is at an acceptably low level for it to be a feasible alternative for Sweco. Though there is no objective truth about this, as different designers will have different experiences with modelling in PCSWMM, the question will be answered based on the author's own experience.

It is the author's belief that modelling in PCSWMM was relatively easy, and that with enough practice, the model can be created fairly quickly. Though the author had no experience with PCSWMM beforehand, the software was intuitive, and basic modelling was easy to learn based on only a simple manual. Therefore, depending on the specifications of the project, the author believes that it should be possible to create a simple model within a few working days, assuming that the user has experience with the software beforehand. The modelling can be expedited if there is an outlined routine/procedure that the designer can follow, if commonly used guideline values are on hand, and if necessary components such as rainfall time series and different detention system designs are readily available. Nonetheless, modelling does take longer than filling out the Excel template, but depending on available time, it could be worth it due to the improved results. However, this is the author's opinion, and whether modelling will be utilised by Sweco going forward will depend on their own evaluation of time needed and time available, as well as difficulty level of creating the model with limited knowledge.

7.2.4 Suggestions

Alternative 1: PCSWMM

If Sweco decide to go forward with PCSWMM as a method for dimensioning, the following procedure and aspects are suggested based on the case work completed and the discussion above. As there is not much to be done about the lack of available information, the designer must model the property and drainage system as best as possible, based on experience from other similar projects and available information. The RCA should be divided into smaller sub-catchments, with estimated sizes, widths and slopes, based on knowledge of what the area compositions and topography will likely look like. Parameter values should be based on guideline values found either in the SWMM manual or from other sources, unless available information suggests otherwise. If possible, on-site testing of infiltration rates should be conducted, as maximum infiltration rate was found to be the most sensitive parameter related to detention system volume in this thesis. If not, a somewhat conservative infiltration rate should be selected, as not to under-dimension the detention system. According to Solheim et al. (2017), a maximum infiltration rate of 202 mm/hr is conservative in urban Oslo.

Since the design of the detention system will likely not have been selected at this stage, a random detention system design must be implemented in the model, with a guesstimated size. A possibility is to have a repertoire of different detention system designs and sizes. This way, the designer can easily try out different designs by selecting them from a library and running simulations in PCSWMM. This could be useful in order to evaluate whether the detention system design influences the results. Contrary to detention system design, the maximum flow allowance from the detention system is commonly known early in the dimensioning project. Ergo, outflow from the detention system should be modelled as accurately as possible, as this has been pointed out as one of the important advantages of PCSWMM compared to the Excel template. Therefore, also flow regulating curves should be stored in a library. The designer can then select a stage-discharge curve from the library that fits the maximum outflow allowance specified in the project, and then modify the detention system design in the model to the specifications of the flow regulating curve. Though the curve might not be identical to the flow regulating curve that is ultimately selected for the detention system, the results of the modelling will likely be more accurate than by not modelling with a flow regulating stage-discharge curve whatsoever. The stage-discharge curves in the library can be obtained by gathering information on flow regulators from previous detention system design projects completed by Sweco.

Once the model has been created, several different rainfall time series should be simulated to find the maximum necessary detention system volume for the specified return period. As with detention system designs and flow regulating curves, a possible solution is to have a small repertoire of rainfall time series saved up, for example the ones that were used in this thesis. This would limit the time needed to identify and select proper rainfalls to simulate, as they will already have been identified. If there is a wish to simulate the model for smaller or larger rainfall events than those with a 20-year return period, or to include a climate factor, this can easily be done by scaling the data points in the time series with a scaling factor. Additionally, as has been illustrated previously, when using symmetrical hyetograms, the runoff volume increases as the event duration increases. Therefore, the designer might also want to specify design event duration, as well as return period. Once all of this has been determined, the simulations can go forth, and the largest detention system volume can be found.

After creating the model and simulating for different rainfall events, it might be wise to conduct a sensitivity analysis of the different parameters. This will help identify parameters that are highly influential on the final volume results and might therefore need extra consideration. If the designer wishes to be conservative, the more sensitive parameters can be set to values that yield higher volumes. Finally, after the sensitivity analysis is completed, and the final volume is determined, a suggestion is to compare this volume to the volume obtained from Sweco's Excel template, if time allows. If using a simplified division into permeable and impermeable areas, and runoff coefficients of 0.3 and 0.9, respectively, one would expect the old Excel template to yield results larger than PCSWMM. If this is not the case, the designer should re-evaluate the trustworthiness of the model and reconsider the information and data from which it was created.

In light of the uncertainties related to future detention system dimensioning in PCSWMM, it is wise to complete any change of method on a trial-basis. As was stated earlier, there should be a long-term plan in place for dimensioning detention systems based on PCSWMM, which includes validation and review of the accuracy of the dimensioned volumes after construction. Validation can be completed by rigging constructed detention systems with necessary measurement equipment. Once enough data is collected, there will be more basis for evaluating whether the dimensioning is adequate. This might require a long measurement period, as a larger rainfall event should be recorded. Additionally, throughout the trial-period of the new dimensioning method, not only result accuracy can be evaluated. A trial basis will also allow for consideration of how difficult and time-consuming modelling is, and whether it is acceptable going forward. Despite the author's belief regarding time and simplicity of PCSWMM, it is possible that the modelling does not fit the criteria of accuracy, difficulty and time needed that is set by Sweco. After all, the author has had several weeks to complete this thesis, and has thus not actually attempted to model an undeveloped catchment in the proposed time-span. Hence, a trial-period for the proposed method is deemed wise in several regards.

7.3 Runoff coefficients

7.3.1 Results – Accuracy, issues, and usefulness

Carefully selected runoff coefficients

Runoff coefficients have been evaluated extensively, and from the case work completed, we have seen that the coefficient selection is highly influential on the volume yielded in Sweco's Excel template. We have also seen that by dedicating more time and consideration into the selection, the resulting runoff coefficients differ significantly from the values commonly used by Sweco. The selection process in this thesis consisted of dividing the property into sub-areas, assigning individual runoff coefficients based on guideline values and area characteristics, and finally, evaluating how these sub-areas interact and how this influences the average runoff coefficient. However, although more consideration was taken in the selection, this is no guarantee that the selected runoff coefficients were more accurate than the coefficients used by Sweco. After implementing the newfound φ and A values into the Excel template and comparing the results to the PCSWMM results, we were shown that the newfound values were not always better. For *Christinedal*, the new φ and A yielded a satisfactory volume when compared to the PCSWMM volume. However, for *Siemens*, the volume yielded by the author's values was smaller than the volume found in PCSWMM. This is problematic, as under-dimensioning of detention systems can have adverse consequences, due to an increased potential for flooding. Hence, this indicates that careful consideration of runoff coefficients is not necessarily always helpful, as the coefficients could still be inaccurate. Therefore, and in-depth and time-consuming evaluation, such as the one completed in this thesis, might be futile.

Runoff coefficients versus PCSWMM results

In the case work, combinations of permeable and impermeable runoff coefficients were tabulated. If used with the new RCA appraisals, these runoff coefficient combinations would yield the same volume in the Excel template as the volume found in PCSWMM. For both *Siemens* and *Christinedal*, a permeable and impermeable runoff coefficient of approximately 0.1 and 0.83, respectively, yielded satisfactory results. Therefore, these values could serve as suggested runoff coefficients to use in future dimensioning. However, based on current knowledge, there are a few issues with doing so. Firstly, these coefficients are only proper if we assume that the PCSWMM model is accurate and reliable, which is not a given. Secondly, these coefficients cannot be trusted completely, as it is not definite that the RCAs used alongside the coefficients in the Excel template were correct. As was stated in Section 5.2, to obtain the sought-after volume in the template, either both or neither of φ and A must be correct simultaneously. Hence, if the RCAs used in these computations were indeed incorrect, so were the suggested runoff coefficients computed. Therefore, although permeable and impermeable runoff coefficients of 0.1 and 0.83 were suitable for both *Christinedal* and *Siemens*, we cannot at this point rely on them to be accurate, as we do not know if the data they are based on is correct.

An additional issue with the suggested permeable and impermeable runoff coefficients of 0.1 and 0.83, is that they are not based on ample data. As far as we know, these values only hold true for two detention system properties, which is not enough to support a general conclusion that applies to other properties as well. To support this, one would have to gather more similar data. This could be done in the same manner as in this thesis, i.e. by modelling other properties in PCSWMM, roughly dividing the properties into permeable and impermeable surfaces, and determining possible combinations of permeable and impermeable runoff coefficients that yield the PCSWMM-determined volume in the Excel template. If any coefficient combinations seem to fit all or most of the plots, in the same manner as 0.1 and 0.83 fit for both *Christinedal* and *Siemens*, then they could more reliably be used as runoff coefficients in future dimensioning in urban Oslo. This is a potential area for future work. However, in this work as well, one will need to be certain that the coefficients are based on accurate and reliable RCA appraisals and PCSWMM model results, or the work will be a waste.

7.3.2 Suggestions

Alternative 2: Excel template

If Sweco decide against the use of PCSWMM for future dimensioning, but rather for the continued use of their Excel template, then the author's suggestion is to lower the runoff coefficients they commonly use when dimensioning detention system. The RCA used in the Excel template should be found by using SCALGO or by other means of determining a reliable estimate. Based on available knowledge and the above discussion, we can say quite certainly that the coefficients Sweco used when dimensioning *Christinedal* and *Siemens*, were excessive. As of now, the best suggestion for new runoff coefficients is 0.1 for permeable surfaces and 0.83 for impermeable surfaces, although these are highly uncertain values. As has been argued for already, more runoff situations should be evaluated before these become standard values, as the foundation for their selection is thus far thin. Additionally, if the former practice is continued, it is important to keep in mind that even with improved runoff coefficients, roughly dividing properties into two large homogenous sub-areas such as this, is a considerable simplification. Therefore, the properties should alternatively be divided into more detailed classifications than just impermeable and permeable surfaces, and the sub-areas should be given runoff coefficients more suited to their characteristics, based on guideline values. This will likely lead to a lower average runoff coefficient and be more accurate than current practice.

If Sweco decide to lower the runoff coefficients according to the suggested values, it is wise to remember that these findings are based on a different Excel template than the one currently being utilised by Sweco. The newer Excel template, which is based on the Aron and Kibler method, yields volumes that are larger than the former template, which would indicate the need for even smaller runoff coefficients. However, due to the likely desire to be somewhat conservative, as under-dimensioning is more expensive than over-dimensioning in the long run, runoff coefficients of 0.1 and 0.83 in the newer template might be a good fit. However, this is ultimately up to Sweco and the designer to determine.

8. Conclusion

8.1 Summary

It has been hypothesised that the company Sweco incorrectly dimension their detention systems. This is unfavourable, as inaccurate dimensioning can be costly. Therefore, this thesis sought to examine ways in which Sweco can improve upon their detention system dimensioning practice. This was done by exploring the software tools SCALGO and PCSWMM and evaluating the importance of runoff coefficients. After completing the work outlined in the methodology, the results yielded were discussed, and possible solutions were proposed.

SCALGO was used to estimate the runoff contributing areas connected to the detention systems *Christinedal* and *Siemens*. This was done by clicking on different locations on the map and assessing the flow direction of runoff. The software was found to be useful in this thesis, and the area appraisals were considered reliable and more trustworthy than Sweco's area appraisal. However, its use is thought to be more problematic for future dimensioning, due to the lack of necessary data and knowledge.

The *Christinedal* and *Siemens* properties were modelled in PCSWMM. Data was either based on documentation from Sweco, estimates from maps and SCALGO, or from guideline values. For both detention systems, the modelled volume was smaller than the constructed volume, thus indicating two over-dimensioned systems. The models seemed to yield trustworthy and logical values, and in this regard, PCSWMM has been identified as a potential way for Sweco to improve upon their dimensioning practice. However, whether the time and skill needed to model is at an acceptably low level for it to be a feasible alternative for Sweco though, has not been determined for certain.

Runoff coefficients were evaluated in more ways than one. Firstly, fitting runoff coefficients were determined based on an in-depth analysis of the *Christinedal* and *Siemens* properties, where the selection process considered guideline values and sub-area characteristics. These coefficients were utilised along with the new runoff contributing area to compare Sweco's and the author's runoff coefficients, and to determine their importance when using Sweco's former dimensioning method. Secondly, combinations of permeable and impermeable runoff coefficients were found, that it used in Sweco's method, would yield the same volume results as in PCSWMM. This showed that a permeable runoff coefficient of 0.1 and an impermeable coefficient of 0.83 yielded coinciding results for both *Christinedal* and *Siemens*.

8.2 Limitations

There were a few important limitations. Firstly, the size of the recorded rainfall events. Since no 20-year event, nor any event large enough to fill the detention system, was recorded, we do not know for certain what the ideal detention system volume for *Christinedal* and *Siemens* is. Therefore, we cannot say for certain which dimensioning method yields the most accurate results, and any thoughts on this is based on assumption and estimates. Secondly, there were not enough cases evaluated to be able to conclude that the findings are applicable for all or most detention systems that have been dimensioned. And thirdly, the two detention systems that were in fact evaluated were both thought to be over-dimensioned. The inclusion of a presumably under-dimensioned detention system, such as *Grefsen,* would have added to the complexity of the evaluations, which would have been favourable. Based on this, the thesis results are not though to be incorrect, but rather incomplete.

8.3 Research questions and recommendations

Based on the above summary of results, the answers to the research questions are summarised below, along with the author's suggestions for how to improve upon the dimensioning practice of detention systems.

- Yes, SCALGO *could* improve upon the selection of runoff contributing area when dimensioning detention systems. However, based on available time and knowledge, it is not advised to utilise it as detailed as it was in this thesis. My suggestion is therefore to use SCALGO to get a quick overview of the runoff situation on and around the property, in order to obtain an estimated runoff contributing area before property development.

- When using Sweco's former dimensioning method, the runoff coefficients are highly influential on the final detention system volume results. Therefore, runoff coefficients should be selected after careful consideration as not to cause excessive over- or under-dimensioning. Additionally, it is my suggestion that if Sweco decide to continue using their Excel template method, the runoff coefficients they currently use should be lowered to values more similar to those found in this thesis, i.e. 0.83 for impermeable surfaces, and 0.1 for permeable surfaces.

- It is believed that modelling in PCSWMM can yield more accurate detention system volumes than Sweco's former and current method. However, both the time and skills needed to obtain these results are far greater than what is required of Sweco's method. Additionally, if PCSWMM modelling is chosen, the results will be less accurate than in this thesis, since the model must be created based on limited available data. Despite this, it is my suggestion to attempt dimensioning by modelling on a trial-basis, and to evaluate further whether it is a feasible alternative or not. The volume from the model should be compared to the volume obtained from Sweco's current method to see if the difference resembles the disparity observed for *Christinedal* and *Siemens* in this thesis.

- Based on the findings of this thesis, it is clear that there are numerous options for how Sweco can improve upon their dimensioning practice of detention systems. The primary proposal is that they change to a more complex runoff model, such as PCSWMM, if they have the time and resources. The secondary suggestion is that they reduce the runoff coefficients they commonly use when dimensioning. In my opinion, these are both deemed acceptable solutions that could yield more accurate results. However, any change should be done on a trial-basis, and the new practice should be evaluated further once it has been initiated. Additionally, SCALGO could potentially improve upon the results by providing additional knowledge on the runoff situation on the property, however, it is not considered an essential tool in the dimensioning process.

8.4 Future work

The importance of this work is justified by the adverse consequences of incorrect dimensioning of detention systems. Over-dimensioning results in added costs for the those who wish to implement the detention system, whilst under-dimensioning can result in overloading of the stormwater drainage system and flooding, which can have detrimental consequences to environment, human health, and economy. Therefore, the aim of future work should be the same as in this thesis, i.e. to identify ways of improving dimensioning of detention systems. Regardless of the dimensioning method utilised going forward, it could be wise to monitor the response of constructed detention systems for a longer time-period. This would provide more data for further evaluation of the detention systems' accuracy and might give an indication as to what dimensioning method yields the best results.

Additionally, future work should be completed to support the specific findings of this thesis. The advocacy of PCSWMM can be supported by the modelling and subsequent monitoring of more detention systems, whilst the suggested runoff coefficients can be supported by collecting more similar data as in this thesis. Such data can be obtained by modelling the runoff on more properties in PCSWMM and evaluating what runoff coefficients are needed to obtain a similar volume when using Sweco's dimensioning method.

References

Critchley, W., Siegert, K., & Chapman, C. (1991). Water Harvesting, A Manual Guide for the Design and Construction of Water Harvesting Schemes for Plant Production. Rome: FAO.

Davie, T. (2008). *Fundamentals of hydrology* (2. ed.). London: Routledge. Dingman, S. L. (2015). *Physical hydrology* (3. ed.). Long Grove, IL: Waveland Press.

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., & Gabarrell, X. (2011). Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. *Water Research, 45*(10), 3245-3254.

FISRWG. (1998). Relationship between impervious cover and surface runoff. In "1998 Stream Corridor Restoration: Principles, processes and Practices." (Eds.): Federal Interagency Stream Restoration Working Group.

Foss, M. (2014). Når regner det minst og mest? Retrieved 05.02.19 from https://www.yr.no/ artikkel/nar-regner-det-minst-og-mest_-1.11977477

Guan, M., Sillanpää, N., & Koivusalo, H. (2015). Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. *Hydrological Processes, 30*(4), 543-557.

Hanssen-Bauer, I. *et al*. (2015). *Klima i Norge 2100. Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015.* Oslo, Norway.

Huang, J., Wu, P., & Zhao, X. (2013). Effects of rainfall intensity, underlying surface and slope gradient on soil infiltration under simulated rainfall experiments. *CATENA, 104*, 93-102.

James, W., Rossman, L. A., & James, W. R. C. (2010). *User's guide to SWMM5*

(13 ed.). Ontario: CHI Press Publication.

Leknes, S. (2018). Befolkningsframskrivinger fram til 2040 for hver enkelt kommune – søk i kart. Retrieved 14.09.18, from Statistisk Sentralbyrå (SSB) https://www.ssb.no/befolkning/artikler-og-publikasjoner/ befolkningsframskrivinger-fram-til-2040-for-hver-enkelt-kommune-sok-i-kart

Lindholm, O. G. (2018). Håndtering av overvann – LOD. *VA-Miljøblad, 104*.

Magnussen, R. A. G. (2015). *Gjennomgang av avrenningsfaktorer*. Oslo: Miljødirektoratet.

Nedza, N. M. (2018). *Comparing observed and dimensioned stormwater detention system volumes in Oslo.* (MSc Specialisation Project), NTNU, Trondheim.

NOU. (2015). *Overvann i byer og tettsteder – Som problem og ressurs*. Oslo: Departementenes sikkerhets- og serviceorganisasjon, informasjonsforvaltning.

NVE. (2018). Urbanhydrologi. *Hydrologi.* Retrieved 10.09.18 from https://www.nve.no/ hydrologi/urbanhydrologi/

Oslo Municipality. (2013). *Strategi for overvannsshåndtering i Oslo 2013-2030*. Oslo: Oslo Municipality.

Shanley, J. B., & Chalmers, A. (1999). The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont. *Hydrological Processes, 13*, 1843-1857

Skotnicki, M., & Sowinski, M. (2015). The influence of depression storage on runoff from impervious surface of urban catchment. *Urban Water Journal, 12*(3), 207-218.

Solheim, E. B., Braskerud, B. C., & French, H. K. (2017). Måling av infiltrasjon fra overflaten for bruk av åpen LOD i praksis. *VANN, 52*(3).

Stanger, G. (1994). *Dictionary of hydrology and water resources*. Adelaide: Lochan in association with the Centre for Groundwater Studies.

Starke, P., Göbel, P., & Coldewey, W. G. (2010). Urban evaporation rates for water-permeable pavements. *Water Science & Technology, 62*(5), 1161-1169.

Thorsnæs, G. (2018). Norges Befolkning. *Store Norske Leksikon.* Retrieved 08.09.18 from https://snl.no/Norges_befolkning

UDFCD. (2016). Chapter 6: Runoff. In *Urban Storm Drainage Criteria Manual: Volume 1: Management, Hydrology, and Hydraulics* (Vol. 1). Colorado: Urban Drainage and Flood Control District.

Viessman, W., & Lewis, G. L. (2003). *Introduction to hydrology* (5. ed.). New York: Pearson Education.

Ødegaard, H. (2014). *Vann- og avløpsteknikk* (2 ed.). Hamar: Norsk Vann.

Åstebøl, S. O., Karlsson, I., Bergom, H. & Kvile, K. R. (2017). *Veileder for lokal håndtering av overvann i kommuner.* Vestfold Fylkeskommune.

Appendix

Appendix 1: Duration and return period for each scaled rainfall event

Table A.1. Return period for each duration for the rainfall event Sandaker 2013. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	1	1	1	3	4	4	5	15	21	22	19	18	10	5

Table A.2. Return period for each duration for the rainfall event Blindern 2008, scaling factor 1. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	14	7	7	10	22	18	13	7	3	3	2	2	1	<1

Table A.3. Return period for each duration for the rainfall event Blindern 2008, scaling factor 2. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	22	10	10	15	33	26	18	9	4	3	3	2	1	1

Table A.4. Return period for each duration for the rainfall event Blindern 2014, scaling factor 1. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	1	2	3	3	5	4	5	4	12	14	16	22	20	10

Table A.5. Return period for each duration for the rainfall event Blindern 2014, scaling factor 2. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	1	3	3	4	6	5	6	6	15	18	21	30	26	14

Table A.6. Return period for each duration for the rainfall event Blindern 170680, scaling factor 1. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	12	15	19	22	7	4	2	1	1	1	<1	<1	<1	<1

Table A.7. Return period for each duration for the rainfall event Blindern 170680, scaling factor 2. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	18	21	26	31	9	5	3	2	1	1	1	<1	<1	<1

Table A.8. Return period for each duration for the rainfall event Blindern 060880, scaling factor 1. The return period is determined based on IDF-values from Blindern.

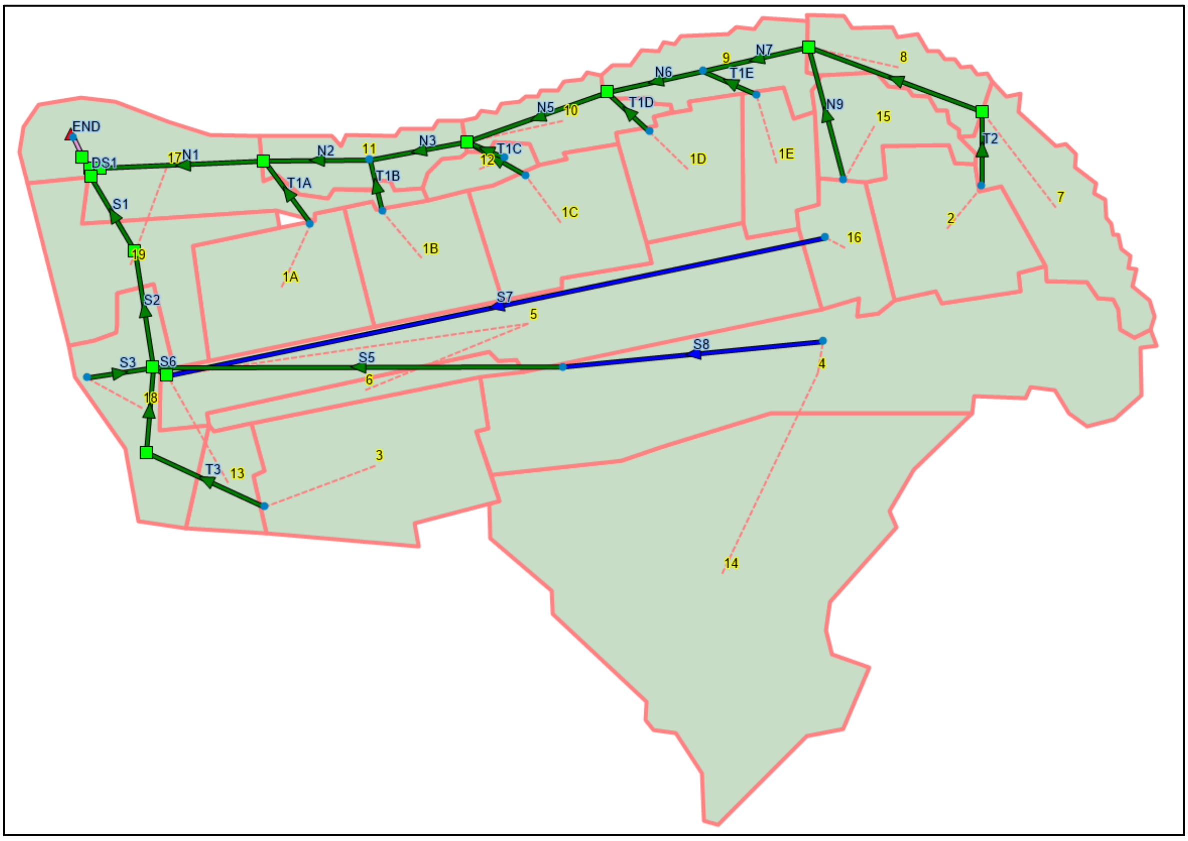
Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	<1	1	1	2	7	13	15	22	18	14	11	10	6	3

Table A.9. Return period for each duration for the rainfall event Blindern 060880, scaling factor 2. The return period is determined based on IDF-values from Blindern.

Time interval [min]	1	2	3	5	10	15	20	30	45	60	90	120	180	360
Return Period [years]	1	1	2	3	9	17	20	29	23	18	15	14	8	4

Appendix 2: Map of *Christinedal* model in PCSWMM

Figure A.1. Screenshot of the Christinedal model in PCSWMM. The names of the conduits are shown with blue back colour and the names of sub-catchments are shown with yellow back colour.



Appendix 3: Input to sub-catchment parameters in the *Christinedal* model in PCSWMM

Table A.10. Name, area size, width and slope of each sub-catchment in the PCSWMM model for Christinedal.

Sub-catchment characteristics			
Name	**Area (m^2)**	**Width (m)**	**Slope (%)**
1A	333	20	0.01
1B	279	17	0.01
1C	331	19.5	0.01
1D	246	14	0.01
1E	173	10	0.01
2	348	19	0.01
3	553	19	0.01
4	1120	14	1.4
5	596	7	0.2
6	82	2	0.5
7	287	8.2	2.2
8	164	6.8	3.1
9	209	8	3.7
10	163	6.5	4.8
11	170	6.7	5
12	61	10	2
13	91	8.2	0.5
14	1672	47.5	17.2
15	184	15	1
16	123	10	1
17	432	30	0.5
18	258	12	0.5
19	332	20	0.5

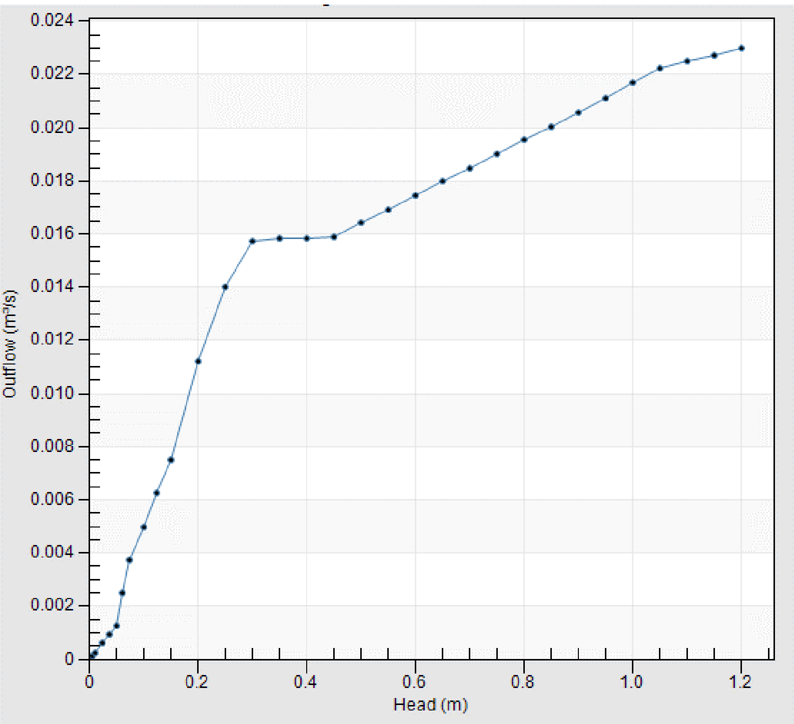
Appendix 4: Input to conduit parameters in the *Christinedal* model in PCSWMM

Table A.11. Name, length, roughness, cross-section shape and geometry of each conduit in the PCSWMM model for Christinedal.

Conduit characteristics					
Name	**Length (m)**	**Roughness**	**Cross-Section**	**Geom1 (m)**	**Geom2 (m)**
N1	21	0.012	CIRCULAR	0.188	0
N2	12	0.012	CIRCULAR	0.188	0
N3	12	0.012	CIRCULAR	0.188	0
N4	3	0.012	CIRCULAR	0.104	0
N5	18.9	0.012	CIRCULAR	0.188	0
N6	11.5	0.012	CIRCULAR	0.188	0
N7	15	0.012	CIRCULAR	0.188	0
N8	24.3	0.012	CIRCULAR	0.104	0
N9	18	0.012	CIRCULAR	0.104	0
S1	11	0.012	CIRCULAR	0.188	0
S2	17	0.012	CIRCULAR	0.188	0
S3	6.5	0.012	CIRCULAR	0.104	0
S4	11.6	0.012	CIRCULAR	0.188	0
S5	48	0.012	CIRCULAR	0.104	0
S6	0.15	0.012	RECT_OPEN	1	1
S7	50.5	0.015	PARABOLIC	0.05	0.2
S8	35	0.035	TRAPEZOIDAL	0.3	0.2
T1A	10.3	0.012	CIRCULAR	0.104	0
T1B	6.7	0.012	CIRCULAR	0.104	0
T1C	9.3	0.012	CIRCULAR	0.104	0
T1D	7	0.012	CIRCULAR	0.104	0
T1E	10	0.012	CIRCULAR	0.104	0
T2	10.1	0.012	CIRCULAR	0.104	0
T3	16	0.012	CIRCULAR	0.122	0
DS1	3	0.012	CIRCULAR	0.297	0
DS2	3	0.012	CIRCULAR	0.297	0
DS3	3	0.012	CIRCULAR	0.297	0
END	1	0.012	CIRCULAR	0.297	0

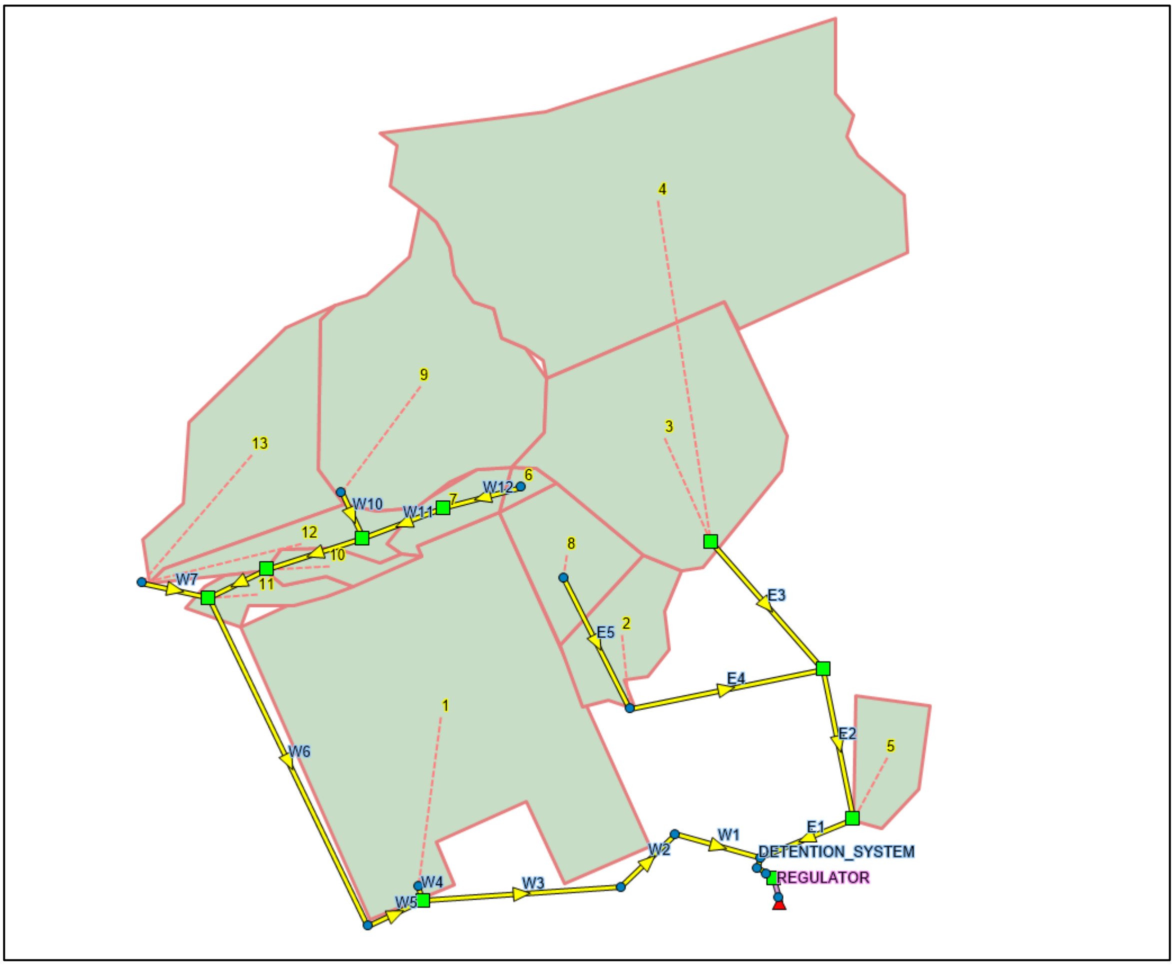
Appendix 5: Stage-discharge curve for flow regulator in the *Christinedal* PCSWMM model

Figure A.2. Stage-discharge curve used to model the vertical vortex valve flow regulation in the Christinedal model.



Appendix 6: Map of *Siemens* model in PCSWMM

Figure A.3. Screenshot of the Siemens model in PCSWMM. The names of the conduits are shown with blue back colour and the names of sub-catchments are shown with yellow back colour.



Appendix 7: Input to sub-catchment parameters in the *Siemens* model in PCSWMM

Table A.12. Name, area size, width and slope of each sub-catchment in the PCSWMM model for Christinedal.

Sub-catchment characteristics			
Name	**Area (m^2)**	**Width (m)**	**Slope (%)**
1	2970	51.5	0.05
2	352	22	2.3
3	1462	38	4
4	3586	75	19
5	249	12.6	32
6	55	9.5	10
7	187	24	0.1
8	366	17	5
9	1421	36	24.5
10	100	20	5
11	134	22	6.5
12	258	30	4.5
13	856	27	20

Appendix 8: Input to conduit parameters in the *Siemens* model in PCSWMM

Table A.13. Name, length, roughness, cross-section shape and geometry of each conduit in the PCSWMM model for Siemens.

Conduit characteristics					
Name	**Length (m)**	**Roughness**	**Cross-Section**	**Geom1 (m)**	**Geom2 (m)**
E1	0.5	0.012	CIRCULAR	0.151	0
E2	28.5	0.012	CIRCULAR	0.151	0
E3	30.3	0.012	CIRCULAR	0.151	0
E4	31	0.012	CIRCULAR	0.151	0
E5	21	0.013	RECT_OPEN	0.2	0.15
W1	0.5	0.012	CIRCULAR	0.151	0
W2	12.3	0.012	CIRCULAR	0.151	0
W3	34	0.012	CIRCULAR	0.151	0
W4	4	0.012	CIRCULAR	0.151	0
W5	11	0.012	CIRCULAR	0.151	0
W6	61.5	0.012	CIRCULAR	0.151	0
W7	15	0.012	CIRCULAR	0.151	0
W8	10.5	0.012	CIRCULAR	0.151	0
W9	15.5	0.012	CIRCULAR	0.151	0
W10	11	0.012	CIRCULAR	0.151	0
W11	17	0.012	CIRCULAR	0.151	0
W12	11	0.012	CIRCULAR	0.151	0
S1	0.5	0.012	CIRCULAR	0.235	0
S2	6	0.012	CIRCULAR	0.235	0
S3	3	0.012	CIRCULAR	0.188	0
DETENTION_SYSTEM	36	0.013	CIRCULAR	2	0

Appendix 9: Stage-discharge curve for flow regulator in the *Siemens* PCSWMM model

Figure A.4. Stage-discharge curve used to model the vertical vortex valve flow regulation in the Siemens model.

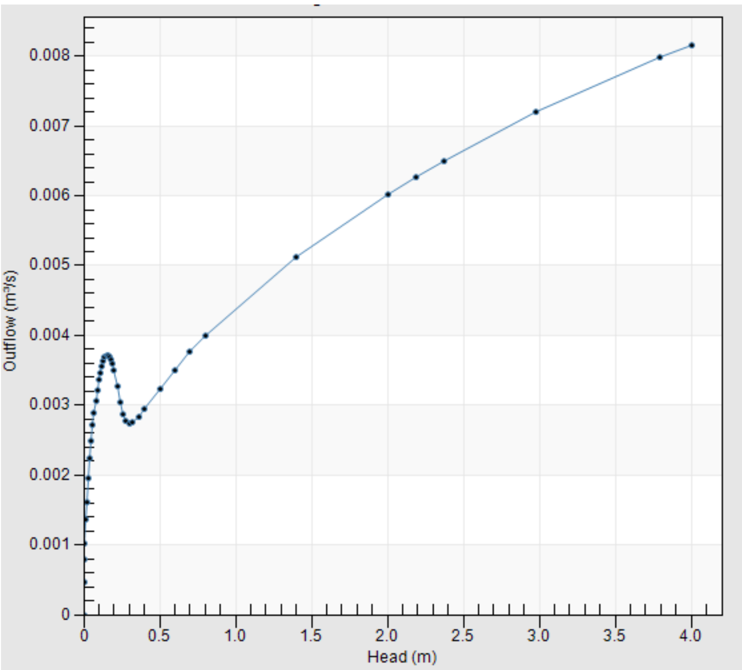


Table A.14. Numerical values on which the above stage-discharge curve is based. Values obtained from the manufacturer of the vertical vortex valve, MFT.

h_r i m	Q_r i l/s	h_r i m	Q_r i l/s	h_r i m	Q_r i l/s
0,002	0,46	0,120	3,56	0,320	2,75
0,005	0,80	0,130	3,64	0,360	2,83
0,008	1,03	0,140	3,70	0,400	2,94
0,014	1,36	0,150	3,72	0,500	3,23
0,020	1,62	0,160	3,72	0,600	3,51
0,030	1,96	0,170	3,70	0,700	3,76
0,040	2,25	0,180	3,65	0,800	4,00
0,050	2,49	0,190	3,59	1,400	5,13
0,060	2,71	0,200	3,51	2,000	6,02
0,070	2,90	0,220	3,28	2,185	6,26
0,080	3,07	0,240	3,04	2,370	6,50
0,090	3,22	0,259	2,87	2,981	7,20
0,100	3,36	0,280	2,77	3,796	7,99
0,110	3,47	0,300	2,73	4,000	8,16

Nicoline Myhre Nedza

Dimensioning detention systems for small urban catchments

NTNU
Norwegian University of
Science and Technology