NTNU
Norwegian University of
Science and Technology

Modeling of overland flow at Overvikfeltet, Trondheim

Mikkel Stensås Svanevik

Master of Science in Civil and Environmental Engineering
Submission date: June 2016
Supervisor: Sveinung Sægrov, IVM
Co-supervisor: Tone Merete Muthanna, IVM
Petter Reinemo, Asplan Viak
Vebjørn Knotten, Asplan Viak

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

Abstract

This thesis looks at what factors influence the hydrology of a catchment, and modeling how low impact development can be used to mitigate the effects of urbanization in a catchment through the use of PCSWMM.

The catchment used for modeling in this thesis is the Overvik area in Trondheim. This area is currently an agricultural area, but plans are made for development, increasing the amount of impervious areas and thus increasing the runoff coefficient. Downstream of the catchment is a culvert dimensioned for the runoff pre-development, so the peak runoff to this culvert cannot increase post-development.

Three models were created for the catchment, one for the pre-development situation, one for the planned post-development situation and one using low impact development. All models are simulated using the same weather events in order to see how the runoff changes between the models. Rainfall events used in the simulation are 1-year measured data from 2011 and design storms based on the IDF-curve for Trondheim with return periods of 2, 20 and 200 years.

Simulation results show that LID controls work well for smaller rainfall events, with reductions in LID total runoff by 22 % and 9 % for the 1-year model and 2-year design storm compared to post-development. For 20- and 200-year design storms the total runoff reduction is 4 % and 2 % respectively. The same results are found in the peak runoffs, where 2-year reduction is 20 % while 20- and 200-year reductions are both 12 %. The calculated storage needed to maintain the pre-development peak runoff in the LID model is 1 062 m^3 for the 200-year design storm.

Sammendrag

Denne oppgaven ser på hvilke faktorer som påvirker hydrologien for et område, og gjennom modellering i PCSWMM se hvordan lokale overvannstiltak kan motvirke de negative effektene av urbanisering i et område.

Området brukt til modellering i denne oppgaven er Overvik som ligger i Trondheim. Området er i dag hovedsakelig et jordbruksområde, men utbygging av området er planlagt i nær fremtid. Dette vil øke andelen tette flater betraktelig, noe som også vil øke avrenningskoeffisienten for området. Nedstrøms området går avrenningen gjennom en kulvert under E6 som er dimensjonert for dagens 200-års flom. Det er derfor ønskelig at maksimalavrenningen til kulverten ikke skal økes som følge av utbyggingen.

Tre modeller ble laget for området, en for dagens situasjon, en for planlagt utbygging og en der lokale overvannstiltak blir benyttet. Alle modeller blir simulert med de samme nedbørshendelsene for å se hvordan avrenningen endrer seg mellom modellene. Nedbørshendelsene brukt til simulering er målt 1-års nedbør for 2011, samt nedbør basert på IVF-kurven for Trondheim med gjentaksintervaller på 2, 20 og 200 år.

Resultatene viser at lokale overvannstiltak fungerer best for små nedbørshendelser, der reduksjonen i total nedbør for LID-modellen er 22 og 9 % i forhold til planlagt utbygging ved simulering med 1-års og 2-år nedbørshendelser. Ved 20- og 200-års nedbørshendelser er reduksjonen i total nedbør 4 og 2 %. De samme resultatene ses for maksimalavrenningen, der reduksjonen ved 2-års nedbør er 20 %, mens den reduseres til 12 % for 20- og 200-års nedbør. For å beholde dagens maksimalavrenning for 200-års nedbør viser resultatene at det trengs 1 062 m^3 lagringsvolum oppstrøms kulverten.

Preface

This thesis is written as my final dissertation at the institute for water- and environmental engineering at NTNU. The task is provided by Asplan Viak AS, so is the data used for the modeled area.

The work on this thesis has at times been both challenging and frustrating, but I've learned a lot about modeling and low impact development, which was my main motivation for writing this thesis. Low impact development is an important subject, and will most likely only become more important in the future as the effects of climate change become a reality.

I would like to thank Sveinung Sægrov at NTNU for being my main supervisor during the writing of this thesis, and for some helpful discussions throughout the semester. I would also like to thank Petter Reinemo at Asplan Viak AS for providing the task for this thesis, and for assistance throughout the semester.

I would also like to thank Sveinn Torfi Thorolfsson and Tone Merete Muthanna at NTNU for some assistance, Vebjørn Knotten at Asplan Viak AS for some initial thoughts and discussion on the scope of the thesis, and Trondheim municipality for providing laser-data for the Overvik area.

Mikkel S. Svanevik

Mikkel Stensås Svanevik, Trondheim, 20.06.2016

Table of Contents

Figure list

Table list

1. Introduction and background

This thesis is structured so that the literature study is presented first, so that the reader will have a better understanding of how different parameters affect the sensitivity analysis and results presented later. During the first part the parameters and LID controls affecting the hydrology are presented, but also briefly discussed. Finally, the model accuracy and results are discussed, before suggestions for future work on the subject is presented.

The background for this thesis is the future development of the Overvik area at Ranheim in Trondheim. A zoning plan has been developed and presented to the municipality by Asplan Viak AS, and this development is expected to greatly increase the runoff coefficient of the area. Downstream of the area there is a culvert, under the main road E6, that is designed for current 200-year flood events. The peak runoff from the area should therefore not be increased as a result of development. The desired method for maintaining the current hydrology is through the use of local low impact development controls.

The purpose of this thesis is to decide which local measures should be implemented, and to what extent measures have to be implemented to keep the runoff at current levels.

This thesis will base its results on uncalibrated models of the areas' current stormwater runoff in both normal- and flood situations, as well as models for the post-development situation and a model utilizing low impact development controls.

The reason the models are not calibrated is because there exist no current measurements of the flow in Overvikbekken, and producing these measurements during this semester would prove too time-consuming. The drawbacks from using uncalibrated models will be discussed later.

1.1. The area today

The area is today mainly an agricultural area with large fields, some scattered trees and groves and some small residential areas. The total area of the modeled Overvik catchment is 724 000 m^2. The area type distribution is illustrated in Figure 1 and shown in Table 1.

Table 1: Area distribution pre-development.

Area type	Area [m^2]	Share [%]
Agricultural	604 711	83.6
Residential	23 213	3.2
Gravel roads & courtyards	19 891	2.7
Roads	15 981	2.2
Buildings	8 082	1.1
Forest	51 921	7.2
Total	**723 798**	**100**

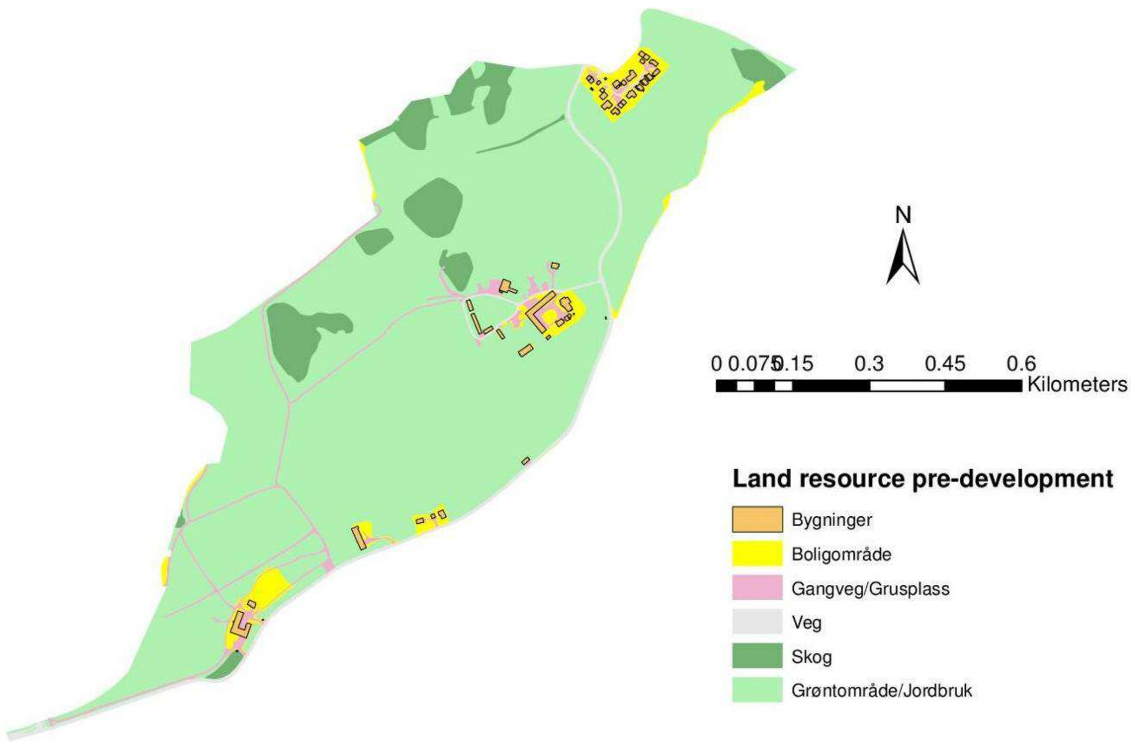


Figure 1: Land resource map pre-development.

The terrain is pretty steep towards the culvert area, which has a height of approximately 20 m, while the highest points in the area is about 140 meters above sea level. This means the precipitation will have a relatively short concentration time, and the runoff can achieve high velocity and be very erosive.

The dominant soil type at Overvik is thick marine depositions, with some areas of “weathering material”, as seen in Figure 7. These are both fine-graded soils where silt and clay are the dominant materials. This means the infiltration capacity of the soil is rather poor, and much of the rainfall is expected to produce runoff during large rainfall events.

1.2. Current hydrology

In (Reinemo, 2015) there are done some calculations and estimations regarding the hydrology and overland flow of rainwater in the Overvik area in its current state. The report says that due to the steep slope of the area, the response time in flood situations can be very low, and is estimated to 35 minutes. Also, since the area is relatively small and has little to no natural ponding areas, the runoff is likely to be closely linked with rainfall, snow melt and soil saturation.

There are not made any measurements of the runoff in Overvikbekken, so the specific runoff is set as the highest value between an adjusted estimation from the specific runoff in Øvre Hestsjøbekk and the specific runoff from the rational formula using the IVD-curve for Trondheim. Øvre Hestsjøbekk is a river flowing into the lake Hestsjøen in Trondheim, where catchment rainfall and runoff are measured, so the catchment can be used for transferring rainfall/runoff relationships to Overvik. Comparison with the Øvre Hestsjøbekk catchment gives a specific runoff for 200-year flood events of 2240 l/s*km^2 before multiplying with the climate coefficient of 1.2. Using the rational formula, with a runoff coefficient of 0.4 and a time of concentration of 35 minutes, the specific runoff is estimated to 2800 l/s*km^2 before climate addition. Seeing that the rational formula gives the highest specific runoff, it is used for flood dimensioning, giving a 200-year flood estimated at 3400 l/s*km^2. This would give the Overvik catchment a peak runoff of 2461 l/s, or 2.5 m^3/s.

1.3. Plans for development

The goal of the zoning plan is to create a compact urban residence district facilitated mainly for pedestrians and cyclists. There will be built a “miljøgate” through the area for use by cars and pedestrians. The plan also opens for a lot of green areas, football fields and pathways through the residential area. The forest in the northwest corner of the area will be zoned as a consideration zone and kept as-is.

The zoning plan is made to control the parent structure of the area development, which could take many years to complete. There are therefore not made any detailed plans for other structures than roads and paths. The zoning plan opens for development of a total of 2300 residence units.

Development of the Overvik catchment will of course lead to an increase in impervious areas, in the form of road and house surfaces, which in turn will lead to increased runoff coefficients. Using the illustration plan shown in Figure 3 as a template, the area distribution for post-development is shown in Table 2, and as an illustration in Figure 2.

Table 2: Area distribution post-development..

Area type	**Area [m^2]**	**Share [%]**	**Change [%]**
Agricultural	307 230	42.4	50.8
Residential	253 784	35.0	1 093.3
Gravel roads & courtyards	27 279	3.8	137.1
Roads	39 612	5.5	247.9
Buildings	75 785	10.4	937.7
Forest	20 107	2.8	38.7
Total	**723 798**	**100**	**100**

After development the amount of impervious surfaces are expected to change from 6.1 % to 19.7 %.

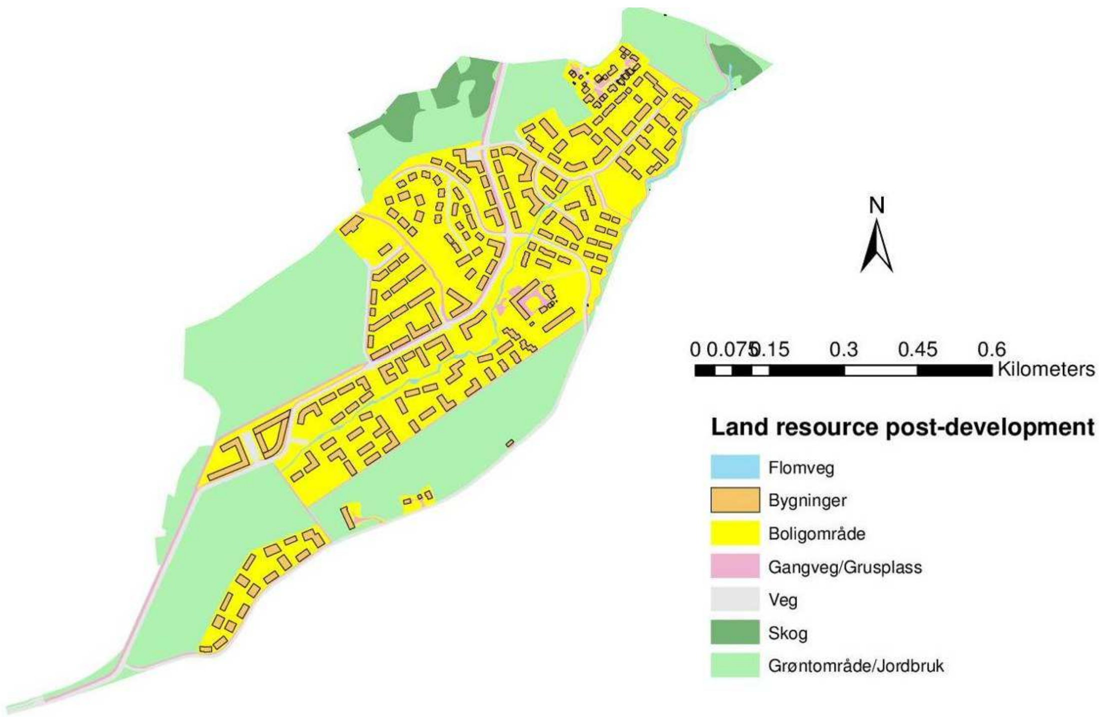


Figure 2: Land resource map post-development.

Figure 3: Illustration plan for the Overvik area. (Source: Asplan Viak)

2. Method

For the literature part of this thesis, I've used www.Oria.no and www.WebofKnowledge.com for researching scientific articles to base my thesis on. Both these services are free for NTNU students, and combined they offer a very large amount of articles on a variety of topics.

For the terrain data in my model, I received measured laser-data from Trondheim municipality over the surrounding area. These laser-data gives very accurate measurements, and the total number of measured points was close to 100 million for the area. These points were used to create the digital terrain model (DTM) used as background in PCSWMM.

The land resource maps in Figure 1 and Figure 2 were created using ArcMap. The pre-development map is based on FKB-data for Trondheim municipality provided by Asplan Viak. The post-development map is based on the illustration plan shown in Figure 3, where the different land resources are manually drawn in ArcMap, using the illustration plan as an overlay. All area distribution tables, as well as the amount of impervious surfaces are based on these two maps.

For the infiltration tests performed at the Overvik area, I used infiltrometer tubes with 5.25 cm radius, as seen in Figure 4. The tube was inserted 5 cm into the ground, and it had an initial water column height of approximately 40 cm. The water column height in the tube was then measured every 10 minutes until it was either empty or enough time had passed to give at least 10 measurements. Dirt samples were collected before and after the test, in order to measure the water content of the earth. All this data was then put into a spreadsheet and run through a program using MATLAB to provide the results shown in chapter 4.2.

Figure 4: Infiltrometer tube used at infiltration test at Overvik.

3. Maintaining original hydrology

The standard or normal runoff is a measure of the average total yearly runoff for the past 30 years, or for a given 30-year period as in Figure 14. With the expected climate change we will see in the future, this measure of standard runoff will likely increase year by year, as the old yearly runoff numbers are replaced with newer more rainfall-intensive years. In order to ensure that new structures are future-proof, the runoff calculations used for dimensioning are often given a climate factor to account for these increases in rainfall intensity.

When developing an area today, it is often required that the hydrology of the area does not change as a result of the development, especially in already urbanized areas. Development of an area will of course affect the hydrology; so countervailing measures needs to be implemented. These measures have in the past been mostly based on end-of-pipe controls, but in later years low impact development has been used to good effect to achieve the same results in a more sustainable and aesthetic way. So when trying to maintain the same hydrology post-development as pre-development it is important to know about how the hydrology changes during development, and how the different measures can counteract these changes.

It is also important to think about what events the hydrology should be maintained for. If the goal is to maintain the hydrology for a storm event with a 200-year return period, it would require a lot more measures than maintaining the hydrology for a storm event with a 2-year return period. Low impact development controls are primarily used for maintaining the hydrology during smaller events that occur frequently. For larger events with high return periods, it will be necessary with a large storage volume in order to collect the additional runoff created from development.

4. What affects the model runoff

4.1. Precipitation

Rainfall and runoff are, as one would expect, closely linked. Rainfall can vary in both intensity and in duration, but more often than not very intensive rainfall has short durations while long duration rainfalls has lower intensity. This is also reflected in IVD-curves, where the intensity increases with lower durations. The IVD-curve for Trondheim is shown in Figure 5.

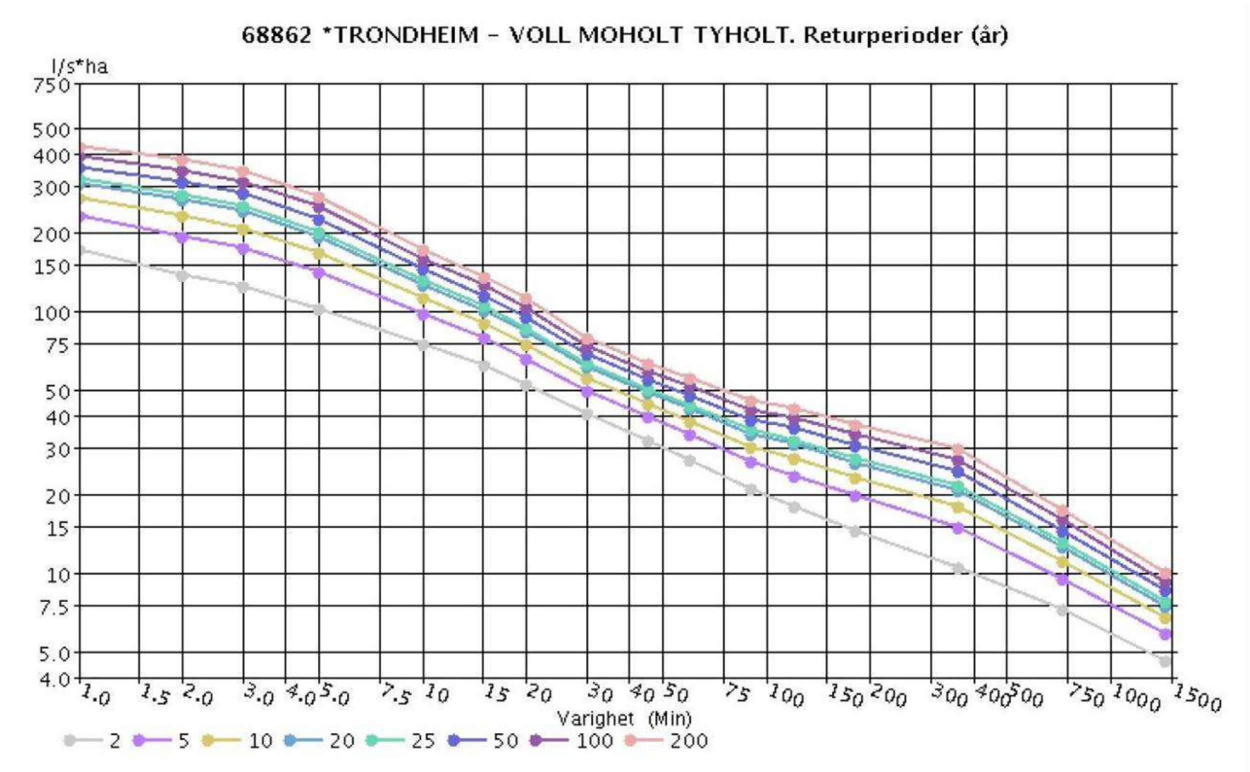


Figure 5: IVF-curve for Trondheim. (Source: VA-Norm)

Another important factor affecting the runoff is the hydrologic memory, or in simplified terms the time since the previous rainfall event. During rainfall events the soil will build up moisture to a certain point, known as the saturation point. When the soil is fully saturated, the runoff coefficient of the soil is increased drastically. This means that the less time since the last rainfall event, the faster the soil will reach its saturation point and the runoff will be increased, and the longer the dry period the more water the soil will infiltrate, reducing the runoff. A series of short but intensive rainfall events in quick succession can therefore be very devastating, as the infiltration capacity of the soil is severely reduced by the previous events.

In Trondheim there are several rain gauges measuring rainfall and other climatic variables constantly. The closest ones to Overvik are Risvollan, Ranheim and Voll rain gauges as seen in Figure 6. The station used for the 1-year modelling in this paper is Voll rain gauge for 2011, due to availability of data and the fact that 2011 is often used as a "normal-year" for water and wastewater modelling by DHI and Trondheim municipality. Risvollan catchment and measuring station is used a lot in scientific research at NTNU, and the supplied data from the station should therefore be quite reliable for use in modelling, but since it's the station furthest away I've opted for using Voll rain gauge.

Figure 6: Rain gauges close to Overvik. (Source: http://eklima.met.no/Help/Stations/toDay/all/en_Stations.html)

The data from Voll rain gauge in 2011 has a time-step of 1-hour, which should be fine for long-term modelling, but it means that the short duration-high intensity rainfall is not caught in the model. Therefore, in addition to the 1-year model, models will be run on design storms of varying return periods based on the IVD-curve for Trondheim and observed design storm data from the Voll and Ranheim rain gauges.

4.2. Soil type

The soil type in specific areas will have a great impact on the infiltration rate and infiltration capacity of the catchment. Different soils will have different porosity and permeability affecting the runoff coefficient differently depending on the soil moisture.

Soils with high porosity and permeability will infiltrate more rainwater, and have a higher storage capacity than a soil with low porosity and permeability. Maps from “Norges geologiske undersøkelse (NGU)” show that most of the Overvik area is defined as thick marine depositions, which basically means silt and clay soils with quite low porosity and permeability.

Figure 7: Soil types at Overvik. Light blue is thick marine depositions and pink is weathering material. (Source: http://geo.ngu.no/kart/losmasse/)

On May 5th I measured the hydraulic conductivity of the soil using an infiltrometer at two locations in the Overvik area. At the first point there were some strange results, as the water in the infiltrometer infiltrated very slowly, and with a constant rate, as seen in Figure 8. The reason for this is not clear, but possible explanations can be that the soil had a very high water content before the testing started, or that there was an object in the ground keeping the water from infiltrating. For point 2 the results looked better, with a high infiltration rate to begin with and a decline in infiltration as the soils water content increases. The results from point 2 are shown in Figure 9.

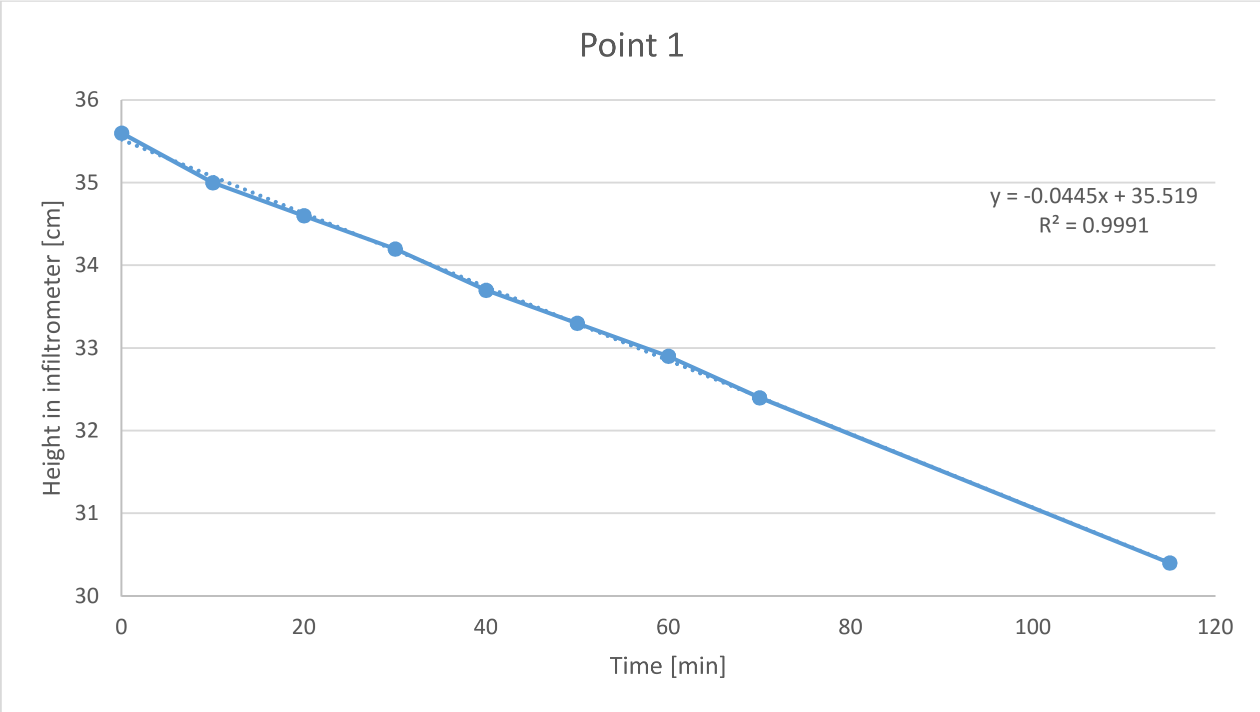


Figure 8: Infiltrometer data in point 1.

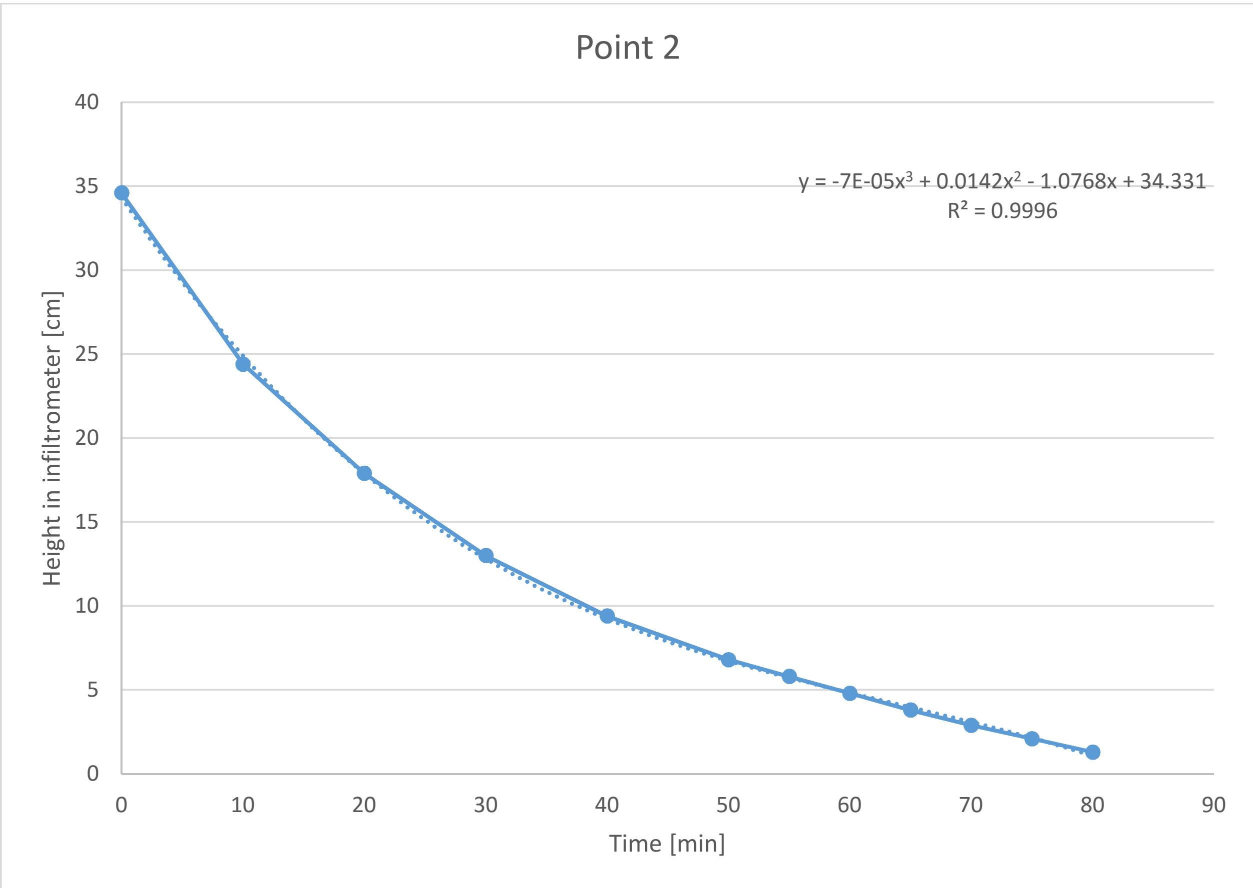


Figure 9: Infiltrometer data in point 2.

The water content of the soil was measured before and after the infiltrometer test in point 1. The reason it was done in point 1, is because I took soil samples before I realized that the results from point 1 looked strange, and I only had the equipment to take one set of soil samples since I assumed the soil moisture would be very similar within the area.

Figure 10: Locations of infiltration tests.

Results from the infiltration tests gave a hydraulic conductivity of 0.014374 cm/h for point 1, and 19.116 cm/h for point 2. The locations of point 1 and 2 are shown in Figure 10.

4.3. Vegetation

The vegetation in an area affects the hydrology in two main ways. The first one is due to the roughness of the surface, and is given as mannings number “n” in the model. The roughness will affect how fast the water will flow, and smoother surfaces will give shorter time of concentration. Surface roughness will also affect infiltration; as higher roughness will give the water more time to infiltrate to the ground.

The second way vegetation affects runoff is through evapotranspiration, and is decided by what vegetation is in the area. Trees, bushes and plants will collect some of the rainwater and prevent it from producing runoff. Some of this water will evaporate directly, while some of the water will be absorbed by the vegetation and later transpired through leaves and flowers. This is why heavily forested areas often have a very low runoff coefficient, as most of the rainwater either never hits the ground or is absorbed by the ground and trees.

The vegetation in the area today is dominated by agricultural fields, and some clusters of trees, as seen in Figure 1. This will give a rather high surface roughness for the summer months while the fields are filled with crop, and a lower roughness when there are no crops in spring and autumn.

After development, the surface roughness of the area is expected to be reduced as most of the crop fields are replaced by lawns and parks, but the roughness might be more stable throughout the year, as there is less variation in vegetation density.

4.4. Terrain

The terrain will affect the runoff hydrograph through mainly size, shape and slope. Time of concentration will increase with bigger areas and vice versa. The Overvik catchment has a total area of 72.2 ha, and is relatively small. The time of concentration is estimated to around 52 minutes pre-development.

The shape of the catchment is important, as catchments with a lot of the area close to the outlet, divergent catchments, will produce a lot of runoff fast, while the areas further away will contribute later. Catchments with most of the area far away from the outlet, convergent catchments, will produce most of its runoff later. This effect is demonstrated in Figure 11. The shape of the Overvik catchment is close to rectangular, so the amount of area contributing with runoff is expected to increase linearly.

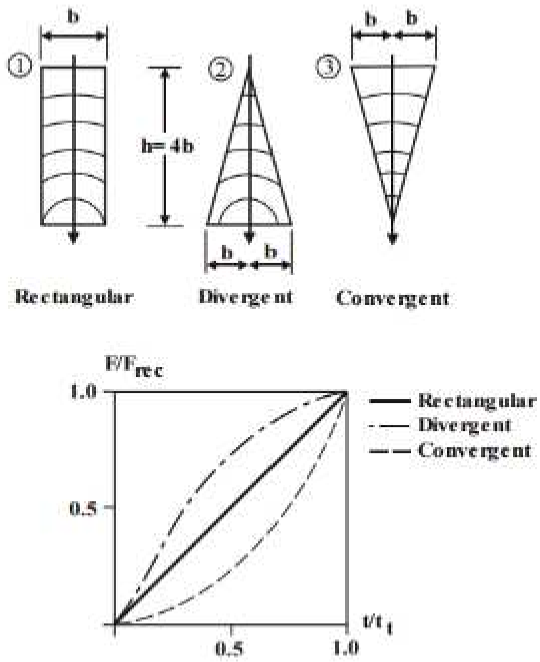


Figure 11: Time/area-curves. Time on X-axis and percentage of total runoff on Y-axis.

The slope of the Overvik catchment is quite steep, with an average slope of approximately 6.8 %, but with instances of slopes upwards of 16 %. The longitudinal section of the Overvik area can be seen in Figure 12. Catchment slopes has a big impact on the time of concentration, and a halving of the average slope in the catchment would increase the time of concentration with about 9 minutes. The high slope will also cause the stormwater to reach high velocities when flowing downstream, which could cause erosion and damages in the flow paths. In the zoning plan for Overvik, a vegetated swale is planned through the residential area, serving as both a floodway during large rainfall events and as a stream during smaller events.

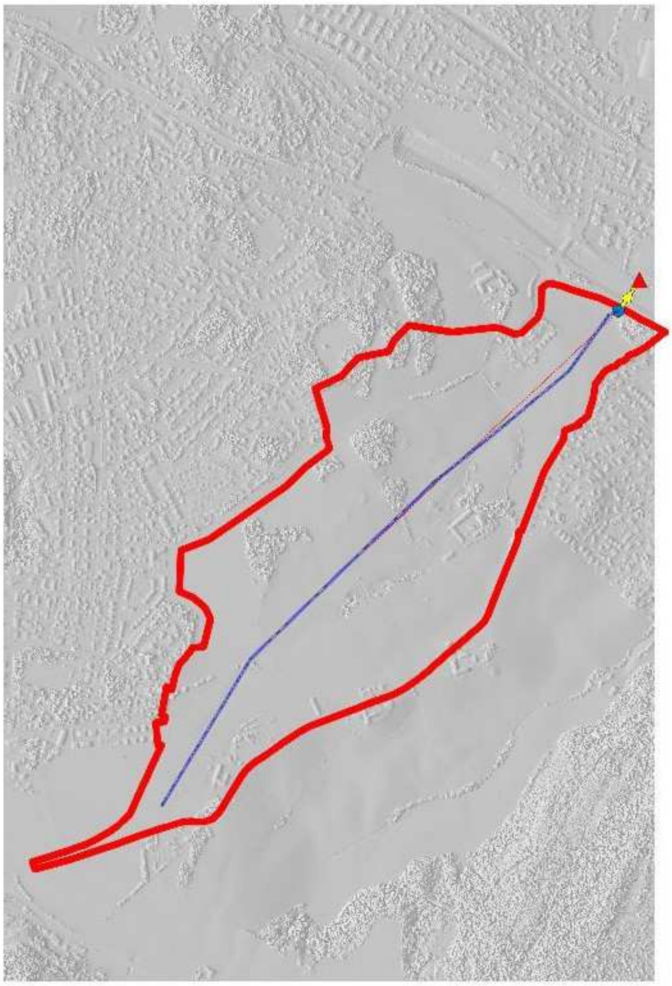
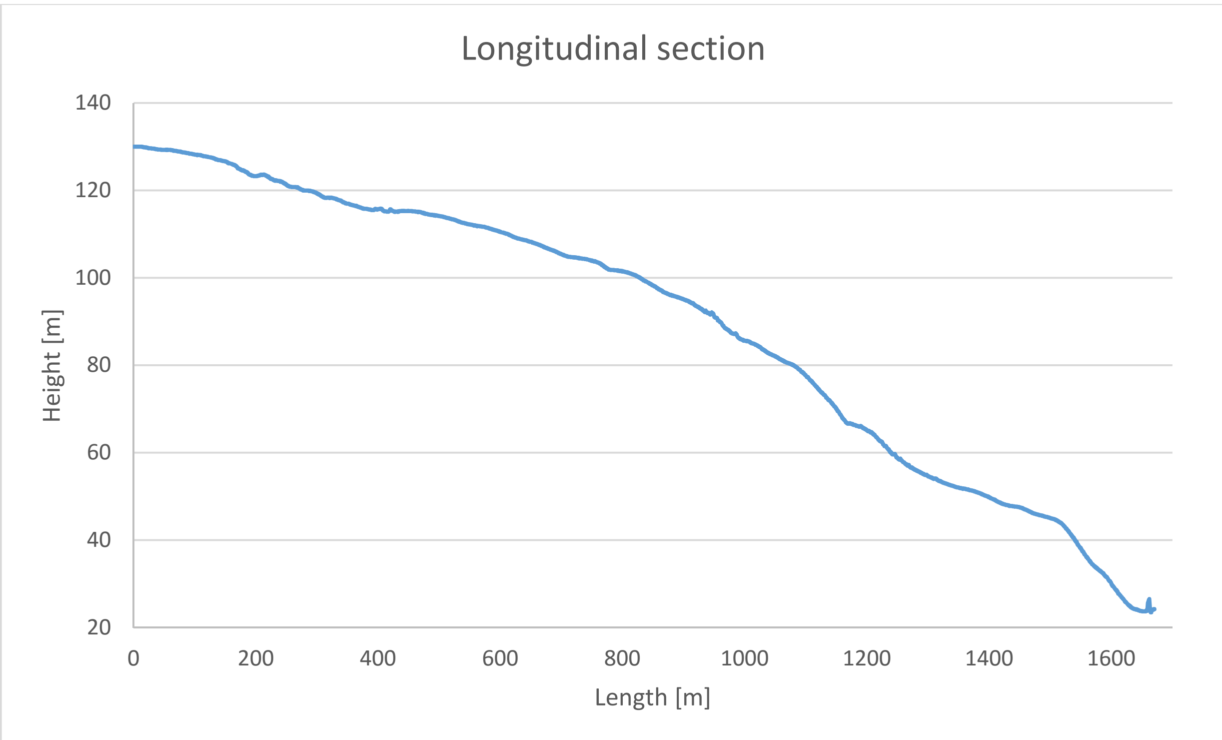


Figure 12: Longitudinal section of the Overvik area.



The Kerby-Hathaway formula is used to estimate the time of concentration for the catchment:

$$t_c = \frac{0.606*(L*n)^{0.467}}{S^{0.234}} = \frac{0.606*(1.4*0.4)^{0.467}}{0.068^{0.234}} = 0.867\ hours = \ 52\ minutes$$

$where\ L = Length\ of\ watercourse\ in\ kilometers;\ S = slope\ in \frac{m}{m};\ n = Mannings\ number\ n$

4.5. Temperature and wind

Temperature and wind will all affect the evaporation and snow storage of the catchment, and thus the total runoff. For the 1-year model of the catchment these parameters are quite important, as most of the rainfall is either infiltrated or evaporated, while single-event simulations are usually insensitive to the evaporation rate (James et al., 2010). For the 2011 1-year model, the climate data is taken from observed temperature and wind data at the Voll rain gauge. The daily evaporation in PCSWMM is estimated using Hargreaves equation for potential evapotranspiration, PET, based on daily temperatures.

Temperature in PCSWMM is given as a minimum and maximum value per day, and the wind is given as average wind speed per day. The temperature is then assumed to reach its minimum temperature at sunrise, and its maximum temperature 3 hours before sunset. The rest of the day is estimated using sinusoidal interpolation, as seen in Figure 13. This method will not catch any local short-term variation in weather and temperature that can arise, but serves as a good method to estimate temperatures during a continuous long-term simulation.

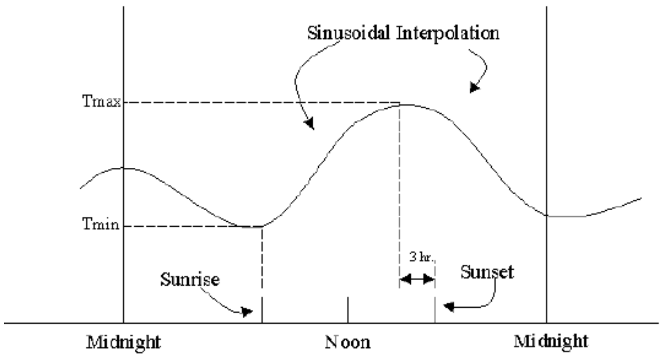


Figure 13: Sinusoidal interpolation of hourly temperatures. Source: (James et al., 2010)

Another important factor affected by the temperature is the snow storage. When precipitation falls as snow in sub-zero temperatures, there will not be any associated runoff until the snow melts during warmer weather. Snow melt in PCSWMM is decided primarily by snow melt coefficients and the temperature, and to some degree the wind speed taken from observed daily averages.

4.6. Climate change

(Skaaraas, 2015) presents climate projections for Norway based on IPCC global models for climate change, based on future climate emissions in three different scenarios; low-, medium- and high global emissions.

For the high emissions scenario, models estimate an increase in average yearly rainfall of approximately 9 % in 2045 compared to the reference period of 1971-2000. The same estimation for 2085 is circa 18 % nationwide.

For heavy rainfall, defined as 24-hour duration events with a return period of 0.5 years, the models estimate an increase in the frequency of these events by approximately 89 percent nation-wide in 2085. The intensity of these events are also estimated to increase by circa 19 % nation-wide, as seen in Figure 14.

For short-term rainfall events, the increase is estimated to be even bigger, and a 3-hour rainfall event with a return period of 5 years can increase by as much as 30 % on average nation-wide. Model results indicates that shorter duration events could see an even bigger increase in intensity. This would mean that the current 50-year return periods in the IVF-curve for Oslo, would have 10-year return period in 2100, meaning a 500 % increase in the frequency for the same intensity/duration storms at the end of this century.

For the rainfall events used in this thesis, the intensities are given a climate factor of 1.2, which is the commonly used factor today. Based on the report from Skaaraas, one could argue that this climate factor should be increased, especially for short duration rainfall events and events with long return periods.

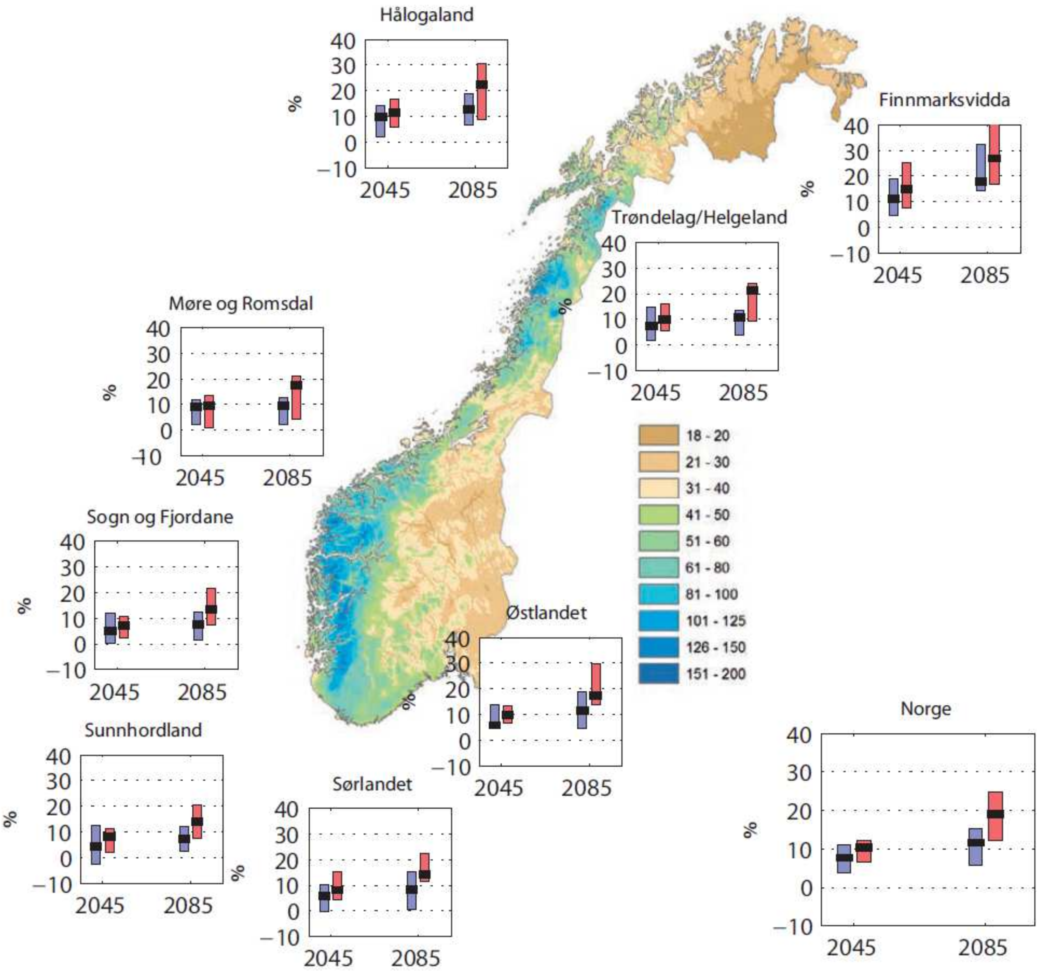


Figure 14: 24-hour heavy rainfall in map for period 1971-2000. Boxes show estimated increase (in %) in rainfall intensity on days with heavy rainfall for 2045 and 2085 based on medium (blue) and high (red) global emissions scenarios. Source: (Skaaraas, 2015)

5. Low-impact development (LID) controls

The low impact development (LID) approach is a method for development that seeks to preserve the pre-development hydrology of the catchment area post-development. In contrast to traditional development, which seeks to quickly drain the stormwater through pipes and uses end-of-pipe methods for detention, LID focuses on detention and treatment of the stormwater locally in the catchment area.

Traditional development has not been able to mitigate the effects of urbanization, and has led to an increase in runoff volume, increased runoff velocity, decreased time of concentration and decreased water quality in urbanized areas (Dietz, 2007). This in turn can lead to increased flood magnitude and frequency, more stream eroding (Bradford and Denich, 2007), decreased fish species richness and abundance, decreased stream base flow (Dietz and Clausen, 2008), increased use of CSO and generally increased costs of stormwater management.

Some advantages to LID compared to the traditional development are:

- Maintains the natural hydrology of the catchment through stormwater attenuation, infiltration and evapotranspiration.
- Provides groundwater recharge to maintain groundwater level and reduce subsidence damages.
- Local stormwater treatment, which reduces groundwater- and stream pollution and can enhance the biodiversity.
- Can combines functional areas with recreational areas, for example using streams and ponds.
- Costs of construction and maintenance aren't necessarily higher than for traditional development.

A study done in Connecticut, USA, followed the construction of a traditional development site of 2.0 ha and a low-impact development site of 1.7 ha over several years, and compared the runoff volume during different stages of development. Both sites were initially natural sites with 0 % impervious area, and was urbanized and ended on 32 % and 21 % impervious area, respectively. Runoff volume was measured every week, and the yearly runoff volume was calculated. Results showed that the traditional subdivision' runoff increased exponentially with increased impervious area (Figure 15), while the runoff volume in the LID subdivision did not change with increased impervious area (Figure 15). The same results were found for the runoff coefficients in both subdivisions (Figure 16). They also concluded that pollutant export regressions were similar to the runoff regressions (Dietz and Clausen, 2008). This study shows that LID can have a big effect on both runoff volumes and pollutant export.

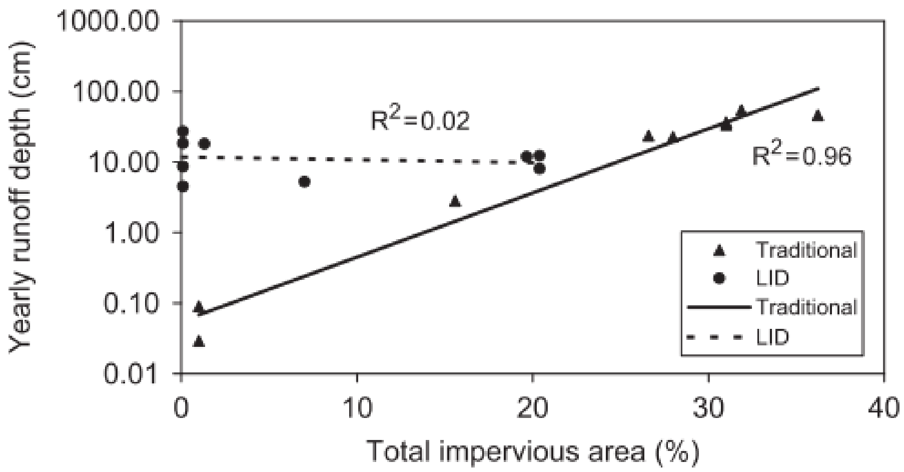


Figure 15: Annual runoff depth vs. total impervious area, traditional and LID subdivisions. 1996-2005. (Dietz and Clausen, 2008).

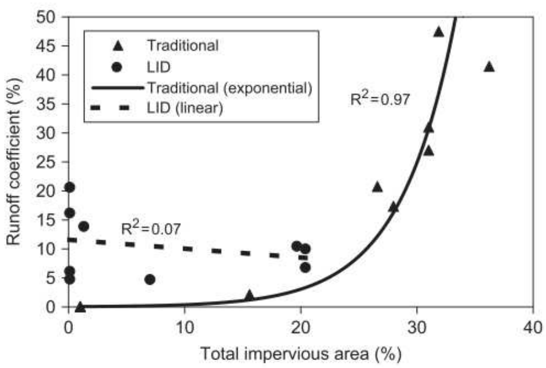


Figure 16: Total impervious area vs. runoff coefficient, traditional and LID subdivision, 1996–2004. (Dietz and Clausen, 2008).

5.1. Bio-retention cell

Bio-retention cells are vegetated, depressed areas designed to collect and infiltrate stormwater. The ponds are designed with a bottom sandy loam soil, a mulch layer and plants designed for retention, infiltration, and treatment of stormwater. The benefits from these ponds are mainly decreased surface runoff, increased runoff lag time, increased groundwater recharge and pollutant treatment.

Bioretention ponds, or rain gardens as they are also called, are often placed in connection with parking lots and large buildings, but can also be used in residential areas. The function of the pond is to collect water, and through evapotranspiration and infiltration reduce the runoff volume and increase the lag time of runoff. The plants and soil will also treat the incoming stormwater for a variety of pollutants. The ponds are best used in areas that have a native soil with high hydraulic conductivity for infiltration purposes, but they can also be made with a drainage pipe at the bottom that drains the infiltrated water. The minimum drainage capacity for native soils should be about 25 mm h^{-1} (Dietz, 2007), otherwise underdrainage is recommended. Since the ponds are depressed, they will have a ponding area where water can collect if the inflow is higher than the infiltration rate. The maximum recommended height of the ponding area is approximately 20 cm, and it should drain within 3-4 hours (Bradford and Denich, 2007).

Reports on the effects of bioretention ponds are all very positive, and there is quite a lot of data on the subject. In a report from Norway looking at the seasonal climatic effects on rain gardens over a 20-month period, there was no recorded overflow events (Muthanna et al., 2008). This study was performed with a under-drainage pipe, which might increase the infiltration rates compared to infiltration to native soils, but other studies show similar results (Dietz, 2007).

One of the concerns of bioretention ponds are their function during winter seasons with prolonged sub-zero conditions. The study done in Norway showed that the peak flow reduction in the winter seasons reduced from a total average of 42 % to a sub-zero average of 27 % (Muthanna et al., 2008). The report concluded that the hydraulic performance of the rain garden was highly dependent on temperature and the antecedent dry-period length. The effects of cold climates can be reduced by using course graded filter materials that ensures high infiltration and low water-content during dry periods. The expected frost depth in the area should determine the depth of the filter media.

5.2. Swales & strips

Swales are open channels with sloped sides, used to convey and control runoff from an area. They are usually made with an erosion- and flood-resistant vegetation. Swales will also contribute to some runoff reduction through infiltration, retention and evapotranspiration, especially for small events. For larger events, the main purpose is conveying water and reducing erosion damage on the surrounding areas.

Swales can be constructed with a series of dams that detain and control the runoff during small events, as seen in Figure 17. This could provide a constant water source during dry periods, which could enhance the areas biodiversity.

Figure 17: Example swale design. Source: (kommune, 2014)

A study done in Maryland, USA on the effectiveness of swales in conjunction with a road, found that swales completely captured the smallest 40 % of storms. They also reduced the total runoff volume for an additional 40 % of storms, while it worked as a water conveyor for the remaining 20 % of storms (Davis et al., 2012). The swales in this study did not have any storage capacity in the form of dams, so the results could improve even more for the larger events if dams were used.

5.3. Green roofs

Green roofs are divided into two categories, intensive green roofs and extensive green roofs. Intensive green roofs have a deep soil layer, and as such need extra structural support from the roof. Extensive green roofs, as this paper will focus on, consists of a thinner soil layer (2.5-15 cm), and does not need the same structural support (Dietz, 2007).

Some consideration need to be made before implementing extensive green roofs on buildings, and the structural support should be calculated before construction. Green roofs can be applied on roofs with slopes up to 40 degrees, but a support grid system is needed on slopes steeper than 20 degrees (Bradford and Denich, 2007). The roof should also be waterproofed, to prevent any structural damage from leakage.

Benefits from implementing green roofs are reduced runoff volume through evapotranspiration and storage, increased lag time, pollutant retention and energy efficiency.

Although studies show that soil depth does not influence rainfall detention significantly, increased soil thickness will reduce frost injury and provide a better environment for plants (Dietz, 2007). Figure 18 shows the rainfall retention as a function of the soil thickness, taken from several reports.

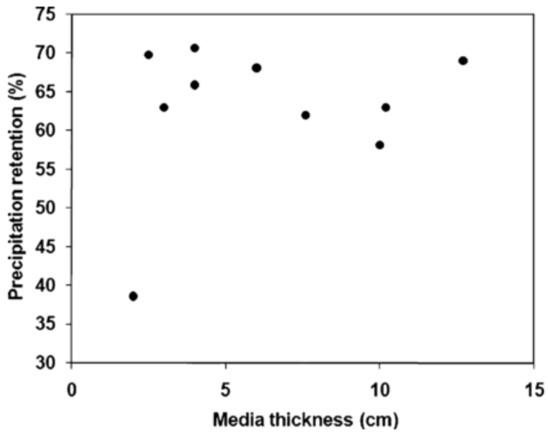


Figure 18: Soil thickness vs rainfall retention (Dietz, 2007).

Some studies claim that green roofs consistently gives a 60-70 % rainfall retention (Dietz, 2007), while European studies report a minimum of 50 % reduced annual roof runoff (Bradford and Denich, 2007). The effectiveness of green roofs are very dependent on the climate, and runoff volume is reduced the most in warm dry periods with short duration storm events (Bradford and Denich, 2007).

The vegetation in green roofs need to be adapted to prolonged dry periods and thin soil, and fertilizations should not be necessary, as that could export high concentrations of TP and TN to the stormwater.

5.4. Pervious pavement

Pervious pavements consist of porous asphalt and concrete produced with little to no fine materials, plastic grids and concrete blocks with openings filled with permeable materials. Pervious pavements are mostly used in parking lots and low-traffic roads, where the rate of clogging is reduced compared to high-traffic roads.

The stormwater is infiltrated into the base layer that detains the storm water until it is either infiltrated into the native soil, or drained through a drainage pipe. Thus, the pervious pavements serve as both infiltrators and for detention (Bradford and Denich, 2007).

The effectiveness of the pavements is highly dependent on the materials in the base layer, which must have good infiltration and storage capacity in addition to ensuring a stable base for the pavement.

(Fassman and Blackbourn, 2010) found that in a study analyzing four different permeable pavement systems, the under-drain discharge volume varied from 37 to 61 % of rainfall volume, while for the normal asphalt it was compared to, the volume was almost identical to the rainfall volume. Another study found that 93 % of the volume from sub-20 mm storms were infiltrated through grassed plastic grid pavement over clay soils (Fassman and Blackbourn, 2010).

Fassman and Blackbourn (2010) also conducted their own study where a 200 m^2 interlocking block permeable pavement with underdrain discharge was compared to a traditional asphalt section. The permeable pavement was placed on top of a clayey silt subgrade with an estimated permeability of 0.01 mm d^{-1}. Even with minimum exfiltration to the soil, the runoff coefficients for the permeable pavement was measured at 0.29-0.67, and the pavement had a median lag-time of 1 h, compared to 12 min for the traditional asphalt.

The problem with most permeable pavements is the maintenance needs, and that sanding and salting during winter should be kept at a minimum. Over time, small particles will clog the pores in the asphalt/concrete or materials in the openings. Laboratory tests have been conducted, finding reduction of the hydraulic conductivity with up to 59-75 % in studies simulating 35 years of sediment delivery (Fassman and Blackbourn, 2010). Maintenance should be done by suction of the top layer, and potentially replacement of the materials in the openings.

Seeing as two thirds of the impervious areas in single-family residential, multi-family residential and commercial land use is pavement (Bradford and Denich, 2007), implementation of pervious pavement can be an important LID measure to reduce the effects of urbanization.

In later years, there has been great improvements to permeable pavements, and some can infiltrate up to 36,000 mm h^{-1} (Garathun, 2015, Olsen, 2015).

5.5. Basins

During large rainfall events most local measures will not be able to reduce the runoff volume enough to keep the existing peak flow runoffs. When these events occur it is necessary with a large detention volume, which can be achieved using basins. Basins can be designed as either wet or dry basins, where the former has a permanent pool of water while the latter drains completely after each rain event.

Figure 19: Example of dry basin in Roskilde, Denmark. Source: (kommune, 2014)

Basins can easily be combined with recreational areas, either as depressed park areas, or as skate parks like in the example from Roskilde in Figure 19.

The basin volume is usually calculated from the volume necessary to keep the outflow at a maximum flow for a specific event, usually for events with 200-year return periods or more.

6. Modeling software

I initially started out learning SHyFT, to be able to use the program in simulating the overland flow for the Overvik area. SHyFT is a program currently under development at Statkraft, and its main purpose is to do simulations of rivers in conjunction with power plants in flood situations. The program is open-source and coded in python, so that anyone can create “add-ons”, which means the program can be used for modelling pretty much anything, so long as one has the required skill to code the needed functions. The program has no user interface, and is wholly code-based, so it requires some knowledge of python to be used properly.

Because the program required skills that I do not have, and was a bit too complicated to learn in the time available I decided to use another program instead. I initially wanted a program which could utilize the DTM- and shape-files of the land resource maps created in ArcMap as input files, in order to give very specific area-based parameters. I therefore set out to learn MIKE Urban/21 by DHI, which is an advanced urban drainage and flooding model. This is also a quite complex program that I have no experience with, and DHI recommended taking a 3-day course just to learn the basics of the program. Seeing as they had no courses available in the time of writing this thesis, this program also proved too difficult to learn on my own.

In the end I ended up using PCSWMM to simulate the overland flow. This is a very easy-to-learn program, that we have previously used in some of the courses at NTNU. The program does not have all the possibilities of the other two programs mentioned, especially regarding the map features, but it is often used for overland flow modeling. PCSWMM uses the dynamic wave equation for routing, which is widely regarded as one of the best methods, seeing as all the terms in the momentum equation are considered in the model. For the infiltration model, PCSWMM uses the Horton equation, using max/min infiltration rates and infiltration decay as input parameters. Evaporations is modeled using Hargreaves equation, where daily temperatures from the climate file are used as input parameters. The rainfall/runoff modeling is done using non-linear reservoir routing, this assumes the rainfall is uniformly distributed throughout the catchment, which is most likely a good assumption in this case as the catchment is relatively small.

One important factor in PCSWMM is the ability to model the hydrologic memory in the catchment, where the soil moisture will vary depending on previous rainfall events. The hydrologic memory can have a large impact on the catchment runoff, and it is therefore important that the program can model this effect.

One big drawback in PCSWMM is the schematization of impervious surfaces illustrated in Figure 20. This means that impervious surfaces cannot be given an area-specific location, but are clustered together. The drawbacks of this are discussed in chapter 9.

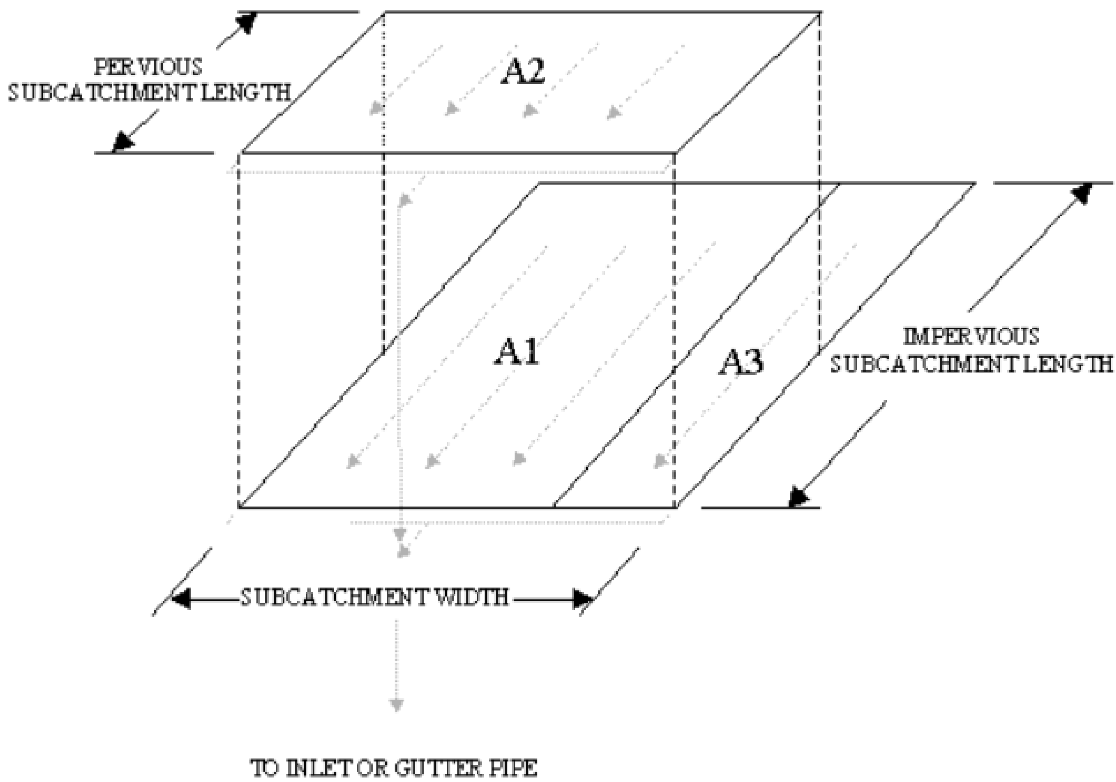


Figure 20: Subcatchment schematization used in PCSWMM. Source: (James et al., 2010)

7. Model

All models are built using the same background information. The DTM for Overvik is used as a background layer in order to get reliable height data. The catchment shape and size is also the same for all models, but with differing parameters for the properties that are expected to change post-development.

All models are simulated using 5-second time steps during rainfall events and 10-second time steps during dry periods. Temperature and wind speed are based on measured data in the climate file, while the evaporation rate is computed from the measured temperatures.

7.1. Pre-development

The pre-development model simulates the catchment as it is today. Catchment shape parameters are based on data from the DTM and the map data from ArcMap. All catchment parameters are shown in the table below.

Table 3: Catchment parameters used for pre-development model.

Parameter	**Value**
Width	500 m
Slope	6.8 %
Impervious surfaces	6.1 %
Roughness impervious surfaces “n”	0.016
Roughness pervious surfaces “n”	0.35
Depression storage impervious surfaces	1 mm
Depression storage pervious surfaces	6 mm
Maximum infiltration rate	12.5 mm/hr
Minimum infiltration rate	0.5 mm/hr
Infiltration decay constant	5 (mm/hr)/hr
LID controls	None

Width is set at 500 m based on measurements. This gives a flow length of 1450 meters, which also fits well with measurements. The slope is also set using measurements, but given the varying terrain in the catchment, this parameter is a bit more uncertain than the catchment width. A way to better represent the actual terrain in the catchment could be to divide it into several smaller catchments with separate slope parameters. This method was the plan to start with, but using PCSWMM I found no way to transfer flow between catchments without using manholes and conduits. As seen in Figure 22, the slope has an impact on both the time of concentration and the peak runoff, so this parameter could give quite large variations in runoff, especially when the amount of impervious surfaces increases.

Amount of impervious surfaces is based on FKB-data for the area. Impervious surfaces include buildings and roads, and since the data availability is good, this parameter has a low uncertainty. One possible uncertainty is that there is no way to tell PCSWMM the exact locations of the impervious surfaces, which would be beneficial to get the most accurate model possible. The .shp-files for the impervious areas are available, but there is no way to utilize them in PCSWMM. As seen in the sensitivity analysis in Figure 23, the impervious area share has a great impact on peak runoffs and time of concentration.

Surface roughness values are based on chapter 24.6 in (James et al., 2010), using a value between “bermuda grass” and “dense grass” for the pervious surfaces, to take both the agriculture fields and forests into consideration in the model. For impervious surfaces, the parameter is estimated to take both rooftops, paved roads and gravel roads into consideration. This parameter is quite uncertain, and sensitivity analysis of the surface roughness in Figure 24 shows that it affects the peak runoff, as well as the duration of the runoff period. During a calibration of the model, this parameter would be an important variable.

Depression storage values are based on chapter 24.5 in (James et al., 2010), using recommended value between pasture and forest litter for the pervious surfaces and the recommended value for impervious surfaces. The uncertainty for this parameter is also quite high, but from the sensitivity analysis in Figure 25, we see that the depression storage has little impact on the peak runoff, while it has a large impact on the duration of the runoff period and total runoff.

For the infiltration rates I used recommended values from chapters 7.7, 24.2 and 24.3 in (James et al., 2010) as advisory parameters, assuming a clay loamy soil. I also used values based on moist soils, to better account for the missing hydrologic memory in the design storm events. Since the infiltration tests performed gave very inconsistent results, and were thus not utilized, there is some uncertainty affiliated with the infiltration rates. As can be seen in Figure 26, Figure 27 and Figure 28, the infiltration rates do not have much impact on the peak runoff, but can give large variation in the runoff duration and total runoff.

It should be noted that the sensitivity analysis is performed using a design storm with 1-hour duration and 2-year return period. For smaller rainfall events the runoff results would probably look better. This is because the rainfall intensity of the design storm exceeds the maximum infiltration rates of the soil for 15 of the 60 minutes, as can be seen in Figure 34. For smaller everyday events, the depression storage and infiltration rates especially, would have a much larger impact on the total runoff. For modeling with area-dependent impervious surfaces the results would also look very different, because the water would then be routed from impervious surfaces on to pervious surfaces where the potential for infiltration and retention would be much greater.

7.1.1. Sensitivity analysis

The catchment parameter sensitivity analysis is performed using a 2-year design storm with a duration of 1 hour. This means that the analysis isn't necessarily valid for smaller events where the rainfall intensity doesn't exceed the soil infiltration rates, but is a good indication of what parameters will have the greatest impact on the runoff values.

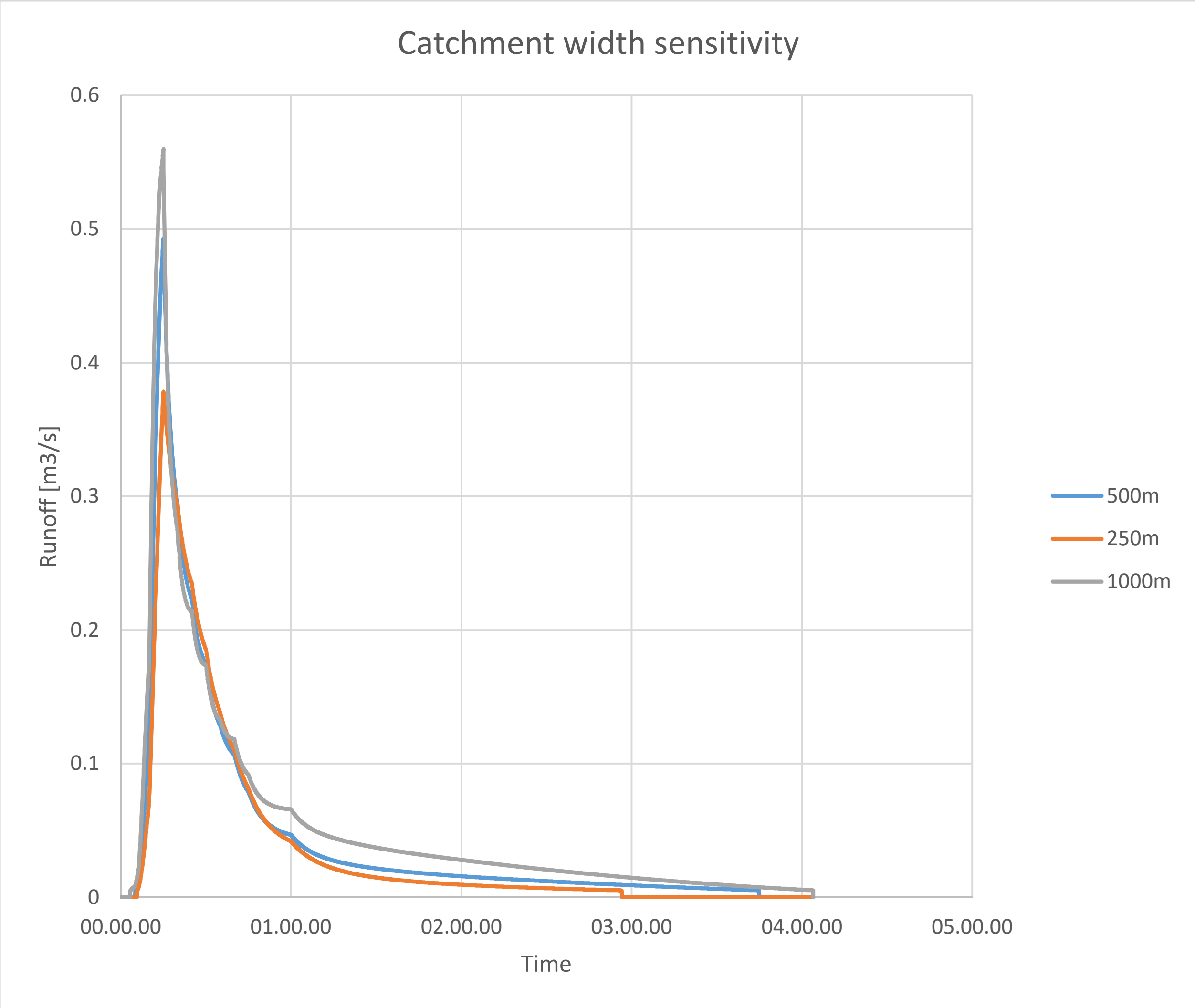


Figure 21: Sensitivity analysis of catchment width on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 500 m, +100 % (1000 m) and -100 % (250 m).

Width	500m	250m	1000m
Peak runoff [m3/s]	0.493	0.378	0.560
Total runoff [m3]	661.56	564.77	813.36

The catchment width impacts both the peak runoff, the total runoff and the runoff duration. All runoff values increase with increasing catchment width and vice versa. This is because the PCSWMM model treats the catchment as a square, and increasing the width will reduce the flow length of the rainwater, thus reducing its residence time on the surface and the infiltration potential. I would expect that the maximum peak runoff would be achieved when the catchment is quadratic, meaning that width = length = √A, because then you would have the averagely shortest flow length from the impervious areas, meaning the time of concentration for the impervious areas are the shortest.

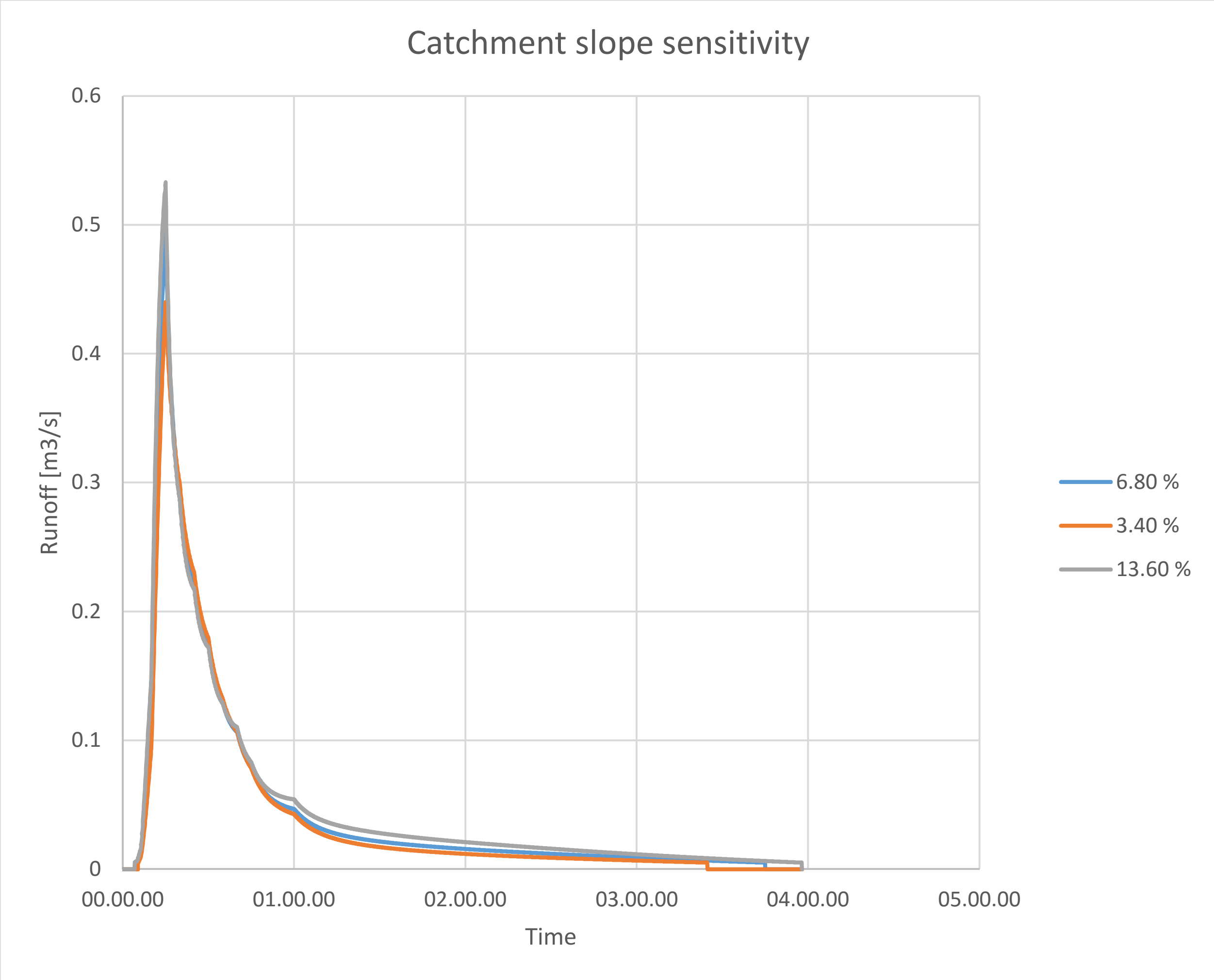


Figure 22: Sensitivity analysis of catchment slope on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 6.8 %, +100 % (13.6 %) and -100 % (3.4 %).

Slope	6.80 %	3.40 %	13.60 %
Peak runoff [m3/s]	0.493	0.440	0.533
Total runoff [m3]	661.56	607.67	729.43

The catchment slope impacts both the peak runoff, the total runoff and the runoff duration. All runoff values increase with increasing catchment slope and vice versa. PCSWMM uses the same slope on the entire catchment length, so using a program that utilizes the DTM, or separating the area into several smaller subcatchments could give other results. Doubling the average slope increases the total runoff by approximately 8 %, and the total runoff by 10 %, indicating that slope is not the most important factor in this catchment. Some might think that the increased runoff duration with higher slope is strange, but this is most likely due to the increase in total runoff, causing the catchment to drain slower.

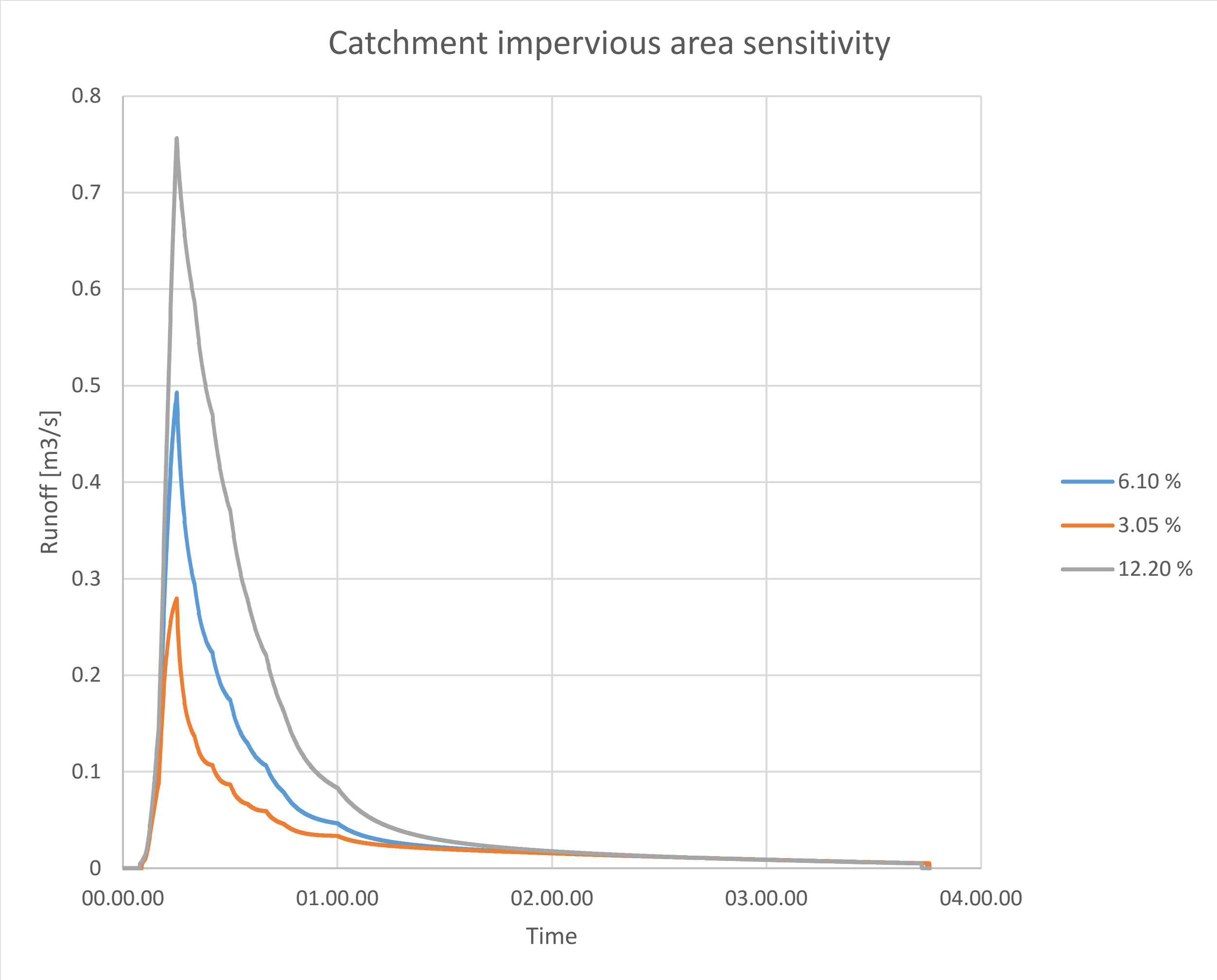


Figure 23: Sensitivity analysis of catchment impervious area on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 6.1 %, +100 % (12.2 %) and -100 % (3.05 %).

Imperv. area	6.10 %	3.05 %	12.20 %
Peak runoff [m3/s]	0.493	0.280	0.757
Total runoff [m3]	661.56	418.75	1142.94

The catchment impervious area impacts both the peak runoff and the total runoff, but has little effect on the runoff duration. Peak- and total runoff increase with increasing catchment impervious area and vice versa. The reason the runoff duration is not affected is because of the subcatchments schematization illustrated in Figure 20, with no aerial distribution of the impervious areas. The runoff duration is therefore driven by the length and properties of the pervious areas, which does not change with increasing impervious areas. Doubling the impervious area increases the peak runoff by 53.5 % and total runoff by 73 %, so impervious area is a very important factor on the runoff results.

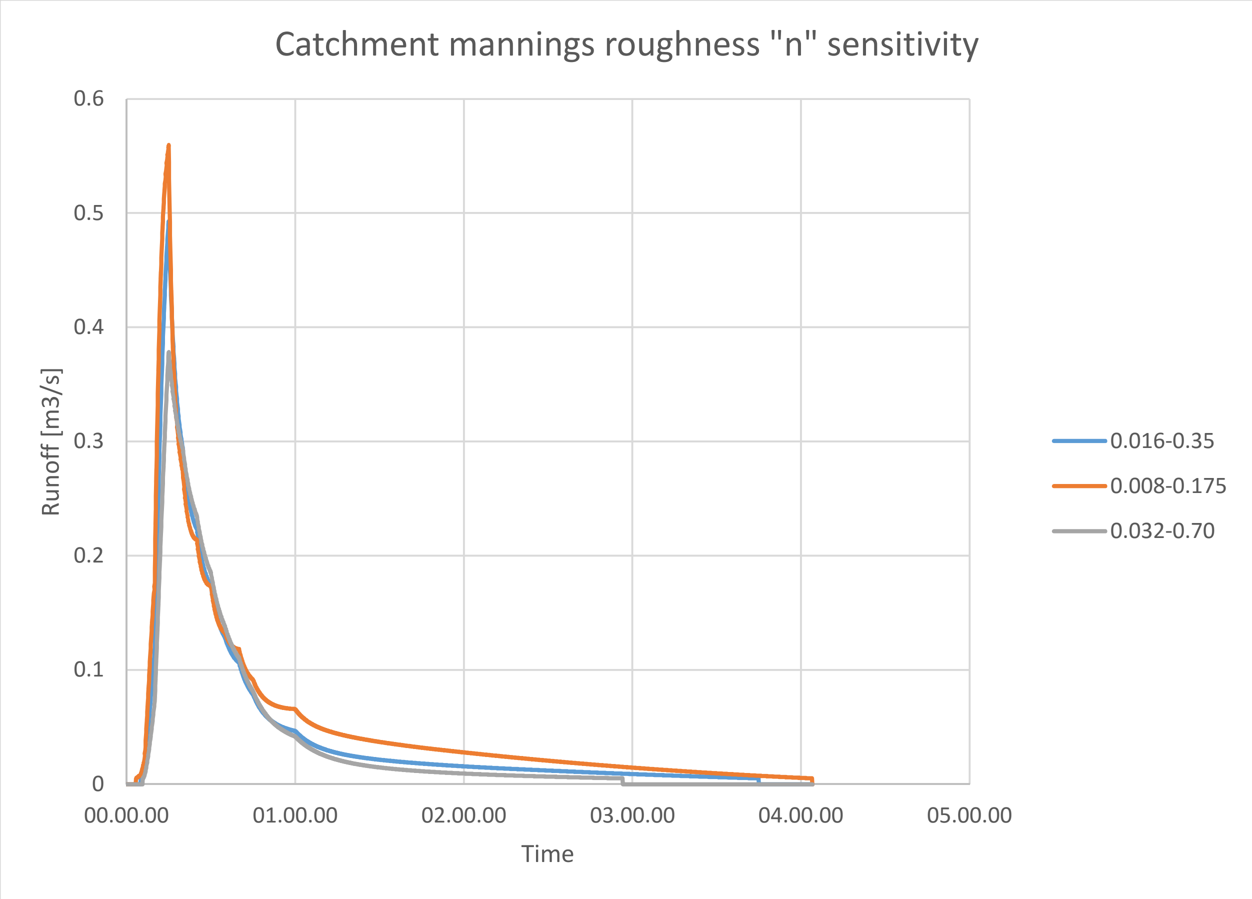


Figure 24: Sensitivity analysis of catchment roughness (Mannings "n") on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 0.016-0.35 %, +100 % (0.032-0.70) and -100 % (0.08-0.175). Values are for impervious and pervious areas respectively.

Roughness	0.016-0.35	0.08-0.175	0.032-0.70
Peak runoff [m3/s]	0.493	0.560	0.378
Total runoff [m3]	661.56	813.36	564.77

The catchment surface roughness impacts both the peak runoff, the total runoff and the runoff duration. All runoff values increase with decreasing catchment surface roughness and vice versa. A halving of the surface roughness for both pervious and impervious areas increases the peak runoff by circa 14 % and the total runoff by 23 %. The surface roughness for pervious areas are expected to have a bigger impact on total volume and runoff duration than for impervious areas, because it gives the water more time to infiltrate into the ground in the impervious areas. The impervious areas have no infiltration, so the runoff volume will be almost the same, but the peak runoff is somewhat dependent on the impervious area roughness.

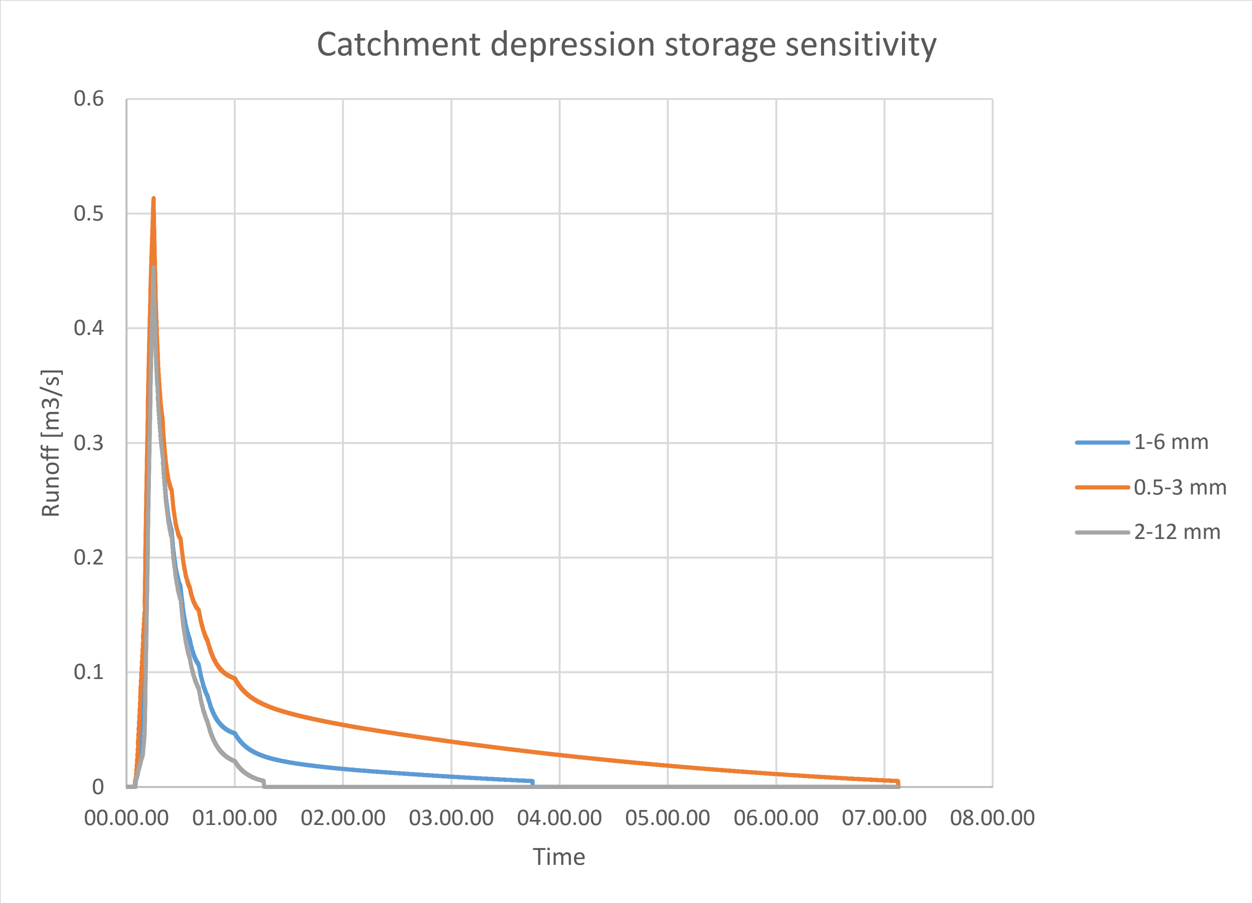


Figure 25: Sensitivity analysis of catchment depression storage on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 1-6 mm, +100 % (2-12 mm) and -100 % (0.5-3 mm). Values are for impervious and pervious surfaces respectively.

Depression storage	1-6 mm	0.5-3 mm	2-12 mm
Peak runoff [m3/s]	0.493	0.514	0.453
Total runoff [m3]	661.56	1338.18	448.22

The catchment depression storage impacts mostly the total runoff and the runoff duration. Depression storage has little effect on the peak runoff, but has a very large impact on both total runoff and runoff duration. This is because water is caught in the surface depressions, giving the water a lot of time to infiltrate to the ground. The depressions will fill up rather quickly, but the water caught will not produce runoff. This is the reason why there is little impact on the peak runoff – when the very intensive rain starts, the depressions are already filled up and will not detain any more rainfall. A halving of the depression storage increases the total runoff by 102 %, while the runoff duration is increased by over 3 hours.

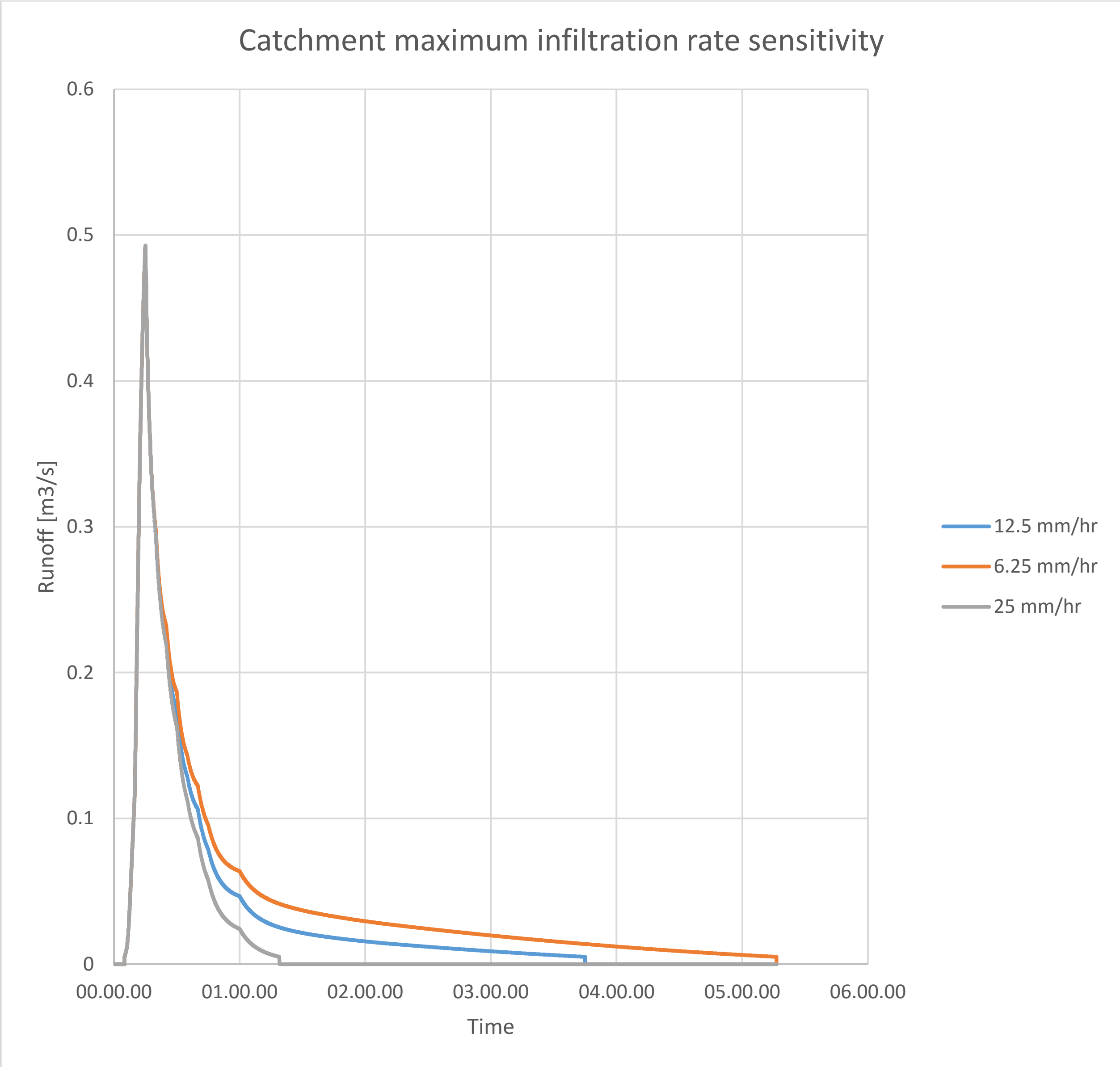


Figure 26: Sensitivity analysis of catchment maximum infiltration rate on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 12.5 mm/hr, +100 % (25 mm/hr) and -100 % (6.25 mm/hr).

Max infiltration	12.5 mm/hr	6.25 mm/hr	25 mm/hr
Peak runoff [m3/s]	0.493	0.493	0.493
Total runoff [m3]	661.56	872.65	488.72

The catchment maximum infiltration rate impacts only the total runoff and the runoff duration. This is because the peak runoff is driven by the impervious areas, while total runoff and runoff duration are more pervious-area-dependent.

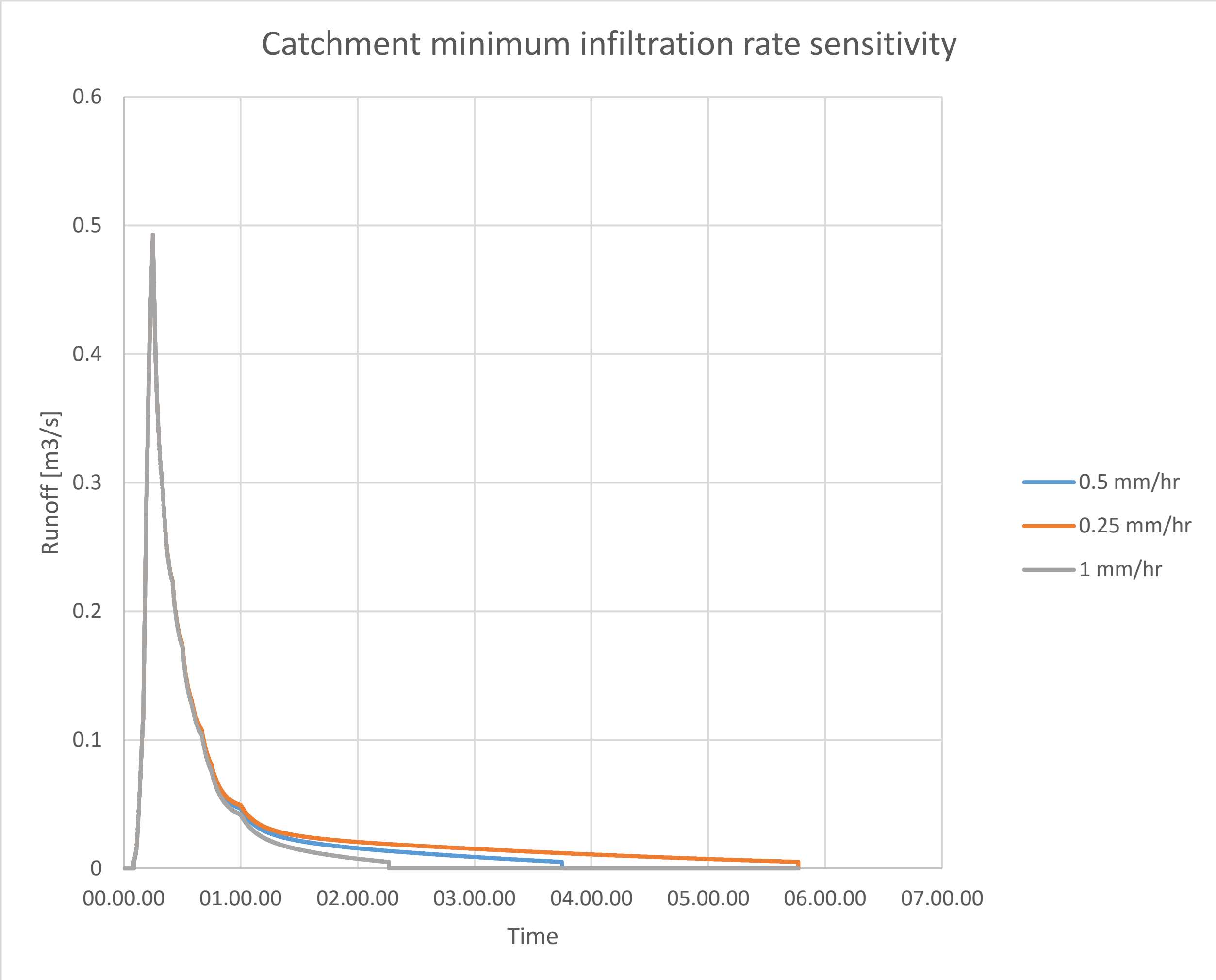


Figure 27: Sensitivity analysis of catchment minimum infiltration rate on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 0.5 mm/hr, +100 % (1 mm/hr) and -100 % (0.25 mm/hr).

Min infiltration	0.5 mm/hr	0.25 mm/hr	1 mm/hr
Peak runoff [m3/s]	0.493	0.493	0.493
Total runoff [m3]	661.56	776.79	575.22

The catchment minimum infiltration rate impacts only the total runoff and the runoff duration, for the same reason as for the maximum infiltration rate. The minimum infiltration rate will however have less of an impact on short-duration storms, because most of the water is routed away before the soil reaches its minimum conductivity. For longer duration storms with less intensive rainfall the minimum infiltration rate, along with the infiltration decay constant, would have a bigger impact on the total runoff.

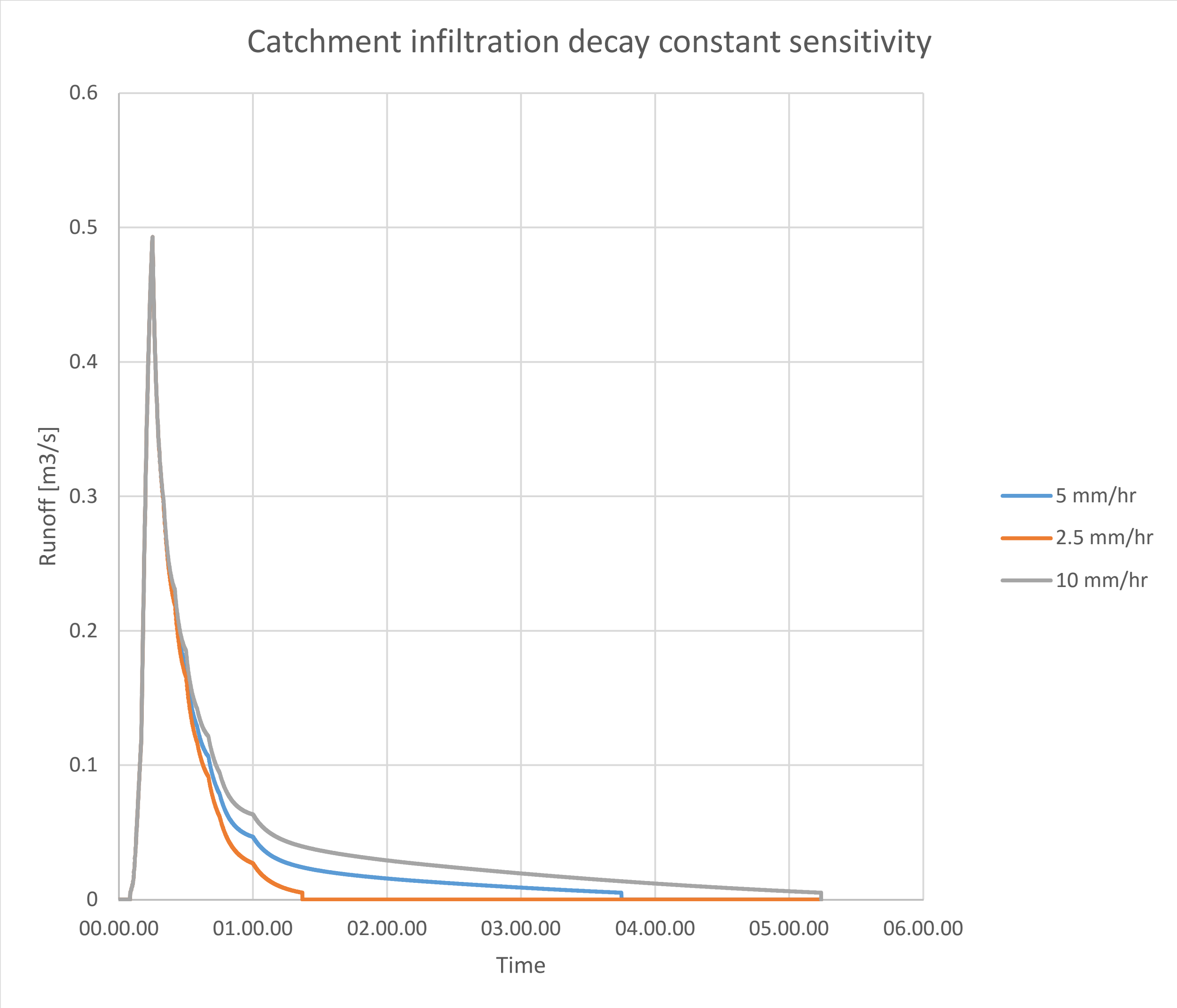


Figure 28: Sensitivity analysis of catchment infiltration decay constant on total runoff for a design storm with 2-year return period. Simulated for the used parameter of 5 mm/hr, +100 % (10 mm/hr) and -100 % (2.5 mm/hr).

Infiltration decay	5 (mm/hr) /hr	2.5 (mm/hr) /hr	10 (mm/hr) /hr
Peak runoff [m3/s]	0.493	0.493	0.493
Total runoff [m3]	661.56	498.97	864.68

The infiltration decay constant describes how much the infiltration rate is reduced each hour. In the main model, the infiltration rate is estimated to decay by 5 (mm/hr)/hr, meaning that the soil is fully saturated in a little over two hours of maximum soil infiltration. Increasing this value gives a higher total runoff and runoff duration, because the soil will reach its minimum infiltration rate faster and infiltrate less of the stormwater. A doubling in the infiltration rate decay gives an increase in total runoff by 31 %.

7.2. Post-development

For the post-development model, the illustration plan provided by Asplan Viak is used as a template for land resource use and catchment parameters. Catchment parameters are shown in the table below.

Table 4: Catchment parameters used for post-development model.

Parameter	Value
Width	500 m
Slope	6.8 %
Impervious surfaces	19.7 %
Roughness impervious surfaces "n"	0.016
Roughness pervious surfaces "n"	0.24
Depression storage impervious surfaces	1 mm
Depression storage pervious surfaces	4 mm
Maximum infiltration rate	12.5 mm/hr
Minimum infiltration rate	0.5 mm/hr
Infiltration decay constant	5 (mm/hr)/hr
LID controls	Vegetated swale

The only differences compared to the pre-development model are impervious surfaces, pervious surface roughness, pervious surface depression storage and LID controls.

Width and slope of the catchment is not changed, even though some terrain features might be adjusted during development, the overall shape of the catchment is expected to stay the same post-development

The amount of impervious surfaces is increased to match the amount of new roads and buildings as shown in the illustration plan in Figure 3. The properties of the impervious surfaces are not changed however, and any changes in the impervious surface runoff are solely due to the increase in area.

When the pervious areas are changed from agricultural fields into lawns and parks, the surface roughness and depression storage are expected to decrease slightly. Most of the forest area will also be removed and replaced by residential areas. New parameters for depression storage and roughness are based on lawns and dense grass in chapters 24.5 and 24.6 in (James et al., 2010).

No changes are made to the infiltration parameters of the catchment, because the native soil will still be a clay loamy soil, even though the land use is changed.

In the post-development model there is implemented a vegetated swale. The swale is designed for flood control, but will receive flow from surrounding areas for all events. In the model, flow from 30 % of the impervious areas are routed through the swale. LID controls properties for the post-development model are shown in the table below.

Table 5: LID control parameters for post-development model.

Name	**Flomveg**
Area [m^2]	4161
# of units	1
Surface width [m]	3
% initially saturated	25
% impervious area treated	30

The swale is given a berm height of 2000 mm, a vegetated volume of 0.05, a surface roughness of 0.45, surface slope of 5 % and a side slope of 1:3 (rise over run). Infiltration rates for the swale are the same as for the pervious area.

7.3. Low-impact development

The low-impact development model is based on the post-development model, but additional LID controls are added. All catchment parameters except LID controls are identical with the post-development model, as seen in the table below.

Table 6: Catchment parameters used for LID model.

Parameter	**Value**
Width	500 m
Slope	6.8 %
Impervious surfaces	19.7 %
Roughness impervious surfaces “n”	0.016
Roughness pervious surfaces “n”	0.24
Depression storage impervious surfaces	1 mm
Depression storage pervious surfaces	4 mm
Maximum infiltration rate	12.5 mm/hr
Minimum infiltration rate	0.5 mm/hr
Infiltration decay constant	5 (mm/hr)/hr
LID controls	Vegetated swale, green roof, permeable pavement and bio-retention cell.

The additional LID controls in the LID model are green roofs, permeable pavements and bio-retention cells (rain garden).

7.3.1. LID controls

The LID controls properties for the LID model are shown in the table below.

Table 7: LID control parameters for the LID model.

Name	Flomveg	Green roof	Permeable pavement	Bio-retention cell
Area [m^2]	4161	100	500	50
# of units	1	20	10	20
Surface width [m]	3	10	4	7
% initially saturated	25	0	20	25
% impervious area treated	30	0	0	30

Green roofs are one of the LID controls implemented in the model. Green roofs only treat direct rainfall, so no additional runon from impervious surfaces are simulated. The reason the green roofs are set as 0 % initially saturated is because any initial saturation produced more runoff than using no green roofs at all. The properties of the green roofs used in the model are shown in the table below.

Table 8: Green roof properties.

Surface		Soil		Drainage mat	
Berm height [mm]	0	Thickness [mm]	150	Thickness [mm]	10
Vegetation volume	0	Porosity	0.3	Void fraction	0.5
Surface roughness	0.35	Field capacity	0.2	Roughness	0.50
Surface slope [%]	15	Wilting point	0.1		
		Conductivity [mm/hr]	15		
		Conductivity slope	10		
		Suction head [mm]	60		

Permeable pavements receive no additional runon from impervious surfaces, and thus only treat direct rainfall. In reality they might receive runon from adjacent surfaces for infiltration, but that is mostly done on parking lots and such where you have a large area capable of infiltrating the extra runon. There are few such areas in the illustration plan, and estimating what amount of impervious surfaces route the flow through permeable pavements would be difficult. Instead the pervious pavements are modeled to replace walkways and roads. Properties for the pervious pavements are shown in the table below.

Table 9: Permeable pavement properties.

Surface		**Pavement**		**Soil**		**Storage**	
Berm height [mm]	0	Thickness [mm]	60	Thickness [mm]	300	Thickness [mm]	300
Vegetation volume	0	Void ratio	0.15	Porosity	0.3	Void ratio	0.5
Surface roughness	0.1	Imperv fraction	0.5	Field capacity	0.2	Seepage rate [mm/hr]	10
Surface slope [%]	3	Permeability [mm/hr]	15	Wilting point	0.1	Clogging factor	0
		Clogging factor	0	Conductivity [mm/hr]	15		
				Conductivity slope	10	Underdrain [mm/hr]	5
				Suction head [mm]	60		

The bio-retention cells receive additional runon from 30 % of the impervious surfaces. This means that for the LID model, 60 % of the impervious surfaces are routed through either the rain gardens or the vegetated swale, while 40 % of the impervious surfaces produces direct runoff. Properties for the bio-retention cells are shown in the table below.

Table 10: Bio-retention cell properties.

Surface		**Soil**		**Storage**	
Berm height [mm]	200	Thickness [mm]	400	Thickness [mm]	400
Vegetation volume	0.2	Porosity	0.5	Void ratio	0.5
Surface roughness	0.3	Field capacity	0.2	Seepage rate [mm/hr]	15
Surface slope [%]	1	Wilting point	0.1	Clogging factor	0
		Conductivity [mm/hr]	15		
		Conductivity slope	10	Underdrain [mm/hr]	5
		Suction head [mm]	60		

It should be noted that the conductivity used for all LID controls is the conductivity when the soil is fully saturated, and is estimated from chapter 24.2 in (James et al., 2010), assuming a loamy sand soil. The saturated conductivity in the model is reduced slightly compared to the table to account for the cold climate in Trondheim.

The maximum conductivity will be higher than the saturated conductivity, and the conductivity for each time step is calculated as a function of the soil moisture content, porosity and the conductivity slope in the following equation:

$K = K_{sat} * e^{-conductivity\ slope*(Porosity-moisture\ content)}$ (Rossman, 2011)

7.3.2. Sensitivity analysis

Sensitivity analysis are done on the peak runoff for varying areas of the LID controls green roofs, bio-retention cells and permeable pavements. All simulations are done using only one type of LID control in addition to the vegetated swale that is included in the post-development model. The sensitivity analysis is simulated for a storm event with a 2-year return period, a duration of 1 hour and a total precipitation volume of 12.2 mm.

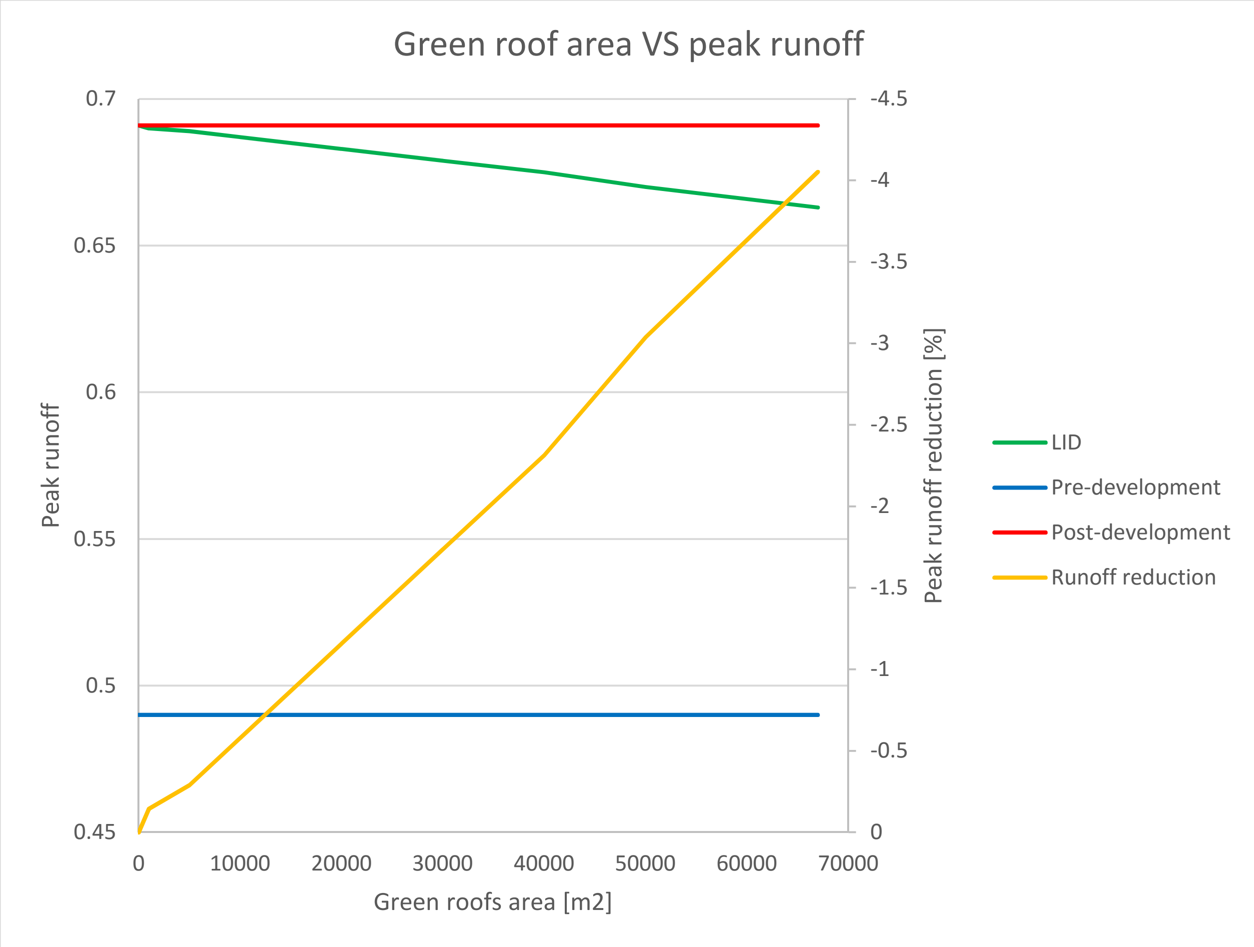


Figure 29: Graph showing total area of green roofs in the model vs. simulated peak runoff, and the runoff reduction compared to the post-development model.

Green roof simulations are done using 100 m^2 units with 10-meter width. The total area is changed by increasing the number of units in the catchment. No additional inflow from impervious surfaces are given to the green roofs, so they only treat direct rainfall. As can be seen in Figure 29, the peak runoff reduction increases linearly with increased area. The maximum peak runoff reduction is -4 % at 67 000 m^2 green roofs, which is equal to the total increase in building area for the catchment. This means that implementing green roofs on all new rooftops only decreases the peak runoff by 4 % for the simulated design storm. Results would probably look better when using smaller everyday rainfall events.

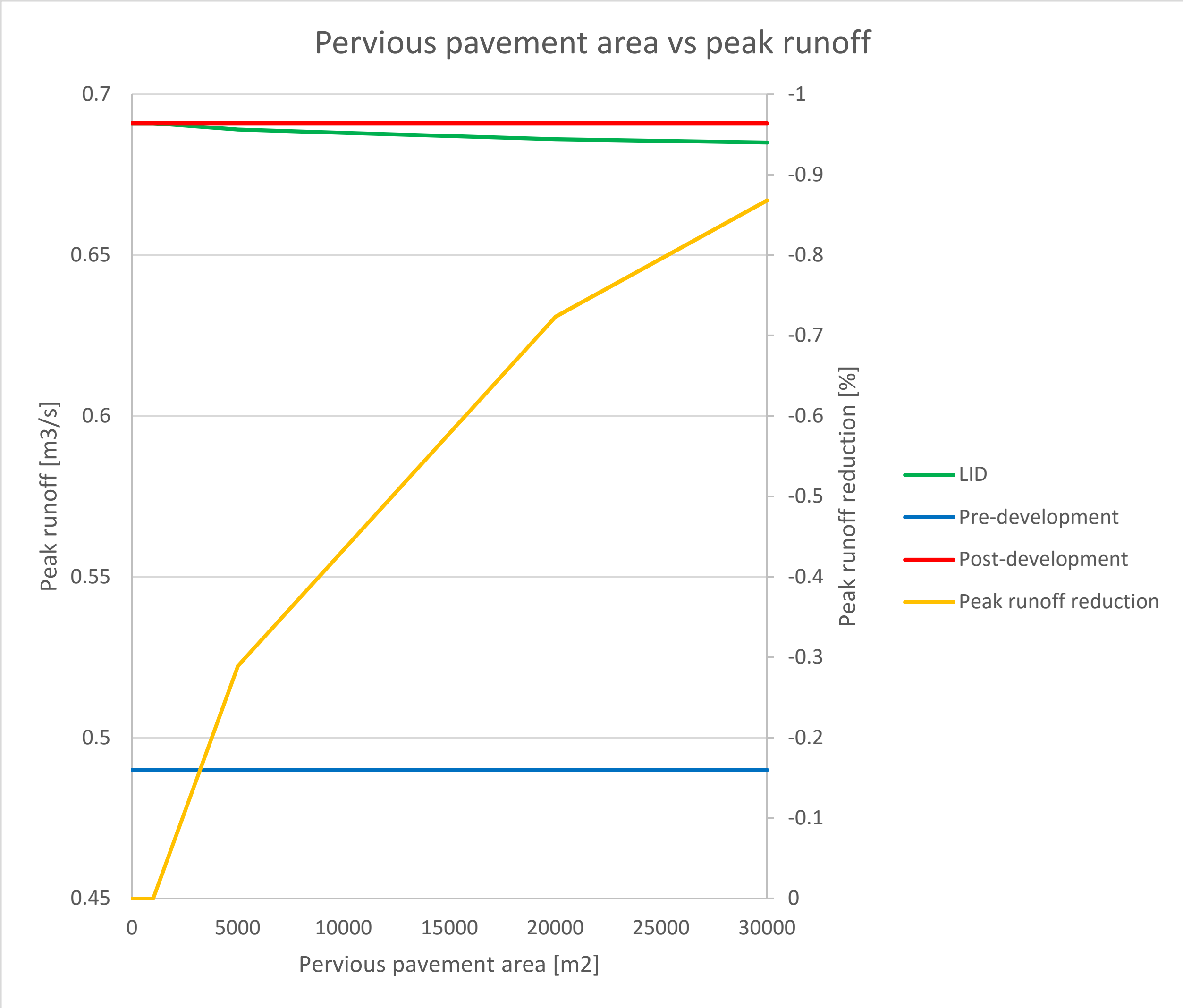


Figure 30: Graph showing total area of permeable pavements in the model vs. simulated peak runoff, and the runoff reduction compared to the post-development model.

Permeable pavement simulations are done using 500 m^2 units with 4-meter width. The total area is changed by increasing the number of units in the catchment. No additional inflow from impervious surfaces are given to the permeable pavements, so they only treat direct rainfall. The peak flow reduction on the full catchment from pervious pavements is small which can be contributed to the fact that is does not receive any additional runon from other impervious surfaces, has low surface roughness and little depression storage, thus the rainfall will drain off the surface rather quickly. Even if 100 % of the road surfaces are permeable pavements, the peak runoff reduction is less than 1 %. As with the green roofs, results would most likely look better using smaller everyday rainfall events.

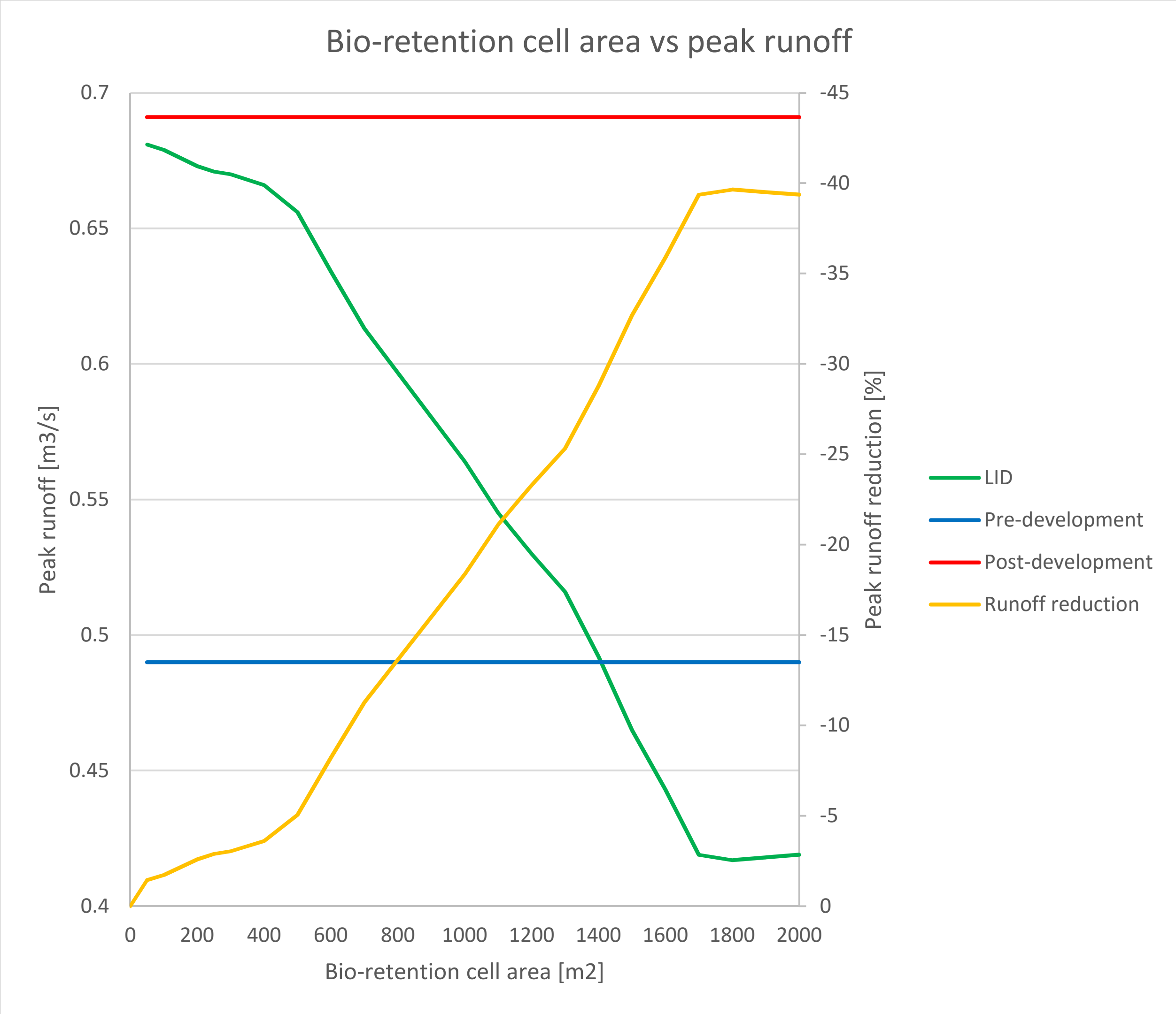


Figure 31: Graph showing total area of bio-retention cells in the model vs. simulated peak runoff, and the runoff reduction compared to the post-development model.

Simulations for bio-retention cells are done using 50 m^2 units with 7-meter width. The total area is changed by increasing the number of units in the catchment. The rain gardens receive additional runon from 30 % of the impervious surfaces in the catchment. From the graph it is clear that the bio-retention area has a large impact on the peak runoff, topping off at 40 % peak reduction. At around 1700 m^2 the peak reduction potential reaches its maximum, indicating that all the additional runon from impervious surfaces is collected and infiltrated through the bio-retention cells. This means that with the properties shown in Table 10, the amount of bio-retention area needed per impervious area to achieve maximum peak runoff reduction is approximately 4 %.

7.4. Weather events

All models are run using four different weather events in order to assess the function of the catchment in many different scenarios. The four scenarios are a long-term 1-year simulation using the 2011 data from Voll rain gauge, and three design storms based on the IVD-curve for Trondheim with differing return periods. The return periods simulated are 2-, 20- and 200 years, with an additional 20 % intensity to account for future climate change.

The 1-year simulation is important to see how the catchment functions in everyday rainfall events, and to look at the normal situation for the catchment and how it changes after development. The everyday rainfall events are also where LID controls are expected to have the most effect, and it is interesting to see how the LID controls changes the catchment hydrology compared to the post-development model. Rainfall and temperature data used in the 1-year simulation are shown in Figure 32 and Figure 33 below.

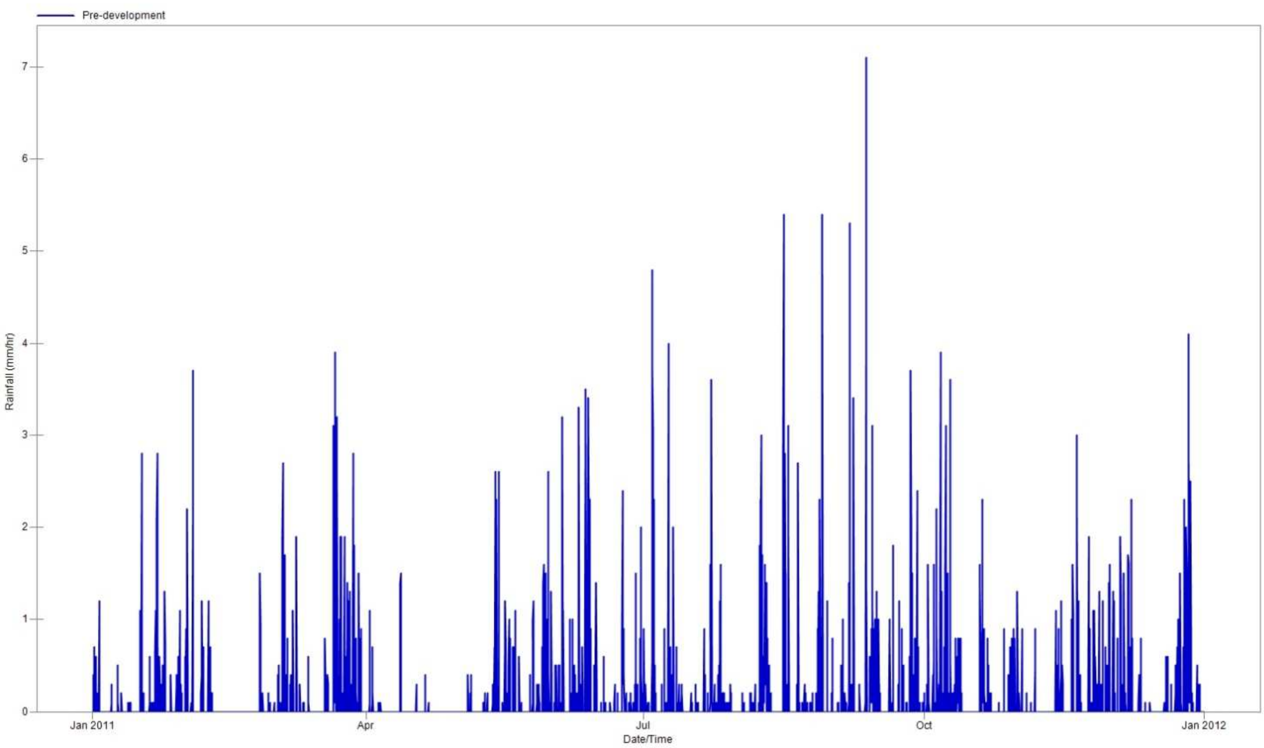


Figure 32: Rainfall hyetograph for Voll rain gauge in 2011. 1-hour resolution.

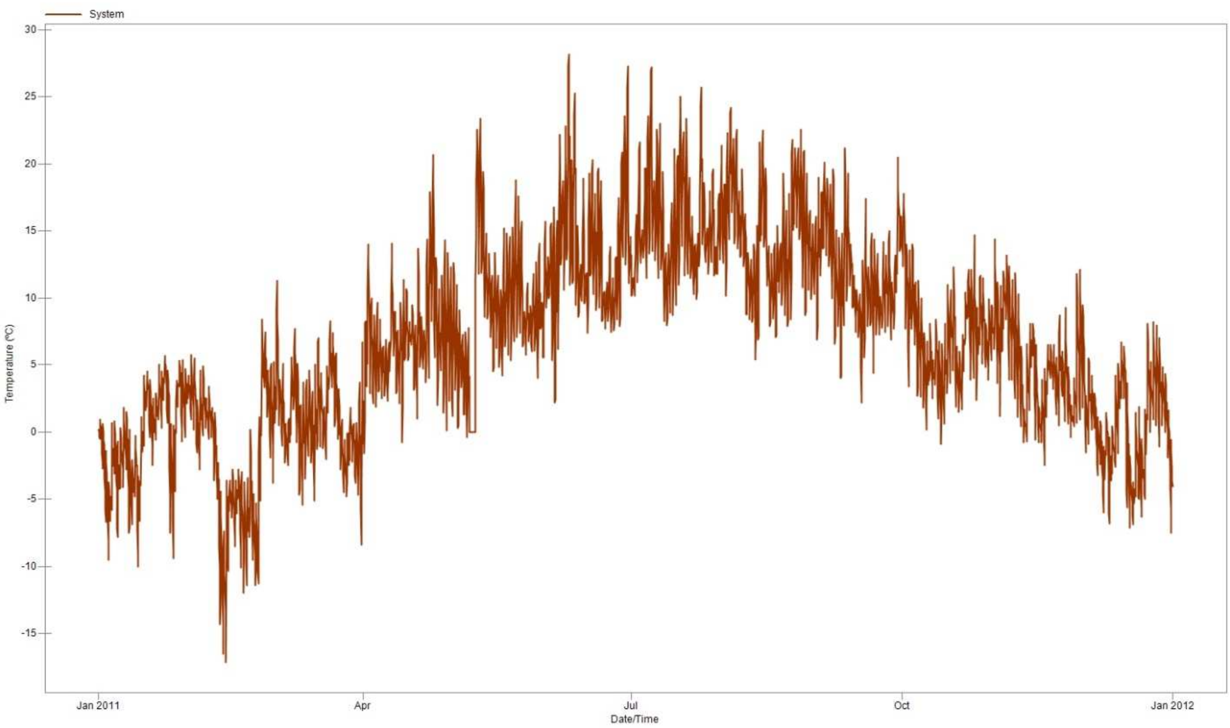


Figure 33: Temperature data for Voll rain gage in 2011. 1-hour resolution.

The 2-year return period was chosen to see how the catchment functions during smaller events that occur semi-frequently, and to see how development changes the hydrology of the catchment during these events. The 20-year return period was chosen because many structures are designed using the 20-year return period flood as a basis for flood prevention measures. It is therefore interesting to see how development will change the catchment hydrology during the 20-year return period storms. The 200-year return period was chosen because the culvert downstream from the catchment is designed for the current 200-year runoffs. It is therefore critical to see how the catchment hydrology changes during this event post-development and how to keep the peak runoff at the pre-development levels.

Rainfall data for the design storms used in the simulations are shown in Figure 34, Figure 35 and Figure 36 below.

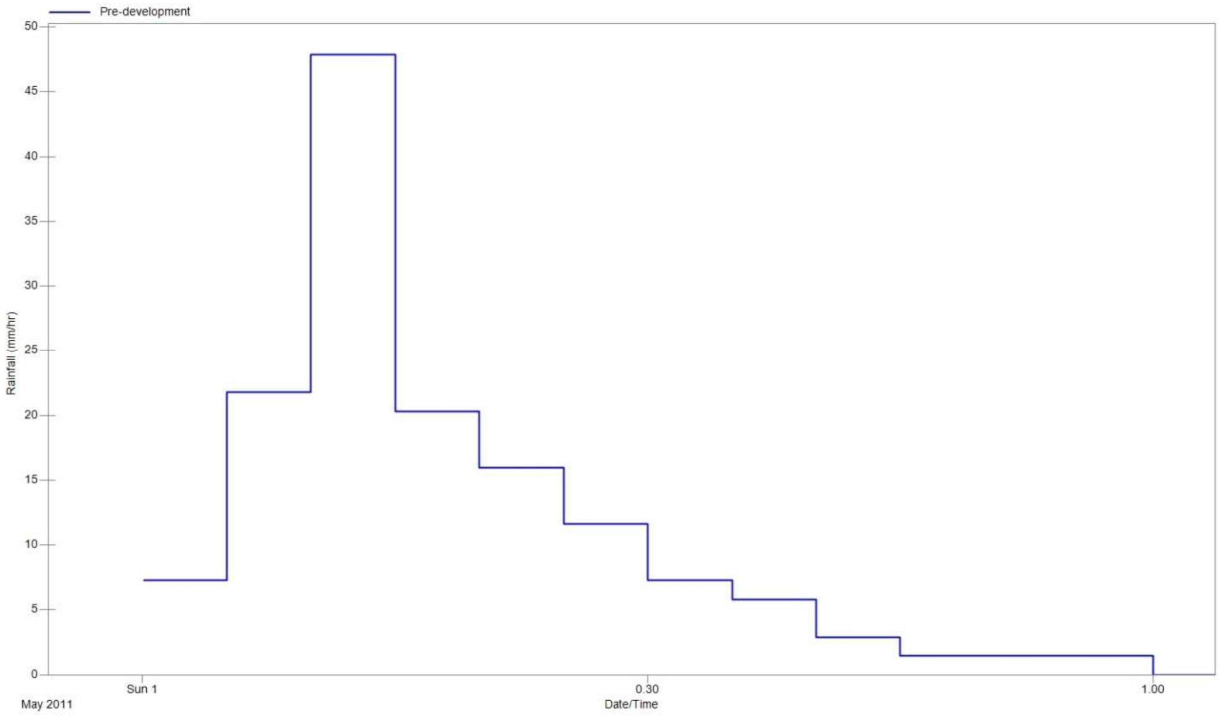


Figure 34: Rainfall hyetograph for 1-hour duration design storm with 2-year return period.

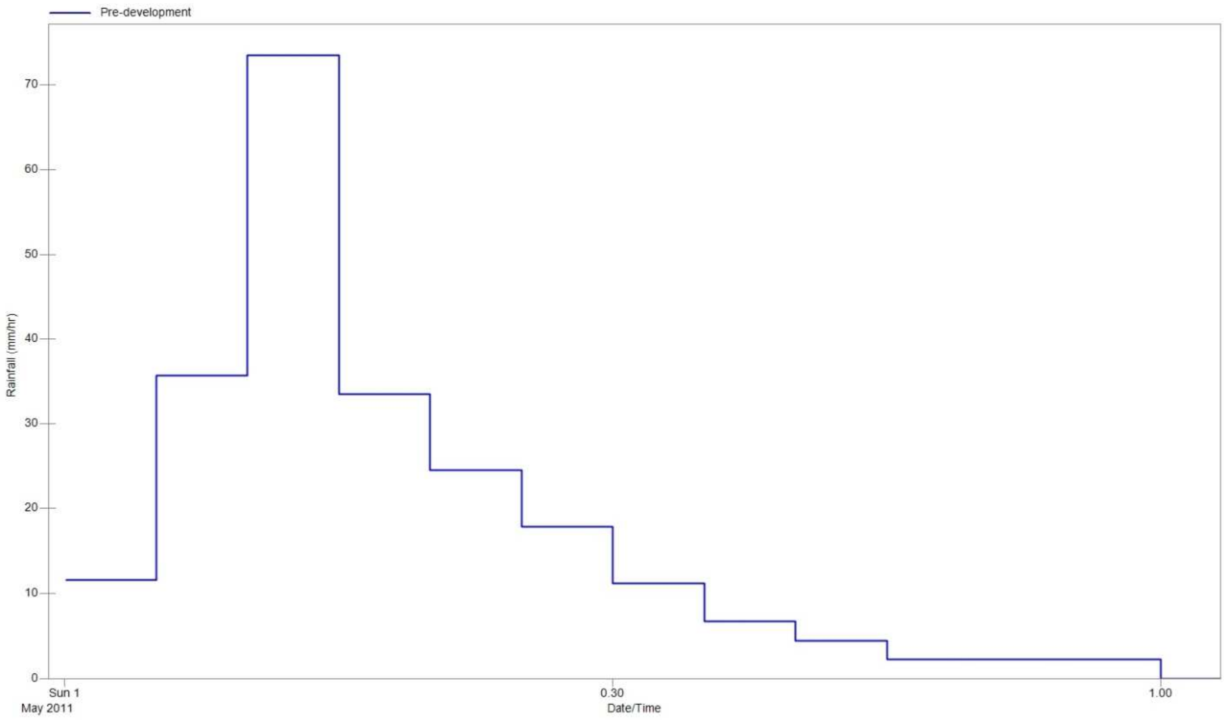


Figure 35: Rainfall hyetograph for 1-hour duration design storm with 20-year return period.

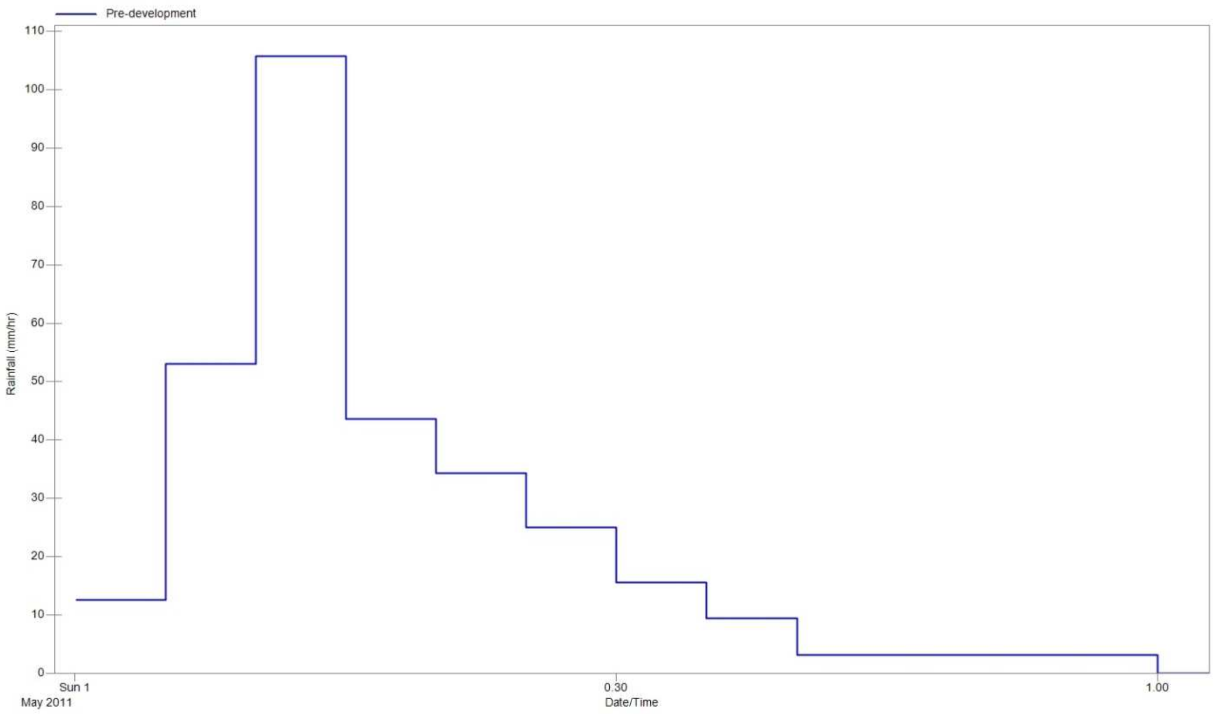


Figure 36: Rainfall hyetograph for 1-hour duration design storm with 200-year return period.

8. Results

All results are obtained through simulating the different models using the parameters and properties described in chapter 7.

8.1. 2011 1-year simulation

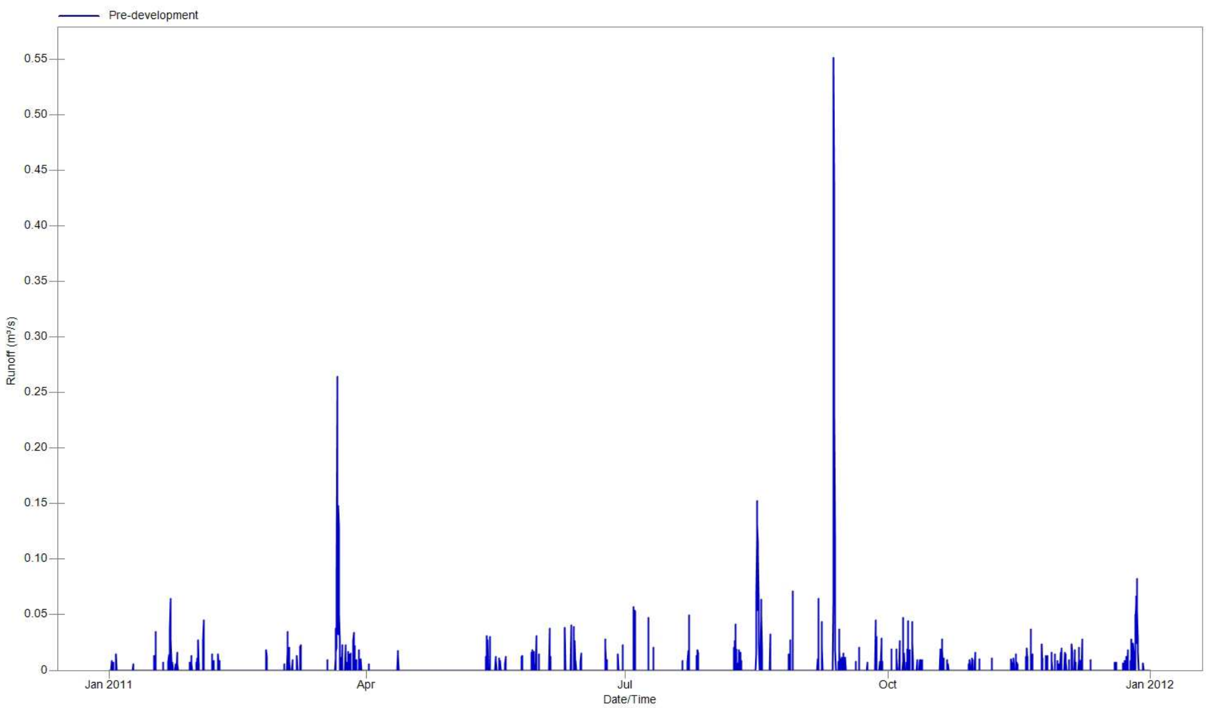


Figure 37: Runoff volume in m3/s for the Overvik catchment in 2011 pre-development (blue).

The pre-development model has a total of 238 runoff events for the year 2011, with a total runoff duration of 603.7 hours. The peak runoff is 0.552 m^3/s reached on September 12th around 01:00. The total runoff for the pre-development model is 59 480 m^3, giving the catchment a runoff coefficient of 0.095. Total evaporation for 2011 is 74.62 mm, while total infiltration is 785.58 mm.

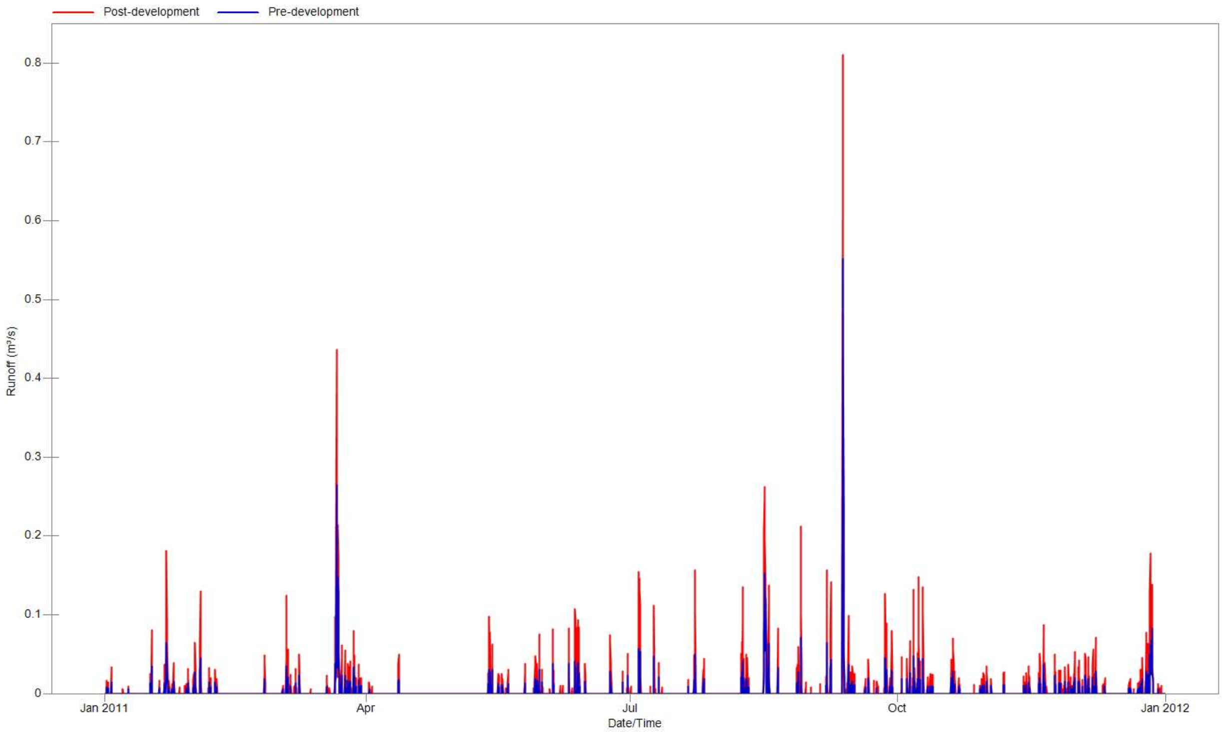


Figure 38: Runoff volume in m3/s for the Overvik catchment in 2011 post-development (red) and pre-development (blue).

The post-development model has a total of 285 runoff events for the year 2011, with a total runoff duration of 1 142 hours. The peak runoff is 0.810 m^3/s reached on September 12th around 01:00. The total runoff for the post-development model is 151 100 m^3, giving the catchment a runoff coefficient of 0.230. Total evaporation for 2011 is 82.66 mm, while total infiltration is 649.33 mm.

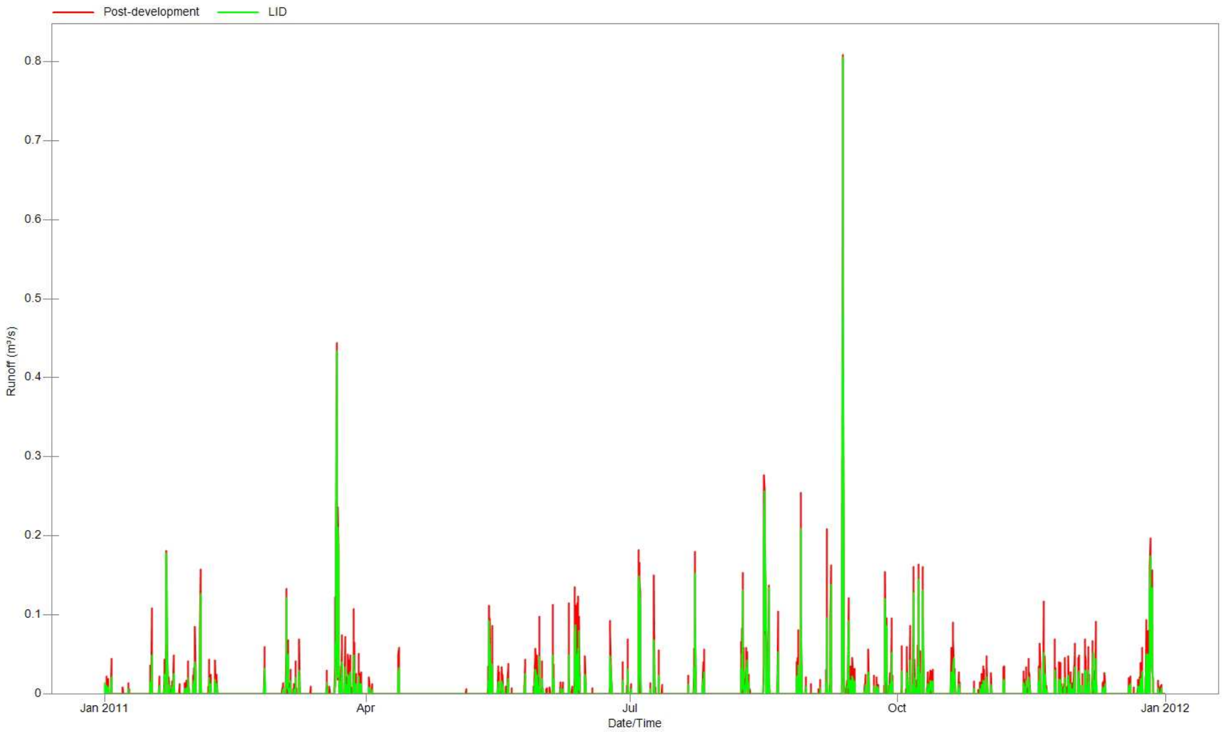


Figure 39: Runoff volume in m3/s for the Overvik catchment in 2011 LID (green) and post-development (red).

The LID model has a total of 217 runoff events for the year 2011, with a total runoff duration of 1 077 hours. The peak runoff is 0.805 m^3/s reached on September 12th around 01:00. The total runoff for the LID model is 117 900 m^3, giving the catchment a runoff coefficient of 0.191. Total evaporation for 2011 is 84.88 mm, while total infiltration is 683.79 mm.

Table 11: Hydrologic parameters for the Overvik catchment for the 2011 1-year simulation.

	Pre-development	Post-development	LID
Precipitation [mm]	950.8	950.8	950.8
Evaporation [mm]	74.62	82.66	84.88
Infiltration [mm]	785.58	649.33	683.79
Runoff depth [mm]	90.56	218.73	181.97
Peak runoff [m^3/s]	0.552	0.810	0.805
Total runoff [m^3]	59 480	151 100	117 900
Runoff coefficient	0.095	0.230	0.191
Duration of runoff [h]	603.7	1 142	1 077
# of runoff events	238	285	217

8.2. Design storm, 2-year return period

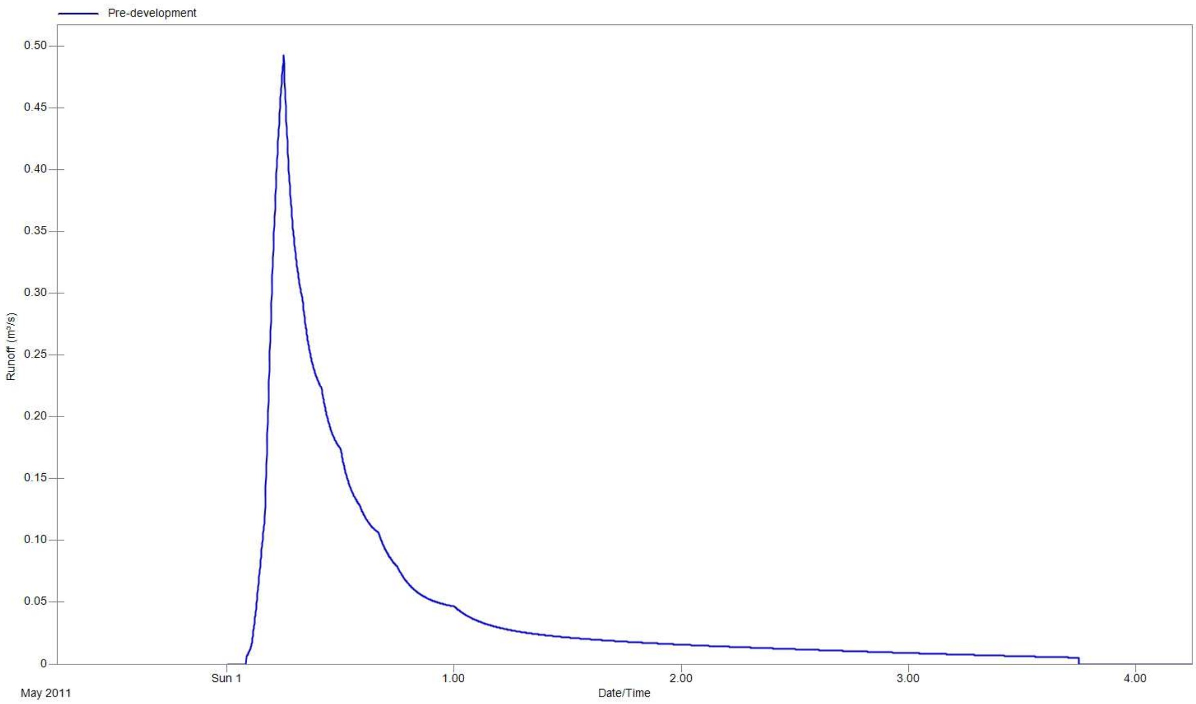


Figure 40: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 2-year return period pre-development (blue).

The pre-development model has a total runoff duration of 3.67 hours. The peak runoff is 0.491 m^3/s reached after 15 minutes. The total runoff for the pre-development model is 661.6 m^3, giving the catchment a runoff coefficient of 0.077. Total evaporation is 1.49 mm, while total infiltration is 9.28 mm.

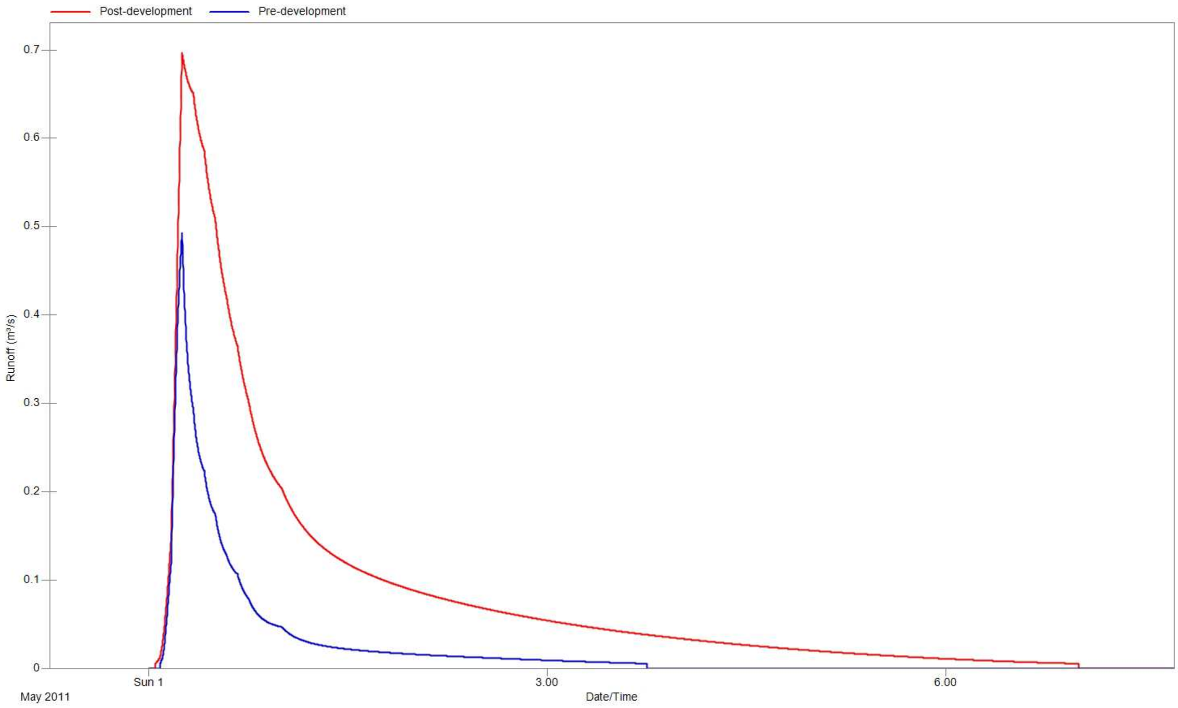


Figure 41: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 2-year return period post-development (red) and pre-development (blue).

The post-development model has a total runoff duration of 7.01 hours. The peak runoff is 0.699 m^3/s reached after 15 minutes. The total runoff for the post-development model is 2 350 m^3, giving the catchment a runoff coefficient of 0.268. Total evaporation is 1.30 mm, while total infiltration is 7.53 mm.

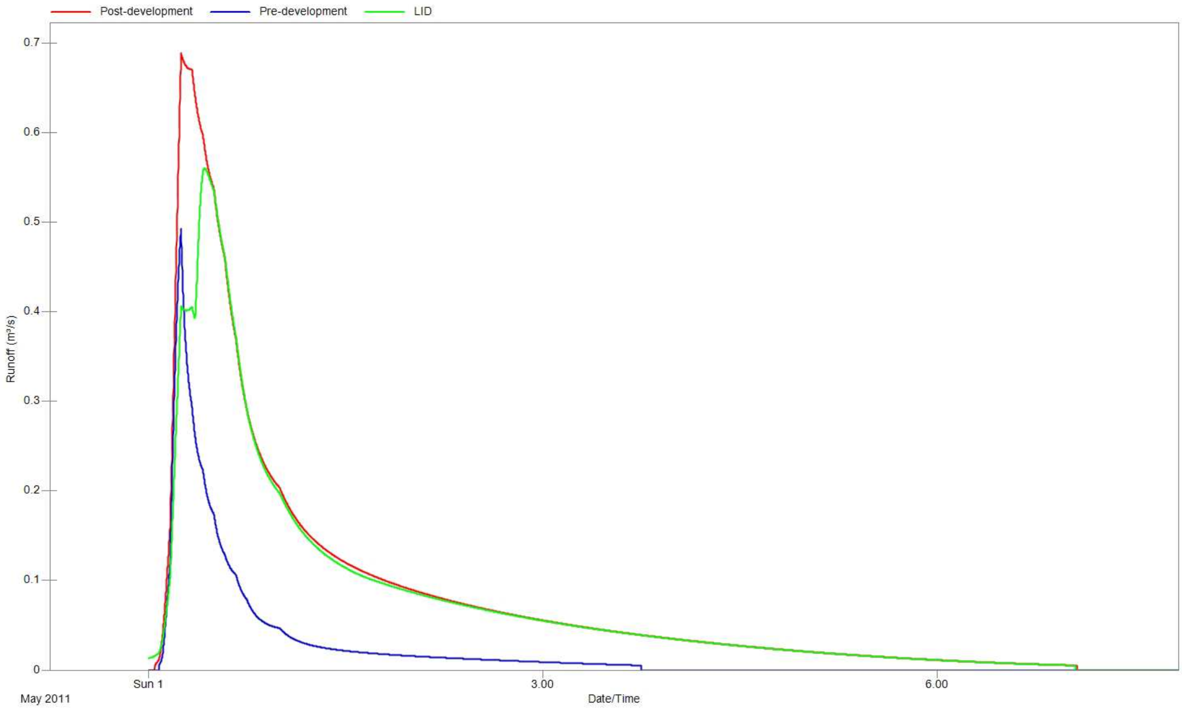


Figure 42: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 2-year return period; LID (green), post-development (red) and pre-development (blue).

The LID model has a total runoff duration of 7.05 hours. The peak runoff is 0.560 m^3/s reached after 26 minutes. The total runoff for the LID model is 2 129 m^3, giving the catchment a runoff coefficient of 0.247. Total evaporation is 1.31 mm, while total infiltration is 7.74 mm.

Table 12: Hydrologic parameters for the Overvik catchment during design storm with 2-year return period.

	Pre-development	Post-development	LID
Precipitation [mm]	12.22	12.22	12.22
Evaporation [mm]	1.49	1.30	1.31
Infiltration [mm]	9.28	7.53	7.74
Runoff depth [mm]	0.93	3.24	3.02
Peak runoff [m^3/s]	0.491	0.699	0.560
Total runoff [m^3]	661.6	2350	2129
Runoff coefficient	0.077	0.268	0.247
Duration of runoff [h]	3.67	7.01	7.05
Time of peak [min]	15	15	26

8.3. Design storm, 20-year return period

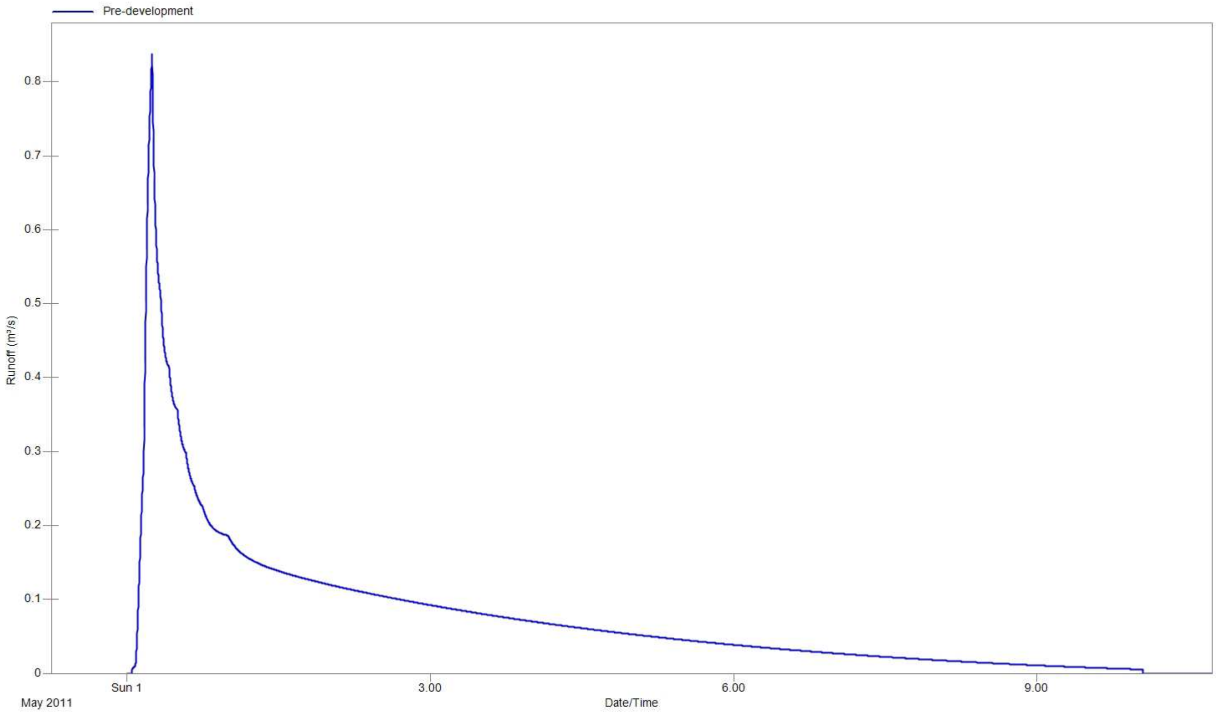


Figure 43: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 20-year return period pre-development (blue).

The pre-development model has a total runoff duration of 10.0 hours. The peak runoff is 0.836 m^3/s reached after 15 minutes. The total runoff for the pre-development model is 2 926 m^3, giving the catchment a runoff coefficient of 0.216. Total evaporation is 1.50 mm, while total infiltration is 9.30 mm.

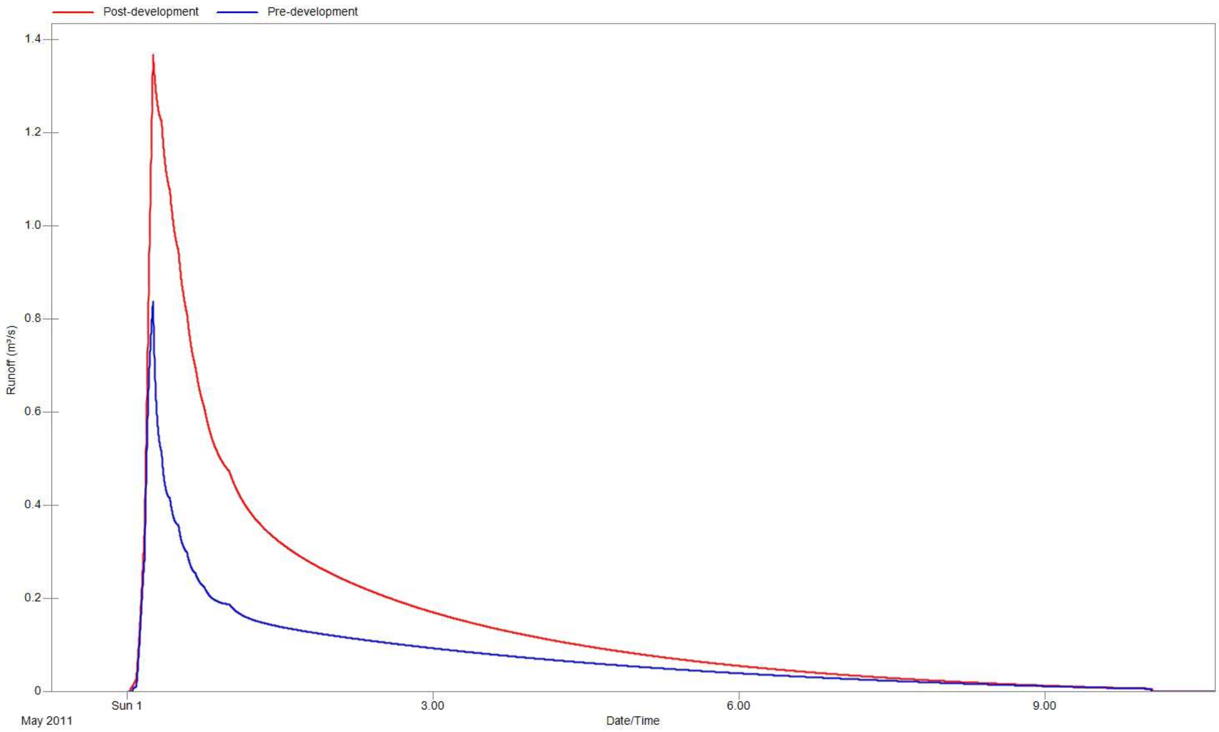


Figure 44: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 20-year return period post-development (red) and pre-development (blue).

The post-development model has a total runoff duration of 10.03 hours. The peak runoff is 1.371 m^3/s reached after 15 minutes. The total runoff for the post-development model is 5 875 m^3, giving the catchment a runoff coefficient of 0.433. Total evaporation is 1.39 mm, while total infiltration is 7.91 mm.

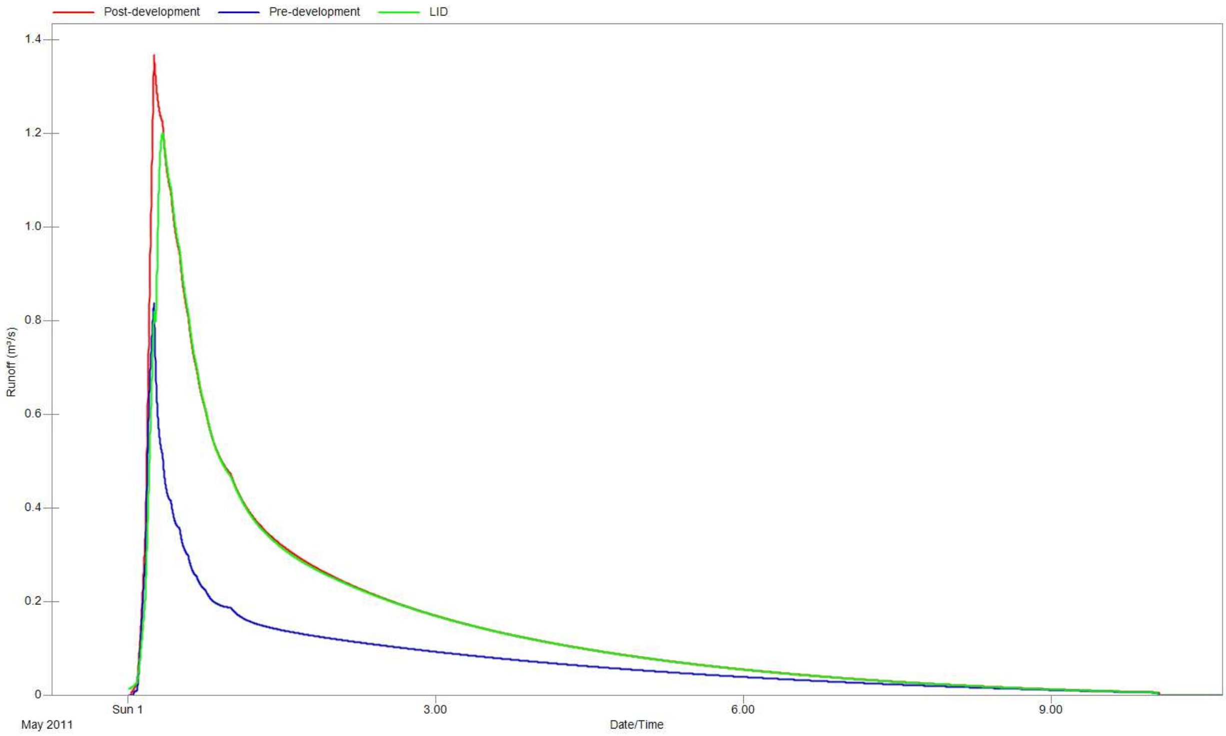


Figure 45: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 20-year return period; LID (green), post-development (red) and pre-development (blue).

The LID model has a total runoff duration of 10.04 hours. The peak runoff is 1.202 m^3/s reached after 20 minutes. The total runoff for the LID model is 5 648 m^3, giving the catchment a runoff coefficient of 0.417. Total evaporation is 1.39 mm, while total infiltration is 8.09 mm.

Table 13: Hydrologic parameters for the Overvik catchment during design storm with 20-year return period.

	Pre-development	Post-development	LID
Precipitation [mm]	18.8	18.8	18.8
Evaporation [mm]	1.50	1.39	1.39
Infiltration [mm]	9.30	7.91	8.09
Runoff depth [mm]	4.05	8.14	7.84
Peak runoff [m^3/s]	0.836	1.371	1.202
Total runoff [m^3]	2 926	5 875	5 648
Runoff coefficient	0.216	0.433	0.417
Duration of runoff [h]	10.0	10.03	10.04
Time of peak [min]	15	15	20

8.4. Design storm, 200-year return period

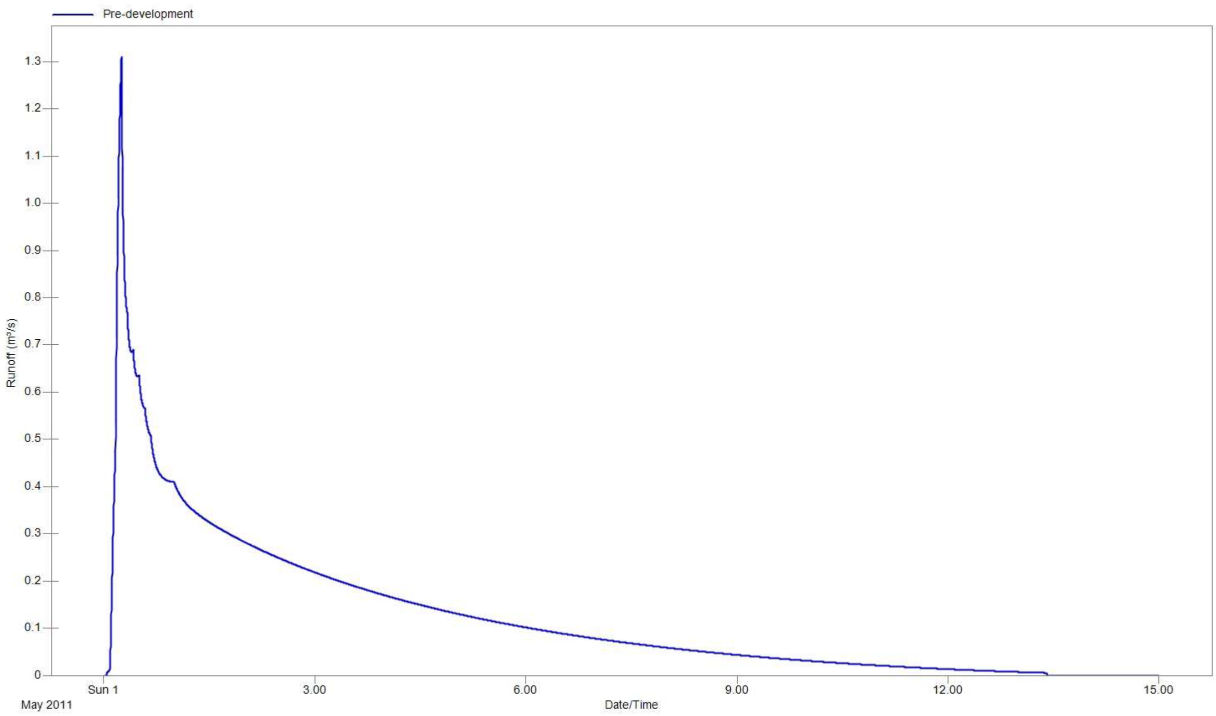


Figure 46: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 200-year return period pre-development (blue).

The pre-development model has a total runoff duration of 13.36 hours. The peak runoff is 1.307 m^3/s reached after 15 minutes. The total runoff for the pre-development model is 6 712 m^3, giving the catchment a runoff coefficient of 0.358. Total evaporation is 1.50 mm, while total infiltration is 9.30 mm.

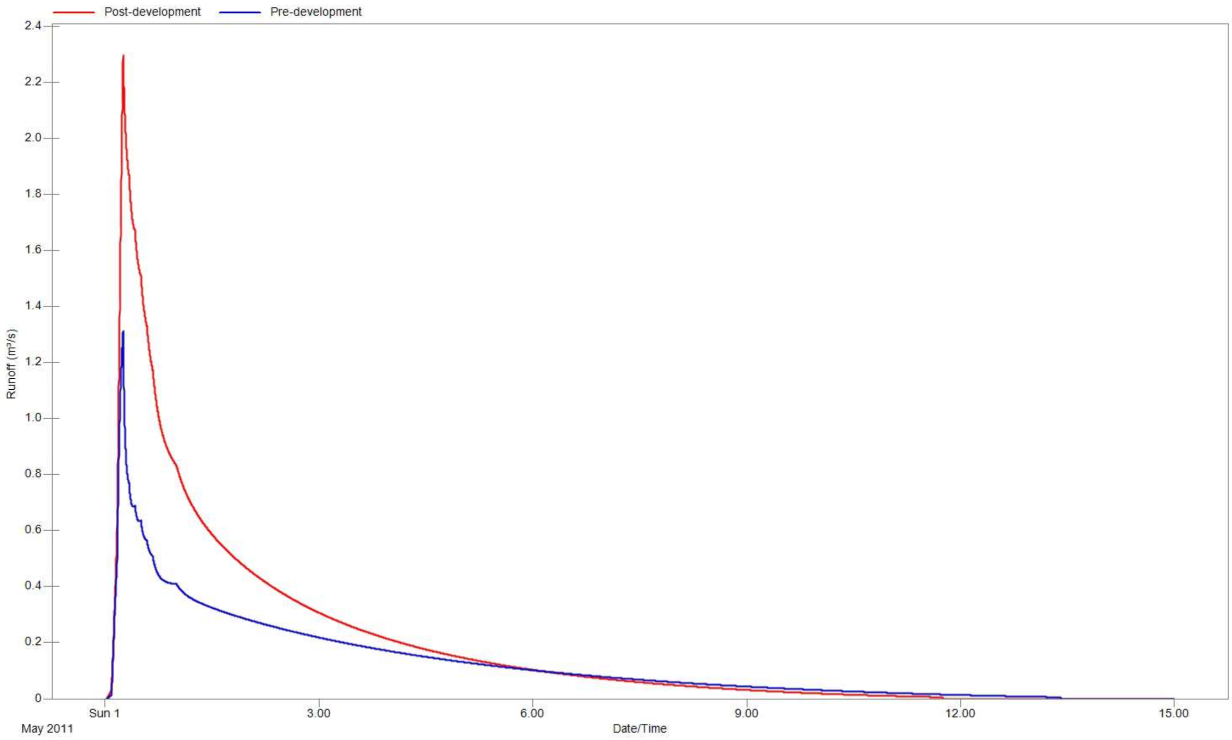


Figure 47: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 200-year return period post-development (red) and pre-development (blue).

The post-development model has a total runoff duration of 11.72 hours. The peak runoff is 2.296 m^3/s reached after 15 minutes. The total runoff for the post-development model is 10 410 m^3, giving the catchment a runoff coefficient of 0.555. Total evaporation is 1.31 mm, while total infiltration is 7.91 mm.

In order to maintain the pre-development peak runoff for 200-year storms, the required detention volume is 1 178 m^3.

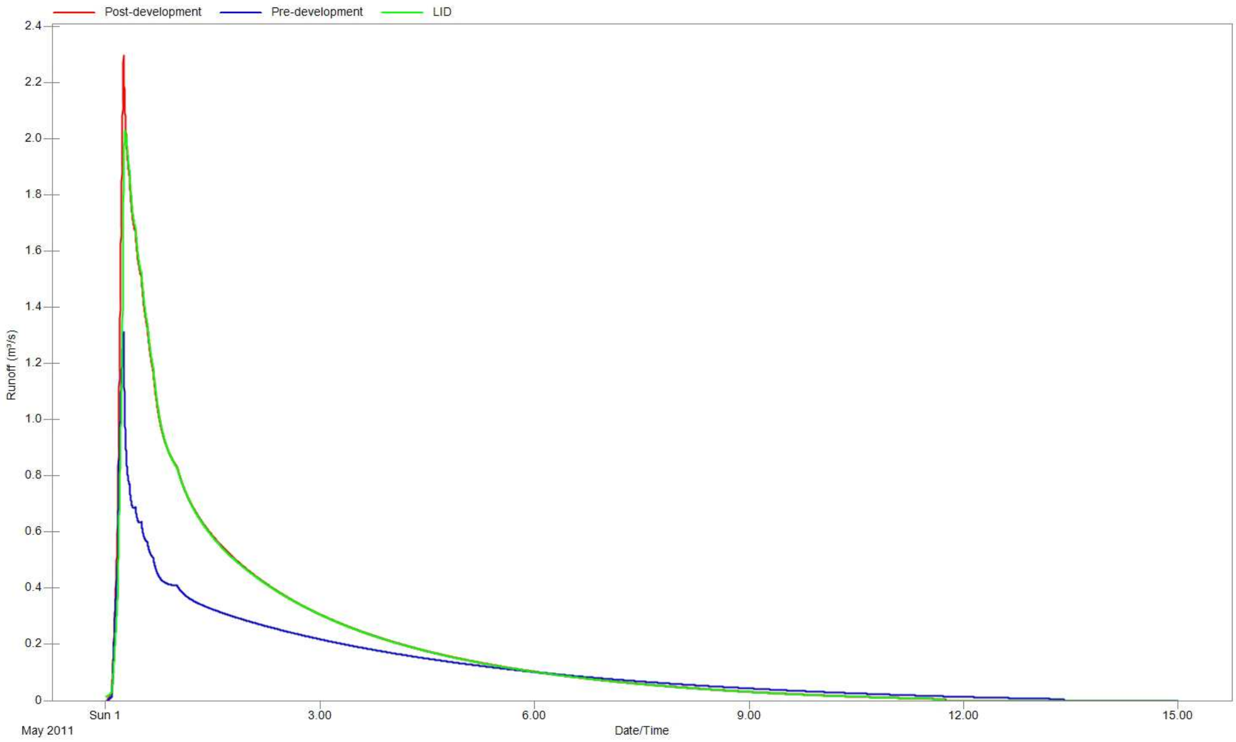


Figure 48: Runoff hydrograph in m3/s for the Overvik catchment during design storm with 200-year return period; LID (green), post-development (red) and pre-development (blue).

The LID model has a total runoff duration of 11.73 hours. The peak runoff is 2.027 m^3/s reached after 16 minutes. The total runoff for the LID model is 10 180 m^3, giving the catchment a runoff coefficient of 0.543. Total evaporation is 1.39 mm, while total infiltration is 8.09 mm.

In order to maintain the pre-development peak runoff for 200-year storms, the required detention volume is 1 062 m^3.

Table 14: Hydrologic parameters for the Overvik catchment during design storm with 200-year return period.

	Pre-development	Post-development	LID
Precipitation [mm]	25.92	25.92	25.92
Evaporation [mm]	1.50	1.31	1.39
Infiltration [mm]	9.30	7.91	8.09
Runoff depth [mm]	9.27	14.38	14.08
Peak runoff [m^3/s]	1.307	2.296	2.027
Total runoff [m^3]	6 712	10 410	10 180
Runoff coefficient	0.358	0.555	0.543
Duration of runoff [h]	13.36	11.72	11.73
Time of peak [min]	15	15	16
Storage needed [m^3]	0	1 178	1 062

During the 200-year return period rainfall event, which limits the culvert downstream, the LID controls in the catchment have little impact. For these large events, a storage volume is required upstream of the culvert. Modeled required storage volume for the post-development model in order to maintain pre-development peak runoffs is 1 178 m^3. For the LID model, the storage volume required is modeled to 1 062 m^3.

9. Discussion and conclusions

As stated earlier, the model used for simulating catchment runoff is not calibrated. This means that the results achieved from the model cannot be trusted 100 %, but can serve as a good indication of what real world results might look like. A calibration of the model would require runoff measurements through the culvert downstream of Overvikbekken for an extended period of time. This could be done, but the problem is that Rønningsbekken, a stream with a whole other catchment, also flows through the same culvert. This means that one would either have to calibrate the model for both catchments, or measure the runoff in both Rønningsbekken and the culvert simultaneously in order to decide how much of the runoff is generated from the Overvik area. This would require a lot of time and work, and thus was not prioritized for this thesis.

The drawbacks from using an uncalibrated model is that you do not know whether the catchment parameters set correlate with the actual properties of the catchment. This means that there are a lot of assumptions made, giving the results a degree of uncertainty.

The modeling software used, PCSWMM, is also a quite "simple" program. Although it uses advanced formulas and equations for flow routing and infiltration, it lacks in other areas. One drawback of the program is that is does not utilize digital elevation models for terrain data, instead the catchment is given a uniform shape and slope. This means that variations in the terrain is not accounted for when routing the flow through the catchment, giving the catchment a shorter time of concentration and probably a higher peak runoff. Another problem is that the subcatchments schematization in PCSWMM clusters the impervious areas together at the downstream edge of the catchment, as seen in Figure 20. This leads to impervious areas producing direct runoff without routing the flow through pervious areas, further reducing the time of concentration and increasing the peak runoff.

It would be beneficial to use a modeling software that utilized the DTM for terrain data and supported area-specific impervious pavements, for example using .shp-files, so that the catchment variations can be reproduced in the most accurate way possible.

When using low impact development to obtain a sustainable stormwater management, there are three main principles to follow. Small rainfall events under 20 mm are to be collected and infiltrated, medium events between 20 and 40 mm are to be delayed and attenuated, and large events over 40 mm are to be safely conveyed through the catchment. In principle this means that it is desired to maintain the existing hydrology for smaller events, while larger events require measures to keep the additional runoff post-development from causing damage to terrain and structures.

This 3-way strategy is obtained using different LID controls and vegetated swales or floodways. Most LID controls, like green roofs and pervious pavements, are designed for infiltrating the small events, while bio-retention cells function as an infiltrator for small events while also delaying medium events through surface ponding. During large events where most LID controls exceed their infiltration and storage capacity, floodways and basins are needed to control the excess runoff. Basins are rather expensive to build, so having an accurate estimate on the detention volume needed can prove to be quite cost-saving, both during construction, but also in eliminating damages to infrastructure downstream of the basin as a result of lack of capacity.

The LID controls sensitivity analysis in chapter 7.3.2 show that green roofs and pervious pavements have little effect on the peak runoff for the simulated rainfall event. These results are probably a little skewed, as the rainfall event has a very high maximum intensity of almost 48 mm/hr, far exceeding the infiltration capacity of both LID controls, and producing a high peak runoff. For events with a lower intensity or longer duration, peak runoff reduction would probably be a lot higher, as results from in-situ studies listed in chapters 5.3 and 5.4 show. Another thing to keep in mind is that the sensitivity analysis is done on the entire catchment, while the LID controls are a small part of this catchment. Looking at the controls area only, the results might look more in line with what was found in earlier studies.

The bio-retention cell sensitivity analysis however shows a very high peak flow reduction for the simulated rainfall event. With 30 % of the impervious area runoff routed through the bio-retention cell, results show that the peak runoff can be reduced to be less than that of the pre-development model. These results are so good because the bio-retention cells have a ponding depth of 200 mm where the inflow from impervious areas can be stored before they are infiltrated through the rain garden. With a ponding depth of 200 mm and an area of 50 m^2, the total surface storage volume is 10 m^3 for each unit. This means that the bio-retention cells can function well both for small and medium rainfall events, where parts of the stormwater can be detained and infiltrated through the rain garden for reduced peak runoffs and increased lag time.

When all these LID controls are used together and runoff from impervious surfaces are routed through rain gardens, most of the rainfall from small events are expected to be infiltrated through the controls. For medium events the green roofs and pervious pavements lose some of their effectiveness, but the runoff will still be reduced and delayed by surface storage in the rain gardens. How much of a reduction is achieved, is chiefly decided by the total bio-retention cell area, and through model simulation you can find the optimum area required to maintain pre-development peak runoffs for different rainfall events.

The sensitivity analysis for catchment parameters in chapter 7.1.1 show that impervious surface area and surface roughness have the largest impact on the peak runoff. Catchment width and slope also impacts the peak runoff, but both are set parameters that are not subject to change during development. Impervious surface area and surface roughness however can be adjusted through the use of chiefly green roofs and pervious pavements. Although not depicted well in the LID controls sensitivity analysis, these LID measures can give quite high peak flow reductions and -delay, especially for small events.

Many of the parameters in the catchment sensitivity analysis give no change in peak runoffs for the catchment. This is chiefly because of the drawbacks to PCSWMM discussed earlier, where the peak runoffs in the model are very impervious area-driven because they produce direct runoff. Using area-specific impervious surfaces where the runoff routed through pervious surfaces, pervious surface parameters like infiltration and depression storage would have more of an impact on the runoff results.

The results for the 1-year simulation can give a good indication on the catchments response for smaller everyday rainfall events and the “standard” runoff. Results shown in chapter 8.1 show that the LID model has a 22 % decrease in total runoff compared to the post-development model, while the peak runoff for the larger rainfall events is nearly unchanged. Also the number of runoff events is reduced from 285 events to 217 events, which is fewer than for the pre-development model, while the duration of runoff is reduced by 6 %. This is a clear indication that the LID controls have little effect on the large rainfall events, but it reduces the runoff from smaller events very well. The high reduction in rainfall events, yet small reduction in duration of runoff also indicates that the LID model gives a longer runoff lag-time, especially for small to medium events. This means less strain on the system downstream, as the runoff is distributed more over time.

For the 2-year design storm results show some change in both peak and total runoff, with reductions of 20 % and 9.5 % respectively, compared to the post-development model. In Figure 42, you can see that the runoff graph for the LID model flattens out at around 14 minutes, this is due to ponding in the bio-retention cell. When the rain gardens reach their surface storage capacity, the runoff shoots up again producing a 11-minute delay in the peak runoff. By increasing the area of bio-retention cells, this peak could be delayed even longer, or even cut completely. This is a good illustration of how the rain gardens can be used for runoff control during small to medium rainfall events.

One thing to make notice of in the results for the 2-year rainfall event is that the duration of runoff is nearly doubled in both the post-development and LID model compared to pre-development. This result might seem a little strange, as the duration of runoff is mostly pervious area driven, whose parameters does not change much between the different models. In fact, for the 200-year rainfall event the duration of runoff is longer pre-development than for the other models, which is more in line with what one would expect. The reason for this result is probably the increase in total runoff, and the fact that 30 % of the impervious areas are routed through the vegetated swale instead of producing direct runoff. This will mean that more water is going through the catchment, increasing the duration of runoff.

For the 20-year design storm, peak and total runoff reduction is 12 % and 4 % respectively, which is less of a reduction than for the 2-year event. These results are in line with the expected functions of the LID controls, where they are most efficient for smaller events. For the 200-year event the peak and total runoff reduction is 12 % and 2 %, respectively. The peak runoff reduction is thus the same for both the 20- and 200-year events, where one might expect the reduction to decrease with larger rainfall events. The lack of reduction seen in the results is hard to explain, and the simulations are run multiple times, producing the same result each time.

All in all, the results obtained from the models correlate well with what one would expect regarding changes in runoff and effectiveness of LID controls. However, since the results are obtained using an uncalibrated model, they should not be used uncritically. The models give a good indication on what changes can be expected post-development, and how LID can influence the catchment hydrology. Most LID controls are not meant as a measure for controlling large rainfall events, for that it will still be necessary with floodways and basins, but LID controls can be used to maintain the catchment hydrology for small to medium events.

The storage volume requirements for the 200-year rainfall event found in chapter 8.4 means that using LID controls the storage volume needed is reduced by approximately 10 %, whilst simultaneously maintaining the existing hydrology much better the traditional development during smaller events.

10. Future work

The models produced during this thesis should be calibrated before being used as a basis for dimensioning. This can be done by flow measurements of the culvert downstream of the catchment, and Rønningsbekken. The contributing runoff from Overvik can then be calculated by subtracting the flow in Rønningsbekken from the culvert flow. The pre-development model can then be calibrated using the flow measurements as a calibration curve, adjusting the catchment parameters to so that the simulated runoff matches the calibration curve.

What could be very interesting to do is performing flow measurements in Overvikbekken during the course of the development, in order to see how the development influences the catchment runoff. This could be done either continuously, or for certain periods on a yearly basis. Voll rain gauge can then be used for rainfall measurements to see the relationship between rainfall/runoff at different stages of the development.

11. References

IVF-kurve for Trondheim [Online]. VA-Norm. Available: http://www.va-norm.no/id_78143 [Accessed 26.04 2016].

2010. *Horton's infiltration model* [Online]. Available: http://www.egr.msu.edu/classes/ce421/lishug/text%20book.pdf [Accessed 20.05.2016 2016].

AHIABLAME, L. M., ENGEL, B. A. & CHAUBEY, I. 2012. Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. *Water Air and Soil Pollution,* 223**,** 4253-4273.

BRADFORD, A. & DENICH, C. 2007. RAINWATER MANAGEMENT TO MITIGATE THE EFFECTS OF DEVELOPMENT ON THE URBAN HYDROLOGIC CYCLE. *Journal of Green Building,* 2**,** 37-52.

BUHLER, L. & UNIVERSITETET FOR MILJØ- OG BIOVITENSKAP INSTITUTT FOR MATEMATISKE REALFAG OG, T. 2013. Analyse av klimaendringenes påvirkning på rustadfeltet med kalibrert modell = Analysis of climate change impacts on Rustadfield with calibrated model. *Analysis of climate change impacts on Rustadfield with calibrated model.* Ås: L. Buhler.

COSTABILE, P., COSTANZO, C., MACCHIONE, F. & MERCOGLIANO, P. 2012. Two-dimensional model for overland flow simulations: a case study. *European Water,* 38**,** 13-23.

DAVIS, A. P., STAGGE, J. H., JAMIL, E. & KIM, H. 2012. Hydraulic performance of grass swales for managing highway runoff. *Water Research,* 46**,** 6775-6786.

DIETZ, M. E. 2007. Low impact development practices: A review of current research and recommendations for future directions. *Water Air and Soil Pollution,* 186**,** 351-363.

DIETZ, M. E. & CLAUSEN, J. C. 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management,* 87**,** 560-566.

FASSMAN, E. A. & BLACKBOURN, S. 2010. Urban runoff mitigation by a permeable pavement system over impermeable soils. *Journal of Hydrologic Engineering,* 15**,** 475-485.

GARATHUN, M. G. 2015. *BLÅGRØNNE BETONGDEKKER* [Online]. Teknisk Ukeblad. Available: http://www.tu.no/samferdsel/2015/11/17/her-sluker-parkeringsplassen-1000-liter-vann [Accessed 19.11 2015].

HANSSEN-BAUER, I. 2015. Klima i Norge 2100 : kunnskapsgrunnlag for klimatilpasning oppdatert 2015. Oslo: Norsk klimaservicesenter.

HANSSEN - BAUER, I., DRANGE, H., FØRLAND, E. J., ROALD, L. A., BØRSHEIM, K. Y., HISDAL, H., LAWRENCE, D., NESJE, A., SANDVEN, S., SORTEBERG, A., SUNDBY, S., VASSKOG, K. & ÅDLANDSVIK, B. 2009. Klima i Norge 2100. Bakgrunnsmateriale til NOU Klimatilplassing. Norsk klimasenter.

HUURNINK, J. E., THOROLFSSON, S. T. & NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET, F. F. I. O. T. I. F. V.-O. M. 2012. Kvantifisering av overvann: Case Brøset ; Quantifying Stormwater: Case Brøset. Institutt for vann- og miljøteknikk.

JAMES, W., ROSSMAN, L. E. & JAMES, W. R. C. 2010. *User's guide to SWMM 5*, CHI Press.

KLOK, T. M. 2012. Modelling of stormwater overland flow in urban areas: Assessment of WOLK as an overland flow modelling tool.

KOMMUNE, A. 2014. Veileder for lokal overvannshåndtering i Asker kommune.

LIU, Q. Q., CHEN, L., LI, J. C. & SINGH, V. P. 2004. Two-dimensional kinematic wave model of overland-flow. *Journal of Hydrology,* 291**,** 28-41.

MUTHANNA, T. M., VIKLANDER, M. & THOROLFSSON, S. T. 2008. Seasonal climatic effects on the hydrology of a rain garden. *Hydrological Processes,* 22**,** 1640-1649.

OLSEN, S. J. 2015. *TOPMIX PERMEABLE* [Online]. tu.no: Teknisk Ukeblad. Available: http://www.tu.no/samferdsel/2015/09/28/ny-type-asfalt-sluker-4000-liter-vann-pa-60-sekunder [Accessed 19.11 2015].

PINA, R., OCHOA-RODRIGUEZ, S., SIMÕES, N., MIJIC, A., MARQUES, A. & MAKSIMOVIĆ, Č. 2016. Semi- vs. Fully-Distributed Urban Stormwater Models: Model Set Up and Comparison with Two Real Case Studies. *Water,* 8**,** 58.

REINEMO, P. 2015. OVERVANN OG HYDROLOGI FOR OVERVIK.

ROSSMAN, L. 2011. *Conductivity slope parameter in LID soil layer and aquifer* [Online]. www.openswmm.org. Available: https://www.openswmm.org/Topic/4312/conductivity-slope-parameter-in-lid-soil-layer-and-aquifer [Accessed 03.05.2016 2016].

ROUSSEAU, M., CERDAN, O., DELESTRE, O., DUPROS, F., JAMES, F. & CORDIER, S. 2012. Overland flow modelling with the Shallow Water Equation using a well balanced numerical scheme: Adding efficiency or just more complexity?

S. CORNELIUS, H. M., E. CHONG 2012. EXPERIENCE AND TECHNIQUES IN MODELLING URBAN STORMWATER NETWORKS AND OVERLAND FLOW PATHS.

SKAARAAS, H. 2015. *Overvann i byer og tettsteder : som problem og ressurs,* Oslo, Departementenes sikkerhets- og serviceorganisasjon.

SVANEVIK, M. 2015. Implementation of LID methods post-development. 5.

VARGO, J., HABEEB, D. & STONE JR, B. 2013. The importance of land cover change across urban–rural typologies for climate modeling. *Journal of Environmental Management,* 114**,** 243-252.

WIDERØE, H. 2012. Lokal overflateavrenning i boligfelt : økonomisk analyse av tiltak mot oversvømmelse ; Local surface runoff in residential areas : economic analysis of measures against flooding. Norwegian University of Life Sciences, Ås.

12. Appendix A: Task description

Modellering av overvannsavrenning i Overvikfeltet, Trondheim

Masteroppgave VA-teknikk 2016 - Mikkel Stensås Svanevik

Bakgrunn

I forbindelse med byfortetting i Trondheim skal området Overvik bygges ut til boligformål. Det skal etableres overvannsløsninger for området under forutsetning «samme avrenning som før» der man også tar hensyn til sikkerhet mot oversvømmelser og minst mulig belastning på nedstrøms avløpsanlegg. Eksisterende kulvert under E6 nedstrøms området har begrenset kapasitet, slik at eksisterende hydrologi i størst mulig grad må beholdes, både mht. minstevannføring (biologisk mangfold), normal og flomvannføring.

Ved dimensjonering av tradisjonelle og eventuelle lokalt tilpassede overvannsløsninger er det ønskelig å etablere en simuleringsmodell. Denne vil kunne brukes til å klarlegge realistiske alternativer til overvannshåndteringen. Det kan være vanskelig å kalibrere en modell som skal brukes i et fremtidig utbyggingsområde, og denne begrensningen må drøftes.

Oppgaven blir ikke nødvendigvis spesifikt for dette prosjektet/området, men det brukes som utgangspunkt for å diskutere og finne ut hvordan ulike løsninger kan påvirke de forskjellige problemstillingene man møter på i et slikt prosjekt.

Spesifisert oppgave

1. Utvikle og forklare målsettingen «samme avrenning som før» ved hjelp av litteraturstudier
    a. Hva er normalavrenning?
    b. Beholde eksisterende hydrologi – 5-, 10-, 200 års avrenning?
    c. Usikkerheter rundt faktorer som påvirker avrenning.
    d. Hva er nåsituasjonen, hva vil vi i fremtiden?
2. Etablere modell for overvannshåndteringen vha. PCSWMM, Mike Urban etc. for hele nedbørfeltet for eksisterende situasjon (før utbygging) og fremtidig situasjon (etter utbygging, alternative løsninger) og gjennomføre relevante analyser. Analysene skal også inkludere forventede klimaendringer
3. Drøfte usikkerhet rundt analyseteknikker og ulike systemløsninger.
4. Generalisere resultatene

Assistanse

Professor Sveinung Sægrov, Institutt for vann og miljøteknikk NTNU vil være hovedveileder for denne oppgaven, støttet av førsteamanuensis Tone Muthanna. Petter Reinemo fra Asplan VIAK vil levere opplysninger fra Overvikfeltet og assistere ved modelloppbyggingen. Prosjektet inngår i Klima 2050.

Presentasjon og leveranse

Prosjektrapporten skal leveres i henhold til gjeldende regler. Studenten er selv økonomisk ansvarlig for 3 kopier som leveres til instituttet. Ekstra kopier som er bestilt av instituttet skal betales av instituttet.

Leveringsfrist 24.juni 2016.