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Monitoring and modelling of water flow and quality at the Hoffselva DEMO site (Oslo)

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Abstract

Hoffselva is one of the main rivers in Oslo, flowing from Holmenkollen in the north and down to the fjord by Bestumkilen. Due to low capacity of the pipes in the sewer network, the river is experiencing a rapid frequency of emissions to the river through combined sewer overflows (CSOs). The water quality is poor due to the CSO emissions and other emissions. The municipality of Oslo wants to reach the target of good chemical and ecological state within 2021, set by the national water regulation. The on-going EU-project DESSIN (Demonstrate ecosystem services enabling innovation in the water sector) aims to improve the water quality by using innovative local treatment solutions that enable cost efficient, sustainable mitigation of overloaded sewer systems and thereby increasing the value of eco system services.

The aim of this master thesis is to contribute to the project by setting up, calibrating and applying a 1D hydrodynamic and water quality model for Hoffselva, and to investigate and discuss the potential influence of improved water quality from CSO spills on selected water quality indicators in Hoffselva. To fulfill the objectives, the author has used modeling programs like MIKE URBAN, HEC-RAS and ArcGIS: ArcMap. An existing model in MIKE URBAN has been used to model the activity of combined sewer overflow events during a selected 9-days rain period from the Autumn in 2014. An one-dimensional steady and unsteady simulation model were built in HEC-RAS to simulate the hydrodynamics of the river, and to make a basis for the water quality simulations in the water quality module in HEC-RAS.

The CSO activity modeling for the selected event in MIKE URBAN showed three active CSO (out of 24) in the southern, urban part of the catchment. The results are consistent when compared to the CSO frequency history. Several problems with numerical instability occurred in the unsteady simulations. The unsteady model had to be reduced and simplified to successfully run an unsteady simulation for the lower part of the river. The first unsteady simulation in HEC-RAS gave higher discharge values in the hydrographs than what were observed. After some calibration, the simulated values made a good visual fit with the observed values.

The water quality analysis had to use the hydraulic plan from the steady flow simulation due to an unknown error massage with the unsteady flow data. Different scenarios were made to simulate the water quality under different river conditions for a selected CSO event. The results were consistent with previous reports about poor water quality in the river. The local treatment solution was able to reduce the concentration peaks, but due to the background concentrations in the river, the water quality remained poor for the river Hoffselva in the investigated scenarios. Based on the findings, future work should measure the water quality during different rain events / scenarios, and compare the observed results with the simulated results from the model. Future work on the models should focus on using more detailed measurements as input to the models, as appropriate information about the river discharges is essential. It is suggested to make an unsteady calibrated model for the whole river network in order to have the opportunity to simulate multiple active CSOs at the same time.

Sammendrag

Hoffselva er et av hovedvassdragene i Oslo. Hoffselva renner fra Holmenkollen i nord, og sørover til utløpet ved Bestumkilen i Indre Oslofjord. Som følge av lav kapasitet på avløpsnettet, opplever elva hyppige utslipp fra overløp langs elva. Vannkvaliteten er dårlig som følge av alle overløp-utslippene og andre kilder til utslipp i elva. Oslo kommune har et ønske om å oppnå målet i Vannforskriften om god kjemisk og økologisk tilstand i alle vassdragene innen år 2021. Det pågående EU- prosjektet DESSIN (Demonstrate ecosystem services enabling innovation in the water sector) arbeider med å forbedre vannkvalitet ved bruk av innovative og lokale behandlingløsninger som muliggjør kosteffektivt, og bærekraftig klimatiltak for overbelastede avløpssystemer og dermed øke verdien til økosystemtjenester.

Formålet med masteroppgaven er å bidra til prosjektet ved å sette opp, kalibrere og benytte en 1D hydrodynamisk modell og en vannkvalitetsmodell for Hoffselva, og undersøke og diskutere potensiell påvirkning av forbedret vannkvalitet for overløp-hendelser ved å se på utvalgte vannkvalitetsindikatorer i Hoffselva. Til å utføre oppgavene, har forfatteren benyttet modelleringsprogrammer som MIKE URBAN, HEC-RAS og ArcGIS: ArcMap. En eksisterende MIKE URBAN modell fra 2011 har blitt brukt til å modellere overløpsaktivitet i løpet av en 9-dagers periode fra høsten 2014. En en-dimensjonal stasjonær og ikke-stasjonær simuleringsmodell ble laget i HEC-RAS for å simulere hydrodynamikken i elva, og for å bli brukt som grunnlag til vannkvalitetsimuleringen i vannkvalitetsmodulen til HEC-RAS.

Simuleringen av overløphendelser i MIKE URBAN viste at tre (av 24) overløp, i den urbane delen sør i avløpsnettet, var aktive for simuleringsperioden. Resultatene stemmer godt overens med tidligere overløphistorikk fra perioden før 2011. Den første ikke-stasjonære simuleringen gav høyere vannføring i elva enn hva som ble observert. Etter litt kalibrering, oppnådde modellen en god visuell passform mellom simulert og observert vannføring.

Vannkvalitetsanalysen måtte benytte de hydrauliske resultatene fra den stasjonære strømning simuleringen, som følge av en error i programmet som oppstod ved bruk av den ikke-stasjonære strømning simuleringen. Forskjellige scenarioer ble laget for å simulere vannkvaliteten under forskjellige forhold i elva for overløphendelsen. Resultatene samsvarer med hva andre rapporter har kommet frem til: dårlig vannkvalitet i Hoffselva. Den lokale behandlingen ved overløpet klarte å redusere toppene av forurensningen, men pga. bakgrunnskonsentrasjonene i elva, forble vannkvaliteten tilnærmet uendret.

Basert på erfaringer underveis, bør fremtidig arbeid inkludere vannkvalitetsmålinger og vannføringsmålinger under forskjellige regnhendelser, og benytte måleresultatene til å sammenligne og kalibrere modellen. Fremtidig arbeid med modellene bør fokusere på å benytte detaljerte målinger da informasjon om vannføringer er helt essensielt for å få til en god modell. Det anbefales å etablere en ikke-stasjonær hydrodynamisk modell for hele elvenettet for å kunne simulere flere overløp-utslipp samtidig og for å få variasjon i vannføring over tid.

Preface

This master thesis is submitted in the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The master thesis is a part of a 2-years master degree within the study programme Civil and Environmental Engineering. It accounts for 30 ECTS, and it was conducted during the spring 2016. It contains the work of the author under supervision of Postdoctoral Fellow Peggy Zinke and secondary supervisor Associate Professor Tone Merete Muthanna from NTNU.

It has been a lot of work and many challenges along the way, but that is also one of the main reasons why I chose this topic. I was triggered by the big potential to explore and learn from the project, as it is a part of something bigger. The use of modeling programs is something I have an interest for, and I have learned a lot from the work in this master thesis. One of my criteria's was that necessary supervision should be in place in order to conduct the different tasks along the way. I have met a lot of interesting and helpful people along the way which have given me extra encouragement and energy to keep working. I have experienced how much this important topic means to the different participants in the project, and how the different interests all relate to the same topic.

Among all the people I have encountered and met along the way, I would especially like to thank some of you. I would like to thank:

- Oslo VAV for their kindness and willingness to share and provide information, and to accommodate a one week stay at their office. Especially thanks to Samatar Abdi Mahammud for supervision on the MIKE URBAN modeling.
- Ashenafi Seifu Gragne for the help with HEC-RAS, and for his work with the calibration of discharges, and all the good talks and discussions along the way.
- Samuel Vingerhagen from SWECO for the supervision with the HEC-RAS model
- Inrigo Water AS, represented by Cheng Sun and Viggo Bjerkelund, for providing information about their treatment solution.
- Herman Helness and SINTEF for providing information and support during the master thesis period.

Lastly I would like to thank my supervisor, Peggy Zinke, for giving excellent guidance and having faith in me. She has been an important support with encouraging attitude and always some thoughts on how we can make things work out, for which I am very thankful.

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1 Introduction

This chapter is meant to give the reader an introduction to the location of the river Hoffselva, and to give a background for the challenges the municipality of Oslo is facing related to the water quality in the river. The master thesis description is also presented.

1.1 Background

Hoffselva is a river located in a peri-urban catchment in the western part of Oslo, the capitol of Norway. The catchment has a population of 25 000 inhabitants and an area of 1427 ha (14.27 km^2). Oslo has been one of the fastest growing cities in Europe the last decade with a population increase of 25 % since year 2000, an increase of 130 000 inhabitants (Oslo kommune, 2014). According to recent population prospects it is likely to increase with 200 000 towards year 2030, with a total population of ca. 800 000 (Oslo kommune, 2014).

The city faces a great challenge in achieving the requirements of good chemical and ecological state in all the watercourses. The national water regulation (Vannforskriften) has given a target of achieving this within year 2021. In order to achieve this the municipality has had a greater focus on reducing emissions from the sewer system going into the watercourses of Oslo (Oslo kommune, 2014).

Hoffselva is one of the main rivers in Oslo starting in the forested and open lands in the north, west of Tryvannshøgda, and it flows down through the urban areas of Holmen and Skøyen before ending up in the inner part of the Inner Oslofjord at Bestumkilen. The sewer network in the catchment consists of a separate system in the upper part and mainly a combined sewer network in the middle and lower parts of the urban area. Due to low capacity of the pipes in the sewer network, the river is experiencing a rapid frequency of emissions into the river.

The water quality in Hoffselva is poor due to pollution from 24 CSOs discharging spill to the river during rain events. Hoffselva provides recreational services, which are affected by water quality. In particular, there are CSOs upstream of Holmendammen, which is a lake that is used for recreational purposes. The utility owning and operating the system, Oslo VAV, has measured high numbers of bacteria in Holmendammen. Measurements also shows elevated concentrations of Nitrogen and Phosphorus in the middle and lower part of the river, flowing through the area with combined sewer system (Helness, 2014).

The municipality of Oslo's goal for the watercourse is to have a good biodiversity with reproduction of fish where it is natural and that the sewage water should not be an obstacle for bathing water quality in the river and in the fjord (Vannmiljø, 2012). With the increasing urbanization and the effects of climate change, it is less likely to improve the water quality in the coming years, unless some measures will be done to improve the water quality.

Increasing rainfall intensities caused by global climate change and the enlargement of impervious urban surfaces have put heavier loads on existing sewer systems, this is expected to cause severe consequences in the form of flooding and a higher frequency of combined sewer overflow. According to the article from Nie et al. several municipalities in Norway have reported frequent and severe flood damage and CSO activity in the last decade. The paper also refers to similar observations in many other countries (Nie et al., 2009).

The on-going EU-project DESSIN (Demonstrate ecosystem services enabling innovation in the water sector) aims to improve the water quality by using innovative local treatment solutions that enable cost efficient, sustainable mitigation of overloaded sewer systems and thereby increasing the value of eco system services. At Hoffselva, DESSIN will demonstrate local treatment solutions for overflow from CSOs. The aim is to improve the water quality and ecosystem services in the catchment.

1.2 Thesis description

The objective of this master thesis was to contribute to the project by setting up, calibrating and applying a 1D hydrodynamic and water quality model for Hoffselva, and to investigate and discuss the potential influence of improved water quality from CSO spills on selected water quality indicators in Hoffselva.

In order to fulfill these objectives, the master thesis should cover the following tasks:

1. Description of the study area and brief summary of the theoretical background related to the role of CSO-spills in sewage systems, hydrodynamic and water quality modelling
2. Analysis of the length of records and quality of the available data
3. Application of an existing hydrodynamic model of the sewage system (e.g. MIKE URBAN) for the simulation of CSO-spill discharges into Hoffselva for selected storm events
4. GPS-Measurement of representative river profiles (Bathymetry and water levels) in selected reaches
5. Set-up and calibration of a 1D hydrodynamic and water quality model including pre-and post-processing (e.g. HECRAS and QUAL2K)

6. Model-based scenario investigations to assess the effect of CSO-treatment solutions on water quality in Hoffselva (“with / without CSO treatment”)
7. Comparison and discussion of the obtained results with regard to the improvement of water quality in Hoffselva

After consulting with the supervisor, it was decided to use GIS-data to extract the river cross sections instead of measuring a few representative river profiles as it says in task 4.

2 Study area and theoretical background

Chapter 2 describes the theory which forms the foundation of the master thesis. It describes some of the scientific concepts and the theory that is used in the modeling programs.

2.1 Catchment description

This sub-chapter is meant to give a more general introduction to the study site. It covers the climate, land use, and geology of the catchment as well as the future plans for the catchment.

2.1.1 Climate

Norway is situated in the "westerly wind belt" which means the air masses from the Atlantic Ocean affect the climate. Norway has an oceanic climate where the monthly average temperature, along the coast, varies from 10 - 15 ^{o}C. Along the coast in the west, south and east of Norway the average annual temperature is about + 6 ^{o}C, while for the whole country the average annual temperature is + 1.3 ^{o}C (Hanssen-Bauer and Hanssen-Bauer, 2015).

The precipitation conditions in Norway are strongly influenced by the wind conditions. If the wind blows from south-east then it is most rainfall in the south and eastern part of Norway, and less on the western part. And the opposite if the wind blows from south-west leading to less rainfall on the eastern parts around Oslo. The annual average precipitation varies from 300 mm in the inland areas in south-east of Norway to 3500 - 4000 mm in the west coast. The contrasts in annual precipitation is huge from the western part towards east of Norway because of the humid air from the ocean on the west coast (Hanssen-Bauer and Hanssen-Bauer, 2015).

The river Hoffselva is situated in Oslo. Oslo is located in the south-east part of Norway at the inner part of the Oslofjord. The climate is a mix of inland climate and coastal climate. Despite the northern latitude Oslo is experiencing a higher sea-temperature than other coastal cities due to the Gulf Stream.

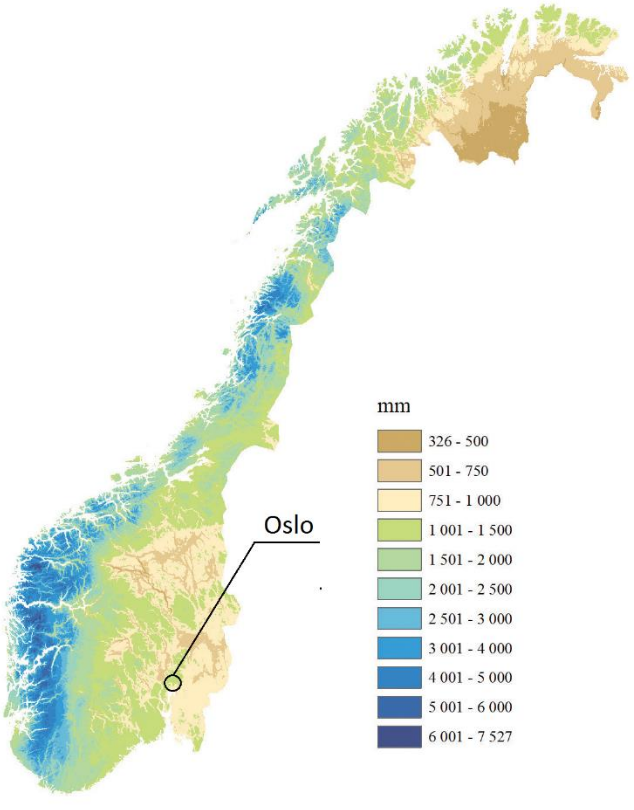


Figure 1: Mean annual precipitation for the reference period 1971-2000

According to NVE (The Norwegian Water Resources and Energy Directorate) Oslo has an annual precipitation of 881 mm and an annual average temperature of + 4.9 ^{o}C.

2.1.2 Land use

The catchment consists of mainly forest, marshes and open ground in the northern upper part of the catchment. The middle and southern part of the catchment consists mainly of urban areas with buildings, infrastructure and dense surfaces. The elevation varies from 528 masl in the northern part of the catchment to 1 masl south by the sea. See also attachment 1.

Table 1: Field parameters for the catchment collected from NVE (The Norwegian Resources and Energy Directorate)

Forest	48.2 %
Urban	37.7 %
Other (open ground, transport systems etc.)	13.1 %
Marshes	0.6 %
Lakes	0.2 %
Farmland	0.2 %

2.1.3 Geology

The last chapter in Norway´s geological development lasted for 11 500 years and is called Holocene. During this time, Norway went from ice age to what it is today. When the inland ice melted away the crust started to regain equilibrium and started to rise. As the ice melted the ocean levels started to rise as well. But the rise of the crust was faster than the rise of the oceans. The rise of the crust is still happening today, in the inner part of the Oslo fjord there has been a 36 cm rise the last hundred years with an annual rise of 2 - 4 mm (Ramberg et al., 2007).

In 10 000 - 9 800 years before now time, the Oslo fjord were a lot deeper and bigger than today. When we look at Figure 2, we can see the light blue areas which were also covered by the Oslo fjord 10 000 years ago. The sea surface stood 220 meters higher than today. The glacial rivers must have been big and transported big amounts of clay. Together with the clay that were washed out from the glacier, the clay has been deposited on the seabed. The marine sediments cover much of the light blue areas today (Andersen, 2000).

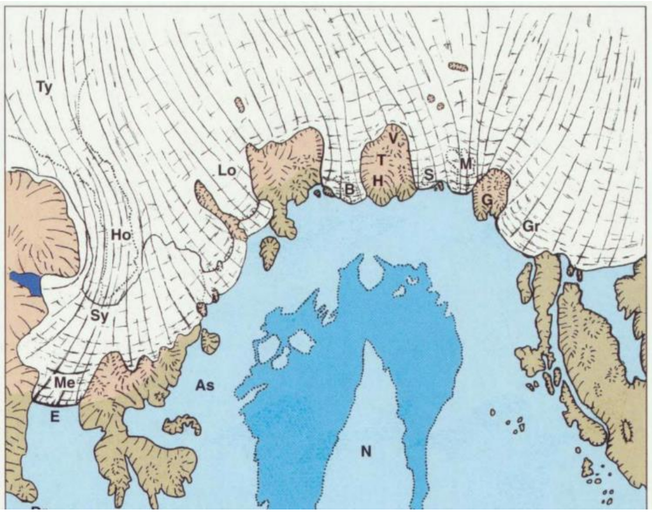


Figure 2: Inner Oslofjord 10 000 -9 800 in the past, "H" is the mark for Holmenkollen. (Andersen, 2000)

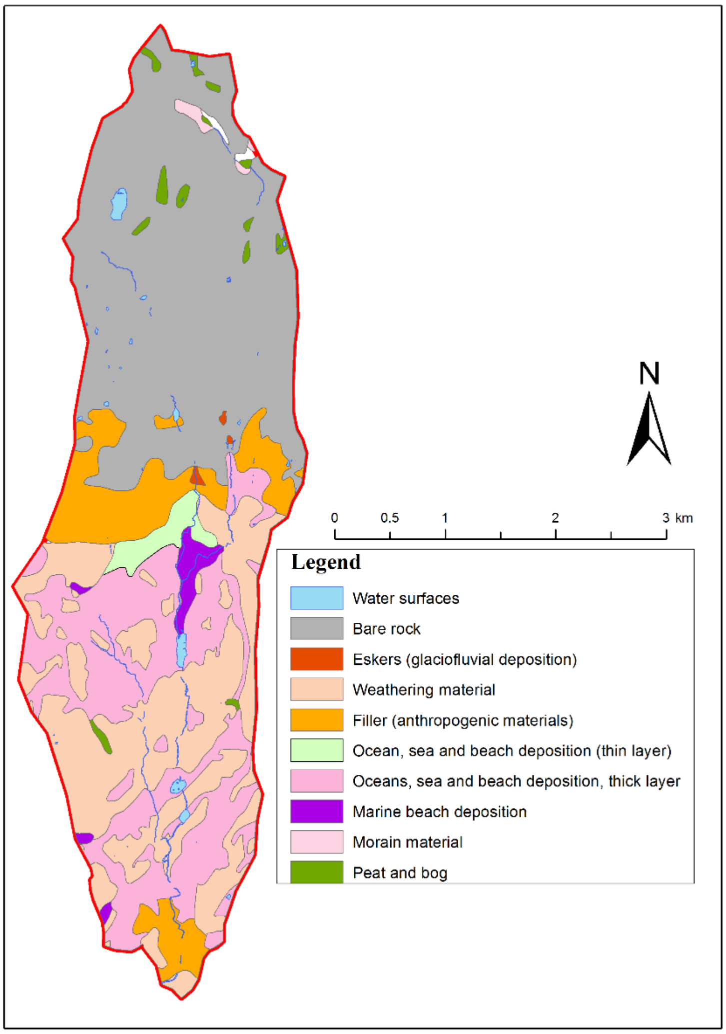


Figure 3: Soil map of Hoffselva generated in ArcMap with WMS (Web Map Service) from NGU (Geological Survey of Norway)

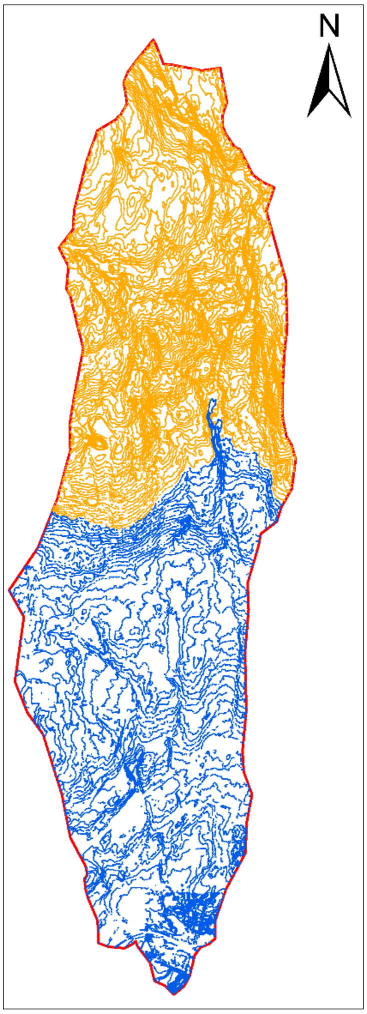


Figure 4:Marine border in ArcMap, Orange: elevation > 222 masl, Blue:

The soil map (Figure 3) shows the different soil types the catchment consists of. Based on the type of soil, and its properties, NGU has made a map of the infiltration capacity. Figure 5 shows the infiltration map where the different soils are rated from unsuitable to well suited for infiltration. The infiltration rates are based on soil species characteristics like soil grain size distribution, permeability, soil depth and terrain conditions.

From the infiltration map we can see that the marine beach deposition is well suited. This is because it has a thickness greater than 0.5 m and the material is rounded off and well sorted. The grain size varies, often sand and gravel are the most common. Weathering material has a less suited capacity for infiltration.
Ocean, sea and beach deposition (thick layer) is unsuitable because of the high amount of finer particles that make the layer compact and sealed. The same goes for bare rock because it is compact. Peat and bog are organic material, which is often regarded as unsuitable for infiltration, because it is already filled with water. Most of the catchment consists of bare rock and clay in form of marine sediments, which has poor infiltration capacity.

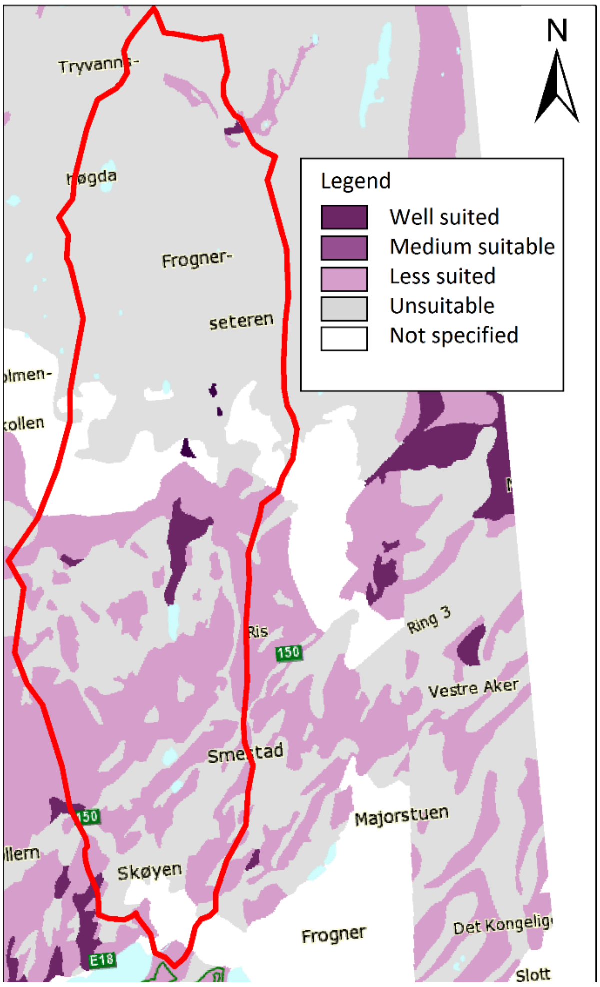


Figure 5: Infiltration map created in ArcMap with infiltration capacity WMS from NGU

Catchments with low hydraulic conductivity, (e.g. clay soils) where less infiltration and more surface flow occur, will have a shorter response time in the catchment than a catchment with high hydraulic conductivity soil. The catchment of Hoffselva is naturally drained by small streams and creeks together with the main river. Due to the geology and morphology, Hoffselva has a short response time in the catchment.

2.1.4 Condition of the river

Information about the condition of the Hoffselva river have been gathered from an information portal named Vann-Nett. Vann-Nett is owned by the environmental authorities and the Norwegian Resources and Energy Directorate (NVE). As mentioned earlier, it has been an environmental target that all water bodies should have good ecological and chemical state by 2021. According to Vann-Nett, the lower parts of Hoffselva have a high risk that the environmental target is not met within 2021. Figure 6 shows the risk assessment for not reaching the target on the left, the chemical state of the river in the middle and the ecological state of the river on the right hand side. Red color indicates “very bad” condition, yellow indicates “moderate” condition, and green indicates “good” condition. What is meant by good and bad conditions are explained in chapter 2.3.3.

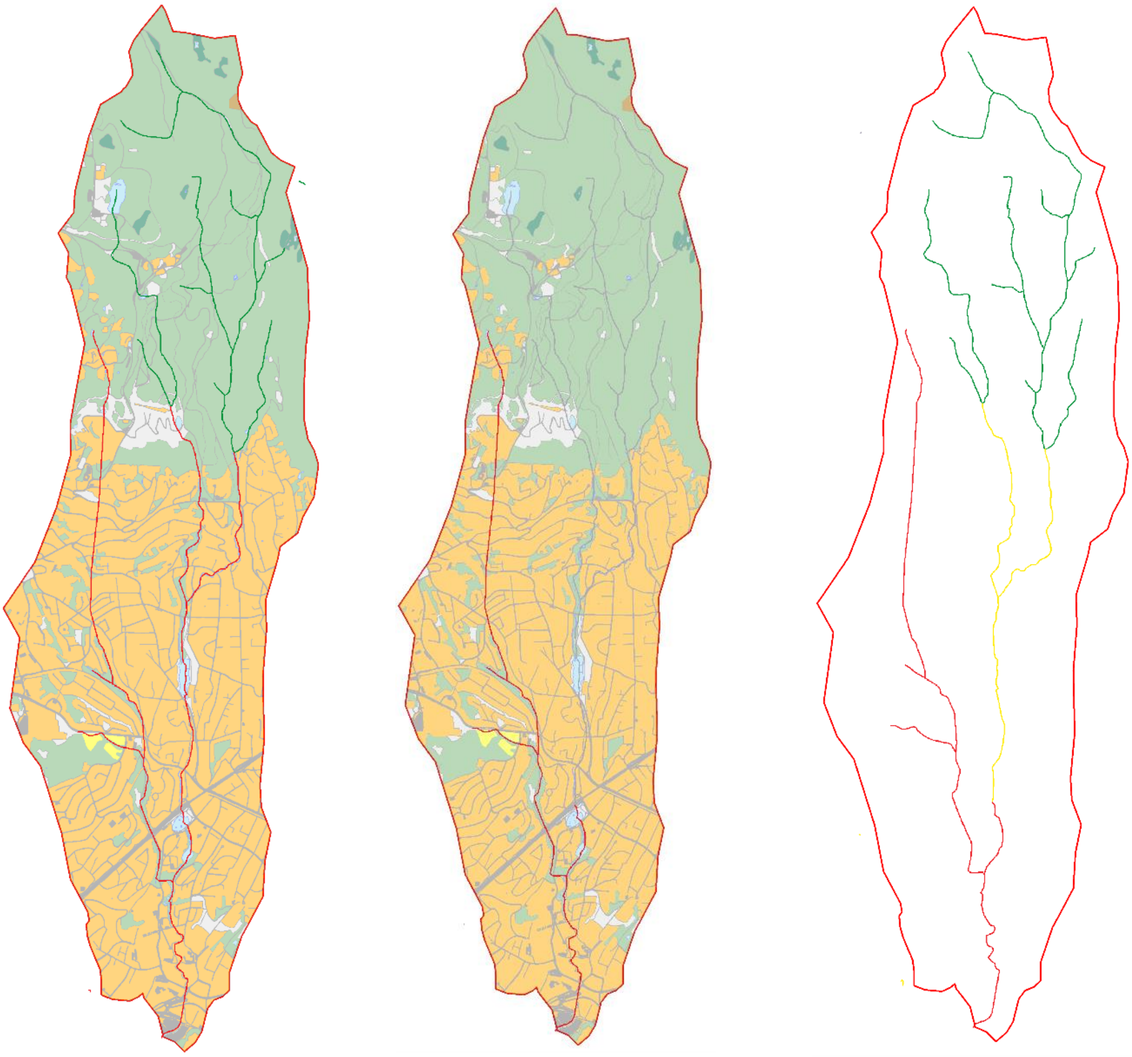
In Vann-Nett the watercourses are given a code of 7 signs which are presented in the order: water category – ecoregion – climate region – size – Calcium – humus – turbidity. The code for the river conditions in Hoffselva are given in table below:

Table 2: Condition of Hoffselva according to Vann-Nett (Vann-Nett, 2016)

Parameter	**Code**	**Hoffselva upstream Smestaddammen**
Water category	R	River
Ecoregion	E	Østlandet
Climate Zone	L	Low lands (< 200 masl)
Size of catch.	1	Small (<10 km2)
Calcium	4	Rich on Calcium (Ca > 20 mg/l, Alk > 1 mekv/l)
Humus	1	Clear: color 10-30 mg Pt/L, TOC 2-5.5 mg/L
Turbidity	1	Clear: SS< 10 mg/L (at least 80% inorganic)

Parameter	**Code**	**Lower part of Hoffselva included Makrellbekken**
Water category	R	River
Ecoregion	E	Østlandet
Climate Zone	L	Low lands (< 200 masl)
Size of catch.	2	Medium (10-100 km2)
Calcium	4	Rich on Calcium (Ca > 20 mg/l, Alk > 1 mekv/l)
Humus	1	Clear: color 10-30 mg Pt/L, TOC 2-5.5 mg/L
Turbidity	1	Clear: SS< 10 mg/L (at least 80% inorganic)

The turbidity classification is divided into 1 = Clear, 2 = Influence by glaciers, and 3 = influenced by clay. As we can see from the geology map in Figure 3, Hoffselva is partly located in marine sediments. However, Hoffselva does not have the characteristics of a clay influenced river. Instead it is classified as “Clear”.



a) *b)* *c)*

Figure 6: a) Risk assessment b) Chemicals state c) Ecological state

2.1.5 Future catchment

Oslo is a city with constant development so the catchment characteristic will change over time. The plan and building agency (Plan- og bygningsetaten) has made a strategic map for land use towards year 2030. In this map the lower part of the catchment is marked as development area in the outer city (see the yellow areas in Figure 7). This means it is an area for city development and with a high rate of area utilization**.** It is suggested to have a high rate of area utilization, high urban/ architectural quality, varied land use, integration of major existing place qualities and a satisfactory shielding against air and noise pollution. For the catchment, this applies to Smestad and Skøyen (Kommuneplan, 2015).

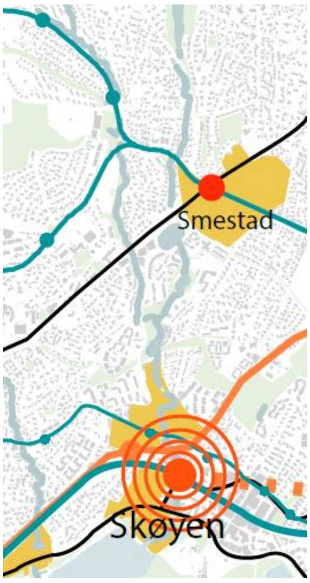


Figure 7: Strategic map for land use, 2030 (Kommuneplan, 2015)

2.1.6 Future climate change

«Klima i Norge 2100» is a report made by 37 scientists to give an updated scientific basis for the climate adaption in Norway. The authors are from 7 institutions in Norway: Institute of marine research, Norwegian Meteorological Institute, Nansen Environmental and Remote Sensing Center, The Norwegian Water Resources and Energy Directorate, Uni Research, University of Bergen and The Norwegian Mapping Authority (Hanssen-Bauer and Hanssen-Bauer, 2015).

The report presents several findings about the Norwegian climate towards year 2100. The mean annual precipitation has increased all over Norway since year 1900, a total increase of ca. 18 % when all of Norway is accounted. For short rain events there has been an increase in both intensity and frequency the last years. To be able to predict the future climate the scientists have used global climate models with three emission scenarios called RCP (Representative Concentration Pathways). "RCP8.5" is the scenario where the emissions continue to increase until the end of this century. "RCP4.5" is the scenario with small emission changes up to year 2050 and then include emission reductions towards 2100. "RCP2.6" implies drastic emission cuts already from year 2020 (Hanssen-Bauer and Hanssen-Bauer, 2015).

Table 3 was made to summarize the results from the report that focus on "Østlandet" the geographical region of the south-eastern part of Norway where Oslo is located. It shows the changes from the reference period 1971-2000 and 2031-2060 for the RCP8.5 and RCP4.5

scenarios. The values are calculated from the 10 Euro-CORDEX climate predictions." Heavy rainfall" is here defined as days with precipitation amounts in the period 1971-2000 that were exceeded in 0.5 % of the days. A value of 100% indicates a doubling in number of days (Hanssen-Bauer and Hanssen-Bauer, 2015).

Table 3: Summarized findings from the report for the county "Østfold"

Change in:	Season	RCP 8.5 Predicted change (median value)	RCP 4.5 Predicted change (median value)
Temperature (°C)	Whole year (annual)	2.1	1.6
Total rainfall (%)	Whole year (annual)	7	6
Number of days with heavy rainfall (%)	Whole year (annual)	40	26
Rainfall intensity on days with heavy rainfall (%)	Whole year (annual)	10	6
Total runoff (%)	Whole year (annual)	1	2

As we can see from the table, temperature and rainfall will increase in both scenarios. As expected the biggest changes is shown for the scenario with increasing emissions (RCP 8.5). To dimension for future climate development a climate factor is used. The climate factor is multiplied with the current dimensioning precipitation values in order to account for the future climate change. In the report "Klima i 2100" they have made an estimation for the climate factor where the climate factor depends on return period, duration, location, reference period, scenario-period and climate model. Table 4 shows the climate factor for change in 3 hours and 1 day duration of precipitation from 1976-2005 to 2071-2100 for the two scenarios RCP4.5 and RCP 8.5. Oslo municipality has set this climate factor to 1.5 in their new municipality plan as a measure (Hanssen-Bauer and Hanssen-Bauer, 2015).

Table 4: Climate factors. The values are mean values for Norway and is based on change in rainfall that is exceeded in 0.5% of the days (q99.5), and values with return period of 5 years (M5) and 200 years (M200)

	RCP 4.5		RCP 8.5	
Method	3 hours	1 day	3 hours	1 day
Q99.5	1.11	1.11	1.20	1.20
M5	1.16	1.13	1.28	1.22

M200	1.19	1.14	1.38	1.26

The findings from the report should be considered with caution, because they are only estimates trying to predict the future. It is not possible to know which scenario that will be most realistic in the future. The results in the report have a “low”, “median” and “high” value in order to deal with some of the uncertainty in the models. In this thesis the “median” values have been used to give an idea of how the climate will change in the future. It is advised to read the full report to fully understand the theory and uncertainty behind the results presented.

2.2 Piped systems

Urban drainage systems handle two types of flow: wastewater and stormwater. Piped systems consists of drains carrying flow from individual properties or larger areas. The word sewage refers to the whole infrastructure system: pipes, manholes, structures, pumping stations etc. There are basically two types of conventional sewerage system: a combined system in which wastewater and stormwater flow together in the same pipe, and a separate system in which wastewater and stormwater flow in separate pipes (David Butnd John, 2010).

Some places there are a mix of separate and combined sewerage system. This tend to happen when the municipalities upgrade from the old combined system version to the modern version with separate system. This may lead to places where we get an “ineffective separate system”, which means the separation is ineffective because the separated flows are reunited downstream of the system with the combined system. This is also the case of some places in the Hoffselva catchment.

2.2.1 Separate system

In the separate system the wastewater goes to the wastewater treatment plant (WTP) and the stormwater flow in pipes to the closest river or watercourse. The stormwater runoff from streets, roads and other paved areas is normally lead through a gully. Gullies consists of an underlying sump to collect heavy material in the flow like sand and gravel that can settle in the stormwater pipes. The big advantage of the separate system is that the flow to the treatment plant is reduced and it reduces the frequency of CSOs. One of the disadvantages is related to misunderstandings during the building process, where wastewater pipes are coupled to the stormwater pipes by mistake (Ødegaard et al., 2012).

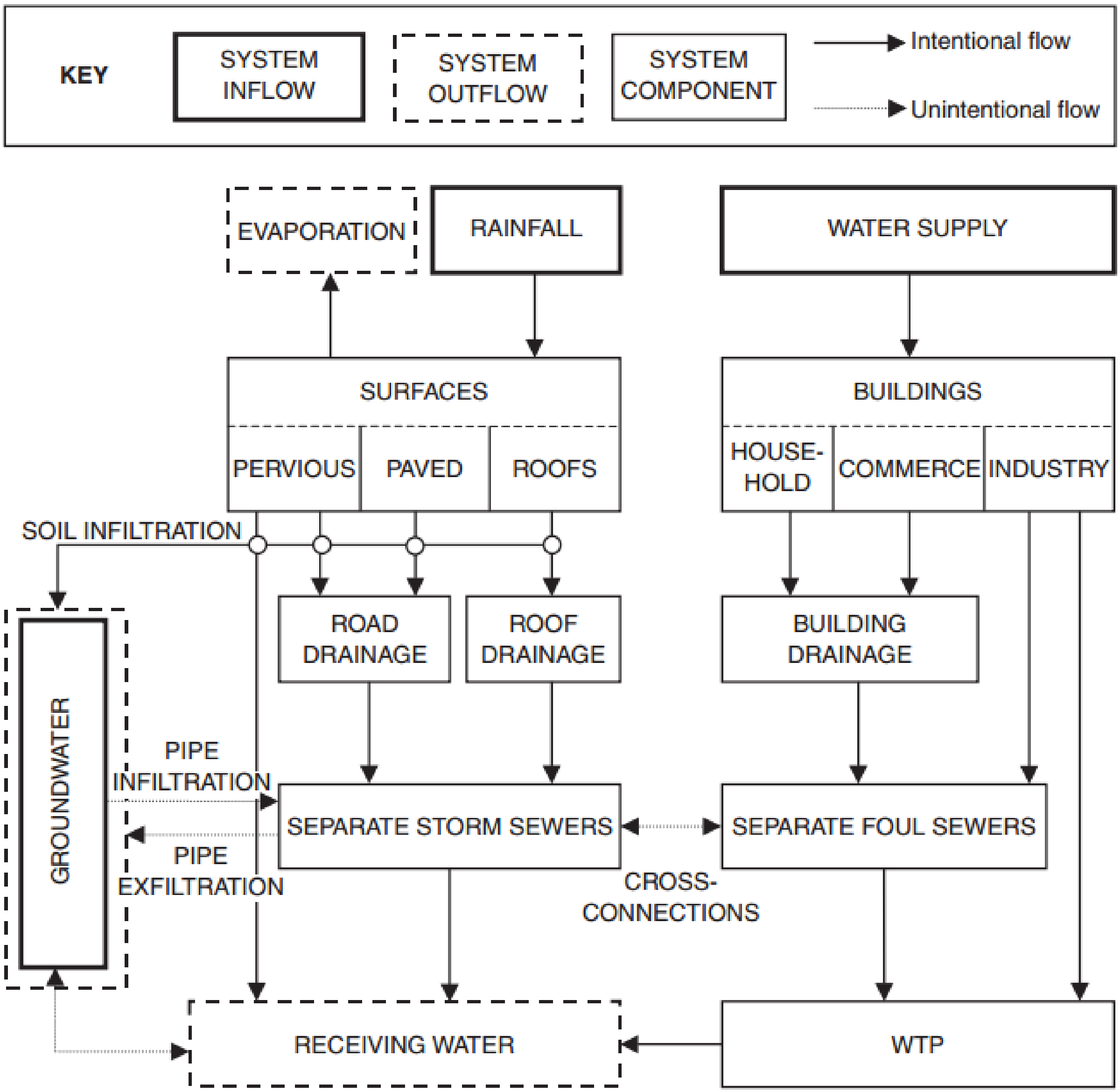


Figure 8: Urban water system: separate sewerage, (David Butnd John, 2010)

2.2.2 Combined system

In the combined system both wastewater and stormwater flow together in the same pipe. In dry weather periods all of the sewage water is sent to, and treated at the treatment plant. In a combined system, the stormwater flow will usually predominate the total flow. When rainfall events occur, the stormwater could be 50 or 100 times the average wastewater flow. From an economical view, it is not feasible to provide the capacity needed for the combined system network during heavy rainfall events. At the treatment plant, it would also be unfeasible to provide the capacity at the treatment process. The solution for combined systems are the CSOs that divert flows when the capacity of the combined system is reached. When the CSO becomes active, a portion of the flow is diverted to the closest natural waterbody to relive the loads on the combined sewage network (David Butnd John, 2010).

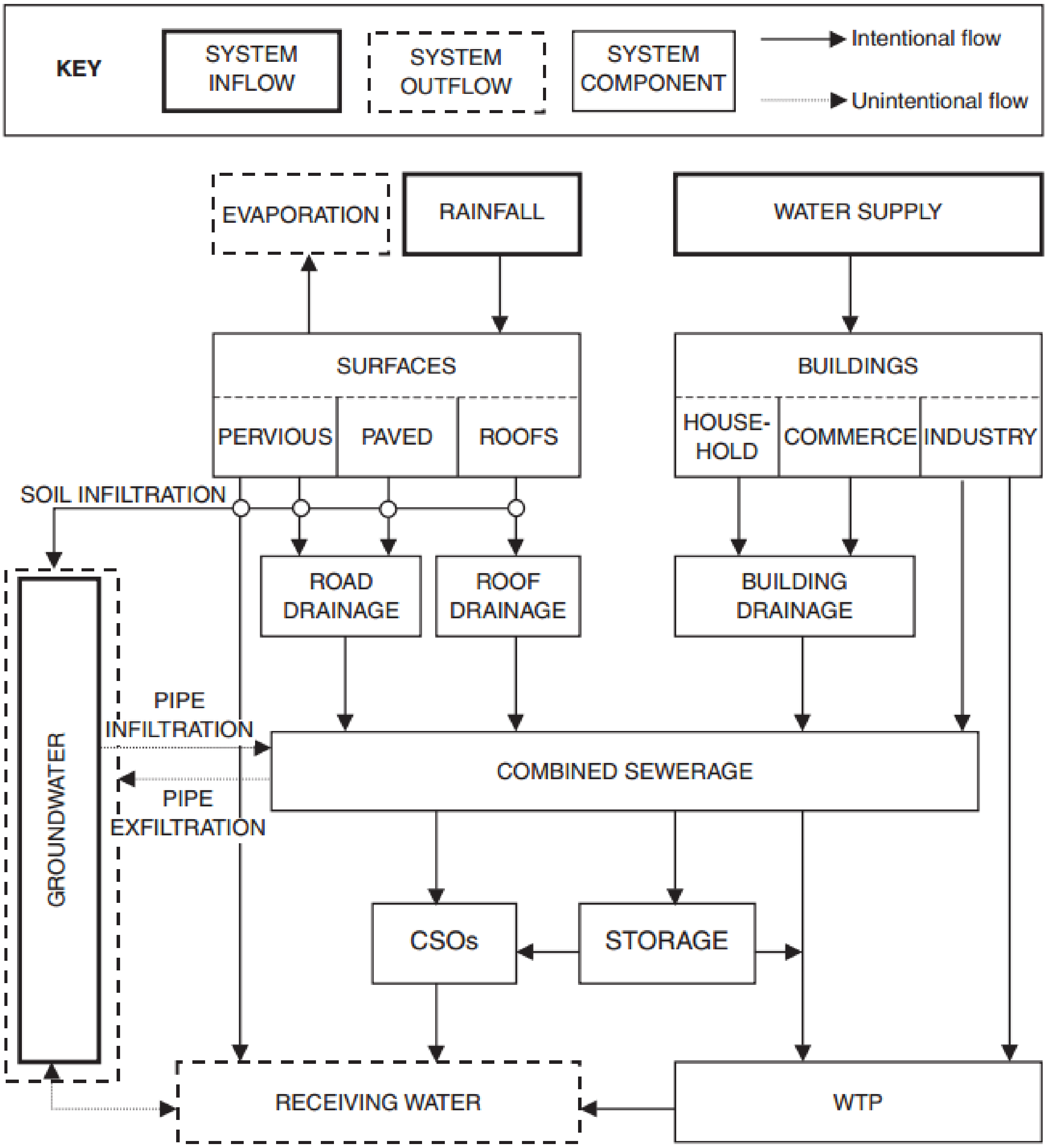


Figure 9: Urban water system: combined sewerage (David Butnd John, 2010)

2.2.3 CSO

During medium or heavy rainfall, the combined sewer overflow diverts flows above a certain level out of the sewer system and into a natural watercourse. The CSO receives an inflow which consists of stormwater mixed with wastewater. The continuation flow is the flow that is retained in the sewer system and continues to the water treatment plant. The amount of continuation flow is an important characteristic of the CSO, and is referred to as the “setting”. The spill flow is remaining flow that is overflowed to the watercourse.

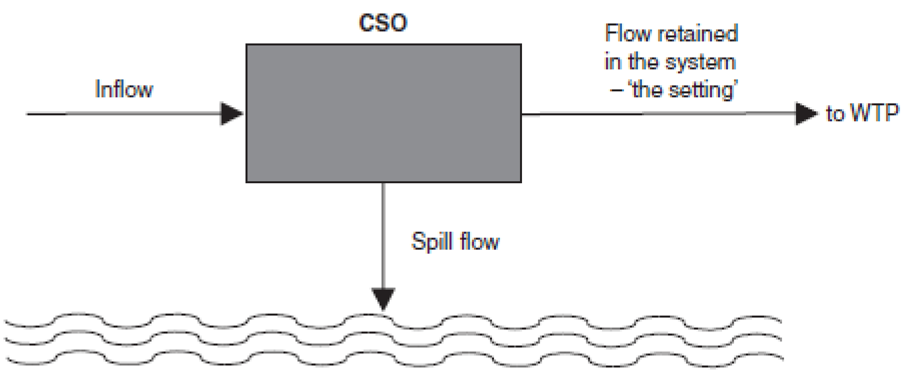


Figure 10: CSO inflow and outflow (David Butnd John, 2010)

The CSOs are also designed with the purpose to retain as many solids as possible in the sewer system. However, during greater rain events, the stormwater can be highly polluted, especially early in the storm when the increased flows have a "flushing" effect in the sewers. The first flush effect is described in chapter 2.3.3.

Combined sewer overflows exist in different sizes and versions. The most modern CSOs are high side weir overflows with screens. The screens purpose is to prevent solids from entering the overflow pipe. An overflow with high weirs, scum boards and a stilling zone upstream, can provide good retention of both floating and sinking solids. The average construction year for the CSOs in Hoffselva is 1950. Therefore, it most likely not top modern design of the CSO's. Some of them are emergency weirs for pump stations and others are normal stormwater CSO's with rectangular shape. To illustrate the theory concepts of CSO's, a basic design of a high side weir overflow without screens is shown, see Figure 11 (David Butnd John, 2010).

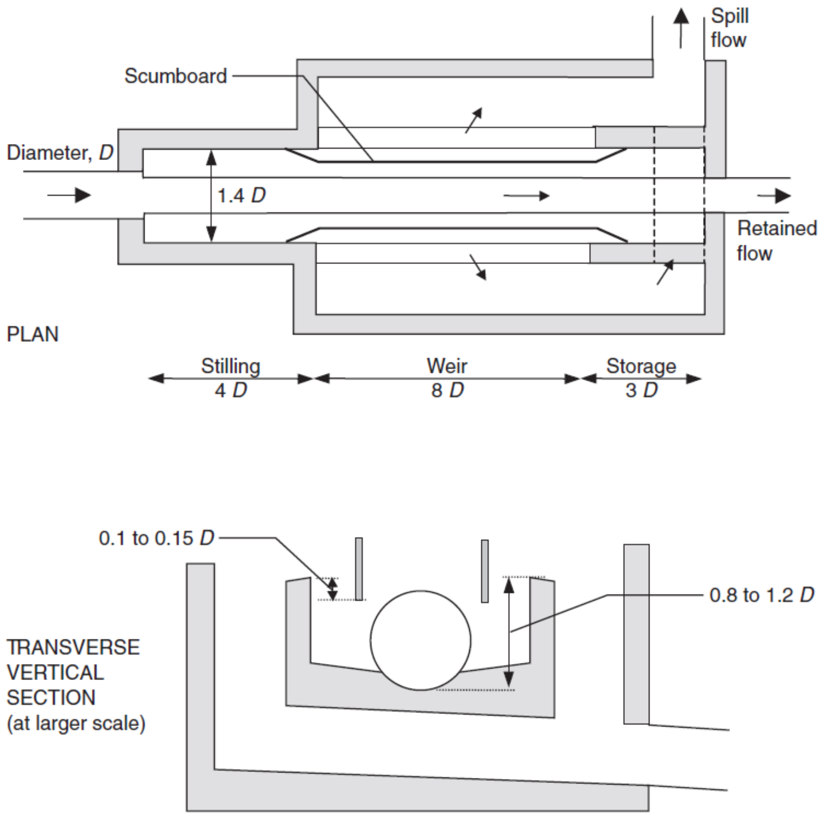


Figure 11: High side weir CSO, general dimensions (David Butnd John, 2010)

The municipality of Oslo has evaluated different measures in order to reduce the overflow events. Some of the measures are to rise the height of the weir, build attenuation volumes, separation of combined systems and to upgrade the dimensions of the pipes.

2.2.4 Origin of CSO water

The inflow to a combined sewer system consists of both wastewater and stormwater. Wastewater is the main liquid waste of the community and it can contain high levels of potentially disease-forming micro-organisms, oxygen consuming organic material and other pollutants. Figure 12 shows the sources of wastewater.

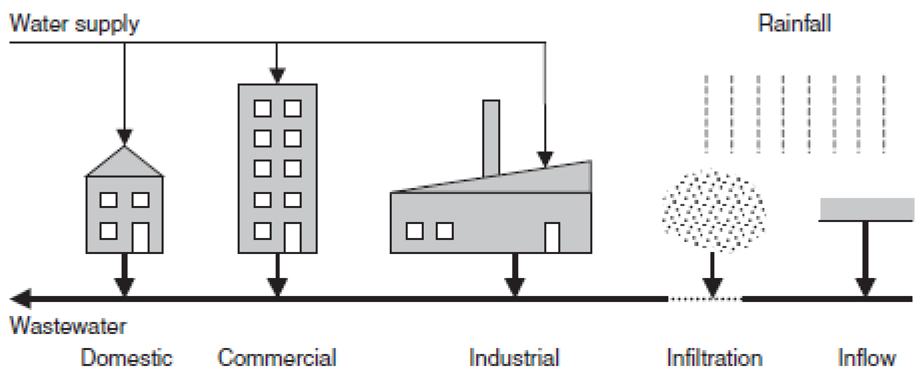


Figure 12: Sources of wastewater (David Butnd John, 2010)

The domestic wastewater is primarily generated from residential properties, but also includes contributions from institutions like schools and hospitals. Commercial wastewater includes business as shops, offices, restaurants, laundries, public houses and hotels. The component of wastewater generated by industrial processes can be important in specific situations, but it is difficult to characterize in general. Infiltration and inflow are defined as water that enters the sewer system through indirect and direct means respectively. Infiltration is groundwater or water from leaking pipes that enters the sewer system through cracks, pipe joints, couplings and manholes. Inflow is the stormwater that enters the system from illegal or misconnected yard gullies, roof downpipes or through manhole covers (David Butnd John, 2010).

The stormwater (surface runoff) is the second major flow in the combined sewer system. Stormwater is generated by rainfall and consists of that proportion of rainfall that runs off from urban surfaces. The quality of the stormwater is related to nature and characteristics of both the rainfall and the catchment. As said earlier when rainfall events occur, the stormwater could be 50 or 100 times the average wastewater flow. This means that the spill flow from the CSOs will seem to be a highly diluted mixture of stormwater and wastewater (David Butnd John, 2010).

2.3 Water quality

Water quality is strongly influenced by chemical and biological reactions that occur as water moves over and through the lands surface toward streams (Dingman, 2008).
The term "Water quality" relates to all the constituents of water, including both dissolved and any other substances carried by the water. The strength of polluted water containing a constituent of mass *M* in water volume of *V* is its *concentration* given by c = M/V, usually expressed in mg/L (David Butnd John, 2010).

2.3.1 Chemical and biological parameters

Solids

In general, solids can be categorized in four types of solids: gross, grit, suspended and dissolved. Gross solids are usually defined as solids captured by a 6 mm mesh screen i.e. solids > 6 mm. Gross solids in wastewater include faecal stools, toilet paper, condoms, etc. Gross solids in stormwater may be bricks, wood, cans, paper, etc. The particular concern about gross solids are the aesthetic impact when they are discharged to an open watercourse. Grit solids may be defined as solids > 150 μm and forms the bulk of what later becomes sewer sediment. Suspended solids (SS) is the solid matter (both organic and inorganic) maintained in suspension. Mesh screens with 0.45 μm openings retain the SS. Solids below 0.45 μm are defined as dissolved solids. Volatile solids are the volatilized fraction from a SS test where the retained solids can be ignited at 550 °C in a muffle furnace. The volatile solids give an indication of the organic content of the suspended solids (David Butnd John, 2010).

Organic compounds

Organic compound is a term used for liquid or solid chemical compounds that has molecules which includes carbon. Organic compounds are usually categorized after how easily biodegradable they are. Examples of oxygen consuming organic compounds: carbohydrates, proteins and fats. These are easily biodegradable and microorganisms consumes dissolved oxygen from the water during the decomposition. The consumption of dissolved oxygen may lead to oxygen depletion, resulting in an anaerobic environment (Ødegaard et al., 2012).

Nitrogen

Nitrogen exist in four main forms: organic, ammonia, nitrite and nitrate. Total Nitrogen is the sum of all the four forms. Organic and ammonia nitrogen make up most of the total in wastewater and stormwater. Organic nitrogen includes materials as proteins that makes up much matter, and ammonia nitrogen comes from ammonia salts. High levels of nitrogen discharged to receiving waters can promote growth of algae and floating macrophytes and even lead to eutrophication symptoms such as water discolor, odors and depressed oxygen levels (David Butnd John, 2010).

Phosphorus

Phosphorus exist in two forms: organic or as inorganic (ortho- and poly-) phosphorus. Total Phosphorus is the sum of the two forms. In comparison, orthophosphates are the dominant amount of the total Phosphorus. Polyphosphates consist of combinations of phosphorus, oxygen and hydrogen atoms. Orthophosphates are simpler compounds and may be in solution attached to particles. Phosphorus-containing compounds also contribute to eutrophication (David Butnd John, 2010).

Sulphur

Sulphurous compounds are found in wastewater in the form of organic compounds and sulphates (SO_4^{2-}). In combination with biofilms, inside the sewer pipes, hydrogen sulphide (H_2S) may be formed. Hydrogen sulphide is a flammable and very poisonous gas which is acutely toxic to aquatic organisms and could be a factor in fish kills near CSOs. Hydrogen sulphide in damp condition can be oxidized to sulphuric acid (H_2SO_4) which can cause damage to the sewer materials (David Butnd John, 2010).

FOG

FOG is a general term for fats, oils, greases and waxes present in wastewater. They are very stable compounds and do not easily biodegrade naturally. Neither do they fully mix with water, and accumulate and float on water surfaces. Fats in sewer systems can cause blockages and when discharged to the environment they cause films and sheets on the water surface, preventing oxygen transfer (David Butnd John, 2010).

Heavy metals

Heavy metals can be found in wastewater and stormwater. Metals can exist in particulate, colloidal and dissolved phases. Metals in stormwater are mostly found in the particulate phase. Environmental mobility and bioavailability (and thus toxicity) is highly related to their concentration in solution. Many heavy metals are known to have toxic effects on aquatic life. (David Butnd John, 2010). Heavy metals have large affinity to particles and are therefore often found in the particulate phase. Toxic heavy metals such as Pb, Co, Cd cannot be biodegraded, but they can be accumulated in living organisms. This accumulation in living organisms can lead to various diseases and disorders even in relatively lower concentrations (Tangahu et al., 2011).

Micro-organisms

Bacterial indicator organisms such as total coliforms, faecal coliforms (*E.coli.)*, and faecal streptococci (FS), are known to occur in large numbers in both wastewater and stormwater. Pathogenic micro-organisms (e.g. salmonella, enteroviruses) can be a threat to human health and may also exist in wastewater and stormwater. Discharges from CSOs are not disinfected, and bacterial standards for recreational activity can be violated during storm events (David Butnd John, 2010).

COD

Chemical oxygen demand (COD) test measures the oxygen equivalent of the organic matter that can be oxidized by a strong chemical oxidizing agent in an acidic medium. Almost all organic compounds are oxidized. Thus, this measurement is a good estimation of the total content of organic matter (David Butnd John, 2010).

2.3.2 Chemical composition of CSO water

As mentioned earlier, the inflow to the CSO is a mix of both stormwater and wastewater and the concentration of wastewater will vary with the intensity of the rain. Wastewater contains a complex mixture of natural organic and inorganic material present in various forms. (David Butnd John, 2010). Pollutants in stormwater include solids, oxygen-consuming materials, nutrients, hydrocarbons, heavy metals and trace organics, and bacteria. (David Butnd John, 2010). The quality of stormwater is even more variable from place to place and from time to time than wastewater. As with wastewater, care should be taken in interpreting “standard” or “typical” values. Typical values and ranges of pollutant discharges from stormwater systems and wastewater systems in the UK are adapted from the book Urban Drainage (David Butnd John, 2010) and given in attachment 4.

A study from 2013, aimed to explore the relationship between rainfall and water quality characteristics of combined sewer overflows (Sandoval et al., 2013). The study showed that CSO water quantity characteristics are mainly influenced by the maximal rainfall intensities, and that the CSO pollutant concentrations were found to be mostly associated with duration of the rainfall. The pollutant loads seemed to be influenced by dry weather duration before the rainfall event.

This makes sense, because thus bigger rain event in intensity and volume, thus higher quantity of CSO water due to incapacity in the sewer system. It is also typical to see a higher concentration of pollutant in after a dry weather period. This is discussed a bit later as the “first flush” effect. The study mentioned above is based on 22 online monitored rainfalls and CSO events in Berlin. The results showed a great variation in chemical composition of the CSO water, depending on the rain event.

CSO discharges contain various pollutants which originates from wastewater as well as from surface runoff. The average proportion of wastewater in the CSO-study from Berlin was 11%

and the average contribution of wastewater to total CSO load was 16%. This means that about 84% of the COD carried in the CSO originates from two other major sources: wash off by stormwater runoff and resuspension of sewer sediments (Sandoval et al., 2013).

The WFD presents a list of 45 substances or groups of substances to be identified as action priorities at the community level. Among these priority pollutants (PP), certain have been identifies as “priority hazardous substances” because they are very toxic or not degradable. Due to lack of available information on priority pollutants levels in wastewater during dry and wet weather periods within combined sewers, a study was conducted by (Gasperi et al., 2008). The study is from the Paris combined sewer in France, and may be representative of sewerage systems found in many other capitals cities in Europe, and therefore capable of accurately describing a range of PPs within typical combined sewers in urban areas.

66 elements were measured, a total of 7 metals (Cd, Cr, Cu, Hg, Ni, Pb and Zn) and 59 organic compounds. 33 of the PPs were observed in raw sewage, and 40 PPs were observed in wet weather emissions. Most of the metals were present in all samples, reflecting their versatile presence in nature. A higher number of substances were detected in wet weather flow samples. Runoff via atmospheric inputs and/or urban surface flush induced a wider range of PPs and lead to higher wet weather flow concentrations of certain metals, PAHs, pesticides, and organic compounds (Gasperi et al., 2008).

2.3.3 Impact of CSO spills on the receiving water in Hoffselva

All receiving waters can manage wastes to some extent, depending on their natural self-purification capacity. The water quality problems arise when pollutant loads exceed this capacity, then it will harm the aquatic ecology and restrict the potential use of the water. The impacts can be divided into direct water quality effects, public health issues and aesthetic influences (David Butnd John, 2010).

Direct water quality effects impacts: eutrophication and toxics. Eutrophication can lead to oxygen depletion, anaerobic conditions in bottom muds, fish kills and aesthetic problems. Toxics can lead to acute or chronic impacts, which leads to rapidly reduce species diversity and abundance.

Public health impacts: pathogens (bacteria, viruses) may lead to suffering and illness for the public.

Aesthetic impacts: the public view of water is also important. These impacts regard the visual impression of the waterbody.

Early in the storm flows it is usual to have a so-called “first flush” effect. The first flush may contain high pollutant loads because of washing off the pollutants accumulated on the surface. A first flush can be identified on hydrographs as a sharp increase in pollutant concentration near the start of the storm. In Figure 13 we can see the first flush effect from a rain event at Hoffselva in 28. November 2015. The data are from measurements done in relation with the DESSIN project. The location of the measurements are showed in Figure 27. The discharge at the measurement station is shown in blue as m^3/s and the turbidity as a pollutant measure in black as NTU (Nephelometric Turbidity Units). A nephelometer is an instrument that measures the turbidity as concentration of suspended particles. As we can see, it is a sharp increase in turbidity near the start of the storm.

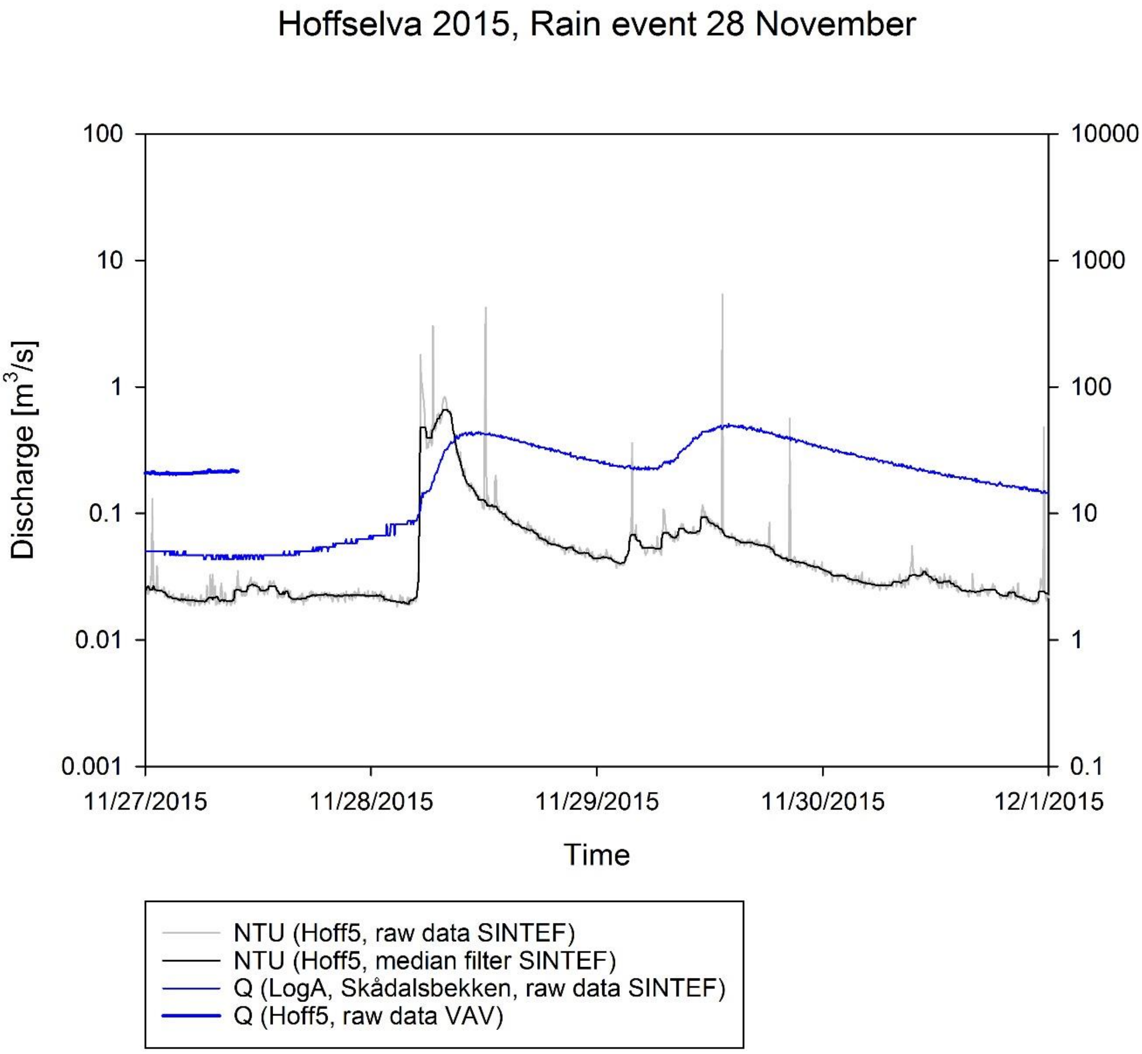


Figure 13: First flush effect illustrated by data from DESSIN project (Oslo VAV and SINTEF)

Classification of ecological and chemical state

In 2000, the EU Water Framework Directive was launched and it put clear and precise definitions of what is good water management. Norway has joined the directive through the EEA agreement, and adopted an own Norwegian water regulation (Lovdata, 2006). The aim is a comprehensive water management and that all water bodies should have good ecological and chemical state by 2021. Together the environmental state of the water is decided upon the chemical and ecological state.

Chemical state

The chemical state is determined based on the occurrence of 45 prioritized pollutants. The prioritized pollutants are toxic and often of low degradability in the water. The chemical state is determined from limits for the prioritized pollutants, called Environmental Quality Standards (EQS). The chemical status can be "Good" or "Bad". To achieve "good" chemical status, the pollutants must not exceed the EQS limits. The EQS values corresponds to the border between "good" and "bad" chemical status. Threshold values can be found in attachment VIII in the National Water Regulation (Lovdata, 2006).

In the water quality simulation later on in this thesis, it was chosen to base the chemical state on the concentrations of Lead (Pb) and Nickel (Ni). In Table 5 below, the threshold values are given for these parameters.

Table 5: EQS for prioritized pollutants in freshwater (Lovdata, 2006)

Prioritized pollutants simulated	Average annual threshold value	Maximum allowed threshold value
Pb	1.2 µg/L	14 µg/L
Ni	4 µg/L	34 µg/L

Ecological state

In fresh water, parameters such as algae, fish, phosphorus, temperature and among others, make up the ecological state of the water. The main principle is that the ecological state should be classified based on biological quality parameters, while the physical and chemical conditions should be used as support parameters. It is the worst of the parameters that decide the ecological state, which means all of the parameters needs to be improve in order to improve the ecological state. The WFD ecological status classification for surface water includes five categories: very good, good, moderate, bad and very bad. “Very good” means it has reached its natural state. Ecological quality ratio (EQR) is used to classify the ecological state. It ranges from 0 to 1.0. The EQR is a measure of deviation between observed values and known values of natural state for the specific water type. EQR = observed values / reference values. An EQR value of 1.0 is the best and equals the natural state of the river. Each ecological quality element is evaluated and given a score, e.g. fish, water plants and algae. The ecological quality parameter that has the lowest EQR score determines the ecological state of the water (Vannportalen, 2013).

In this thesis the ecological state is classified with the chemical parameters of Total Nitrogen and Total Phosphorus in lack of biological quality parameters. Total Nitrogen is an essential nutrient for plants and animal, but in excess amounts of total Nitrogen may lead to low levels of dissolved oxygen. Total Phosphorus is an important nutrient for plant growth. The more phosphorus available, the more plants and algae there are in the lake. High levels of total Nitrogen and total Phosphorus lead to low levels of oxygen, which will have a negative effect on various plant life and organisms in the water. Therefore, concentrations of total Nitrogen and total Phosphorus are often used as indicator parameters for ecological stat in the water. When it comes to total Phosphorus and total Nitrogen, the limits for the river Hoffselva are:

Table 6: Ecological threshold values for Hoffselva (river type 9) (Vannportalen, 2013)

Parameter (mg/L)	Reference Value	Very good	Good	Moderate	Bad	Very bad
Total P	0.009	0.001-0.015	0.015-0.025	0.025-0.038	0.038-0.065	>0.065
EQR	1.0	0.60	0.36	0.24	0.14	

Parameter (mg/L)	Reference Value	Very good	Good	Moderate	Bad	Very bad
Total N	0.275	0.001-0.425	0.425-0.675	0.675-0.950	0.950-1.425	>1.425
EQR	1.0	0.65	0.41	0.29	0.19	

The classification for each parameter should be done based on annual values or season values based on mean, median or a specified percentile value of several observations in time. If possible, a 3-years period of data should be used for averaging the differences caused by natural variations between years (Vannportalen, 2013).

In 2012, only one of the main watercourses in Oslo satisfied the EU-classification “good” environmental state. In Hoffselva, 2012, the total Phosphorus = 0.066 mg/L → very bad and total Nitrogen = 1.311 mg/L → bad (Vannmiljø, 2012).

Bathing water quality

It is almost impossible to monitor the water content of all the different pathogens that exist. Instead, we analyze microbes that are commonly occurring in the faeces of humans and animals. To prove faecal contamination, some indicator bacteria have been chosen. Escherichia coli (E. coli) is an indicator of the content of fresh faeces in the water. It goes under the parameter “thermostable coliforms” (TBK in Norwegian) and they do not survive very long in the water. Intestinal enterococci is another type of faecal bacteria. They are more resistant to water, and thereby stay alive longer than the coliform bacteria (Folkehelseinstituttet, 2016).

In EU, the Bathing Water Directive regulates the bacteriological water quality of coastal and inland bathing waters based on two faecal indicator parameters: Intestinal Enterococci (IE) and Escherichia Coli (EC) (David Butnd John, 2010).

Table 7: For inland waters. All values are based on 95-percentile evaluation except from "sufficient”, which is based on 90-percentile. (Union, 2006)

Parameter	*Excellent*	*Good*	*Sufficient*	*Poor*
IE (cfu/100 ml)	≤ 200	≤ 400	≤ 330	> 330
EC (cfu/100 ml)	≤ 500	≤ 1000	≤ 900	> 900

In Norway EC < 100 is defined as “good”, 100 < EC< 1000 is defined as “less good” and EC > 1000 is defined as “not acceptable”. Bacteria measurements were conducted at the inlet to Holmendammen in 2012. The water quality varied, but none of the test results showed extreme high bacteria values. The colors in Table 8 refer to the Norwegian definitions.

Table 8: Bacterial measurements for Holmendammen 2012 (Vannmiljø, 2012)

Date	Holmendammen (TKB/100 ml)	Rain last 24 hours [mm]
15.05.2012	800	0
30.05.2012	1000	0
13.06.2012	300	0
27.06.2012	400	0.6

11.07.2012	3700	35.4
01.08.2012	2100	0.9
08.08.2012	200	0.4
22.08.2012	1400	0

2.3.4 Turbidity and suspended solids as measures of pollution

Turbidity is a measure of the cloudiness of the water. The cloudiness is caused by colloidal particles, which are very small particles that settle very slowly, or not at all if there are some movement in the water. In Norway, turbidity is often measured in FTU (Formazine Turbidity Units) which is equal to the NTU (Nephelometric Turbidity Units) which is used among other countries. The turbidity meter measures the light intensity of the light that goes in to the sample and compare with the light intensity going out. Particles in the sample will scatter the light and thereby give a higher turbidity number because of change in the light intensity. The turbidity meter does however, not measure the size of the particles.

Turbidity in itself does not represent a health hazard, but high values of turbidity indicate a high number of particles. The particles can absorb dissolved pollutants in the water to the surface of the particles. In sewage water, there are so many particles, so the particle amount is found by looking at suspended solids instead of turbidity. The suspended solids may contain micro-organisms and bacteria (Ødegaard et al., 2012). Heavy metals, are also known to associate with the organic fraction of total suspended solids.

Suspended solids < 63 µm are extremely efficient carriers of pollutants. High concentrations of suspended solids of this size may have a negative effect on the receiving water. This effect may be increased turbidity, reduced light penetration, blanketing of the riverbed, and interference with many types of fish and aquatic invertebrates. Even after deposition, they produce a risk since the attached pollutants may re-suspend at high flows (David Butnd John, 2010).

2.3.5 The DESSIN treatment plant and its treatment efficiency

At Hoffselva, DESSIN has run some tests of a local treatment solution for overflow from a CSO. The main objectives of the project are to demonstrate and promote innovative solutions for water scarcity and water quality related challenges and to demonstrate a methodology for the valuation of ecosystem services. Inrigo Water AS has developed a high rate filtration solution for local combined sewer overflow treatment. The treatment solution has been tested during autumn 2015 and spring 2016 (Helness, 2014).

Inrigo Water AS is a Norwegian company that develops and commercialize technology for treatment of drinking water, treatment of municipal and industrial wastewater as well as developing new concepts for water recycling. The Inrigo Water treatment solution is based on advanced filtration techniques. As a part of the DESSIN-project, a testing container has been placed at the site with one of the CSOs along Makrellbekken. For the test-container, spill water from the overflow is pumped into the container, treated, and released back into the sewer system. Measurements are taken at the inlet of the filter (before it is treated) and after the treatment. For the testing container, the sludge and remaining particles from the filtration are flushed back into the combined sewer and continues to the river, so the treatment should not have any effect on the existing system.

Figure 14: Local treatment container

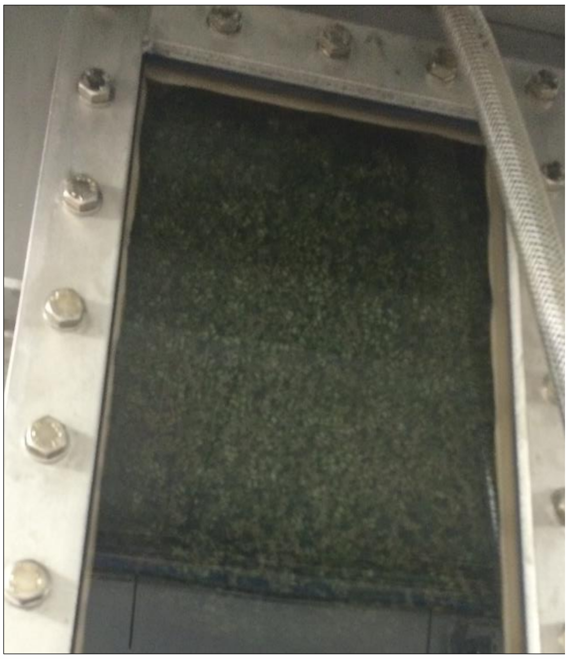


Figure 15: High-rate filter

The principle behind the treatment is to let the water flow through a high rate filter consisting of small plastic particles. The water gets filtrated and continues to a clean-water tank where it is pumped back into the sewer system when the capacity is back to normal. The debris from the filtration will accumulate at the bottom of the filter and start to clog the filter. The water pressure is automatically measured and when it reaches above 6 kPa, due to the clogging of the filter, it will initiate a backwash flush. The backwash flush will clean the filter by flushing in the opposite way of the filterflow, removing the sludge and debris stuck in the filter. See Figure 16.

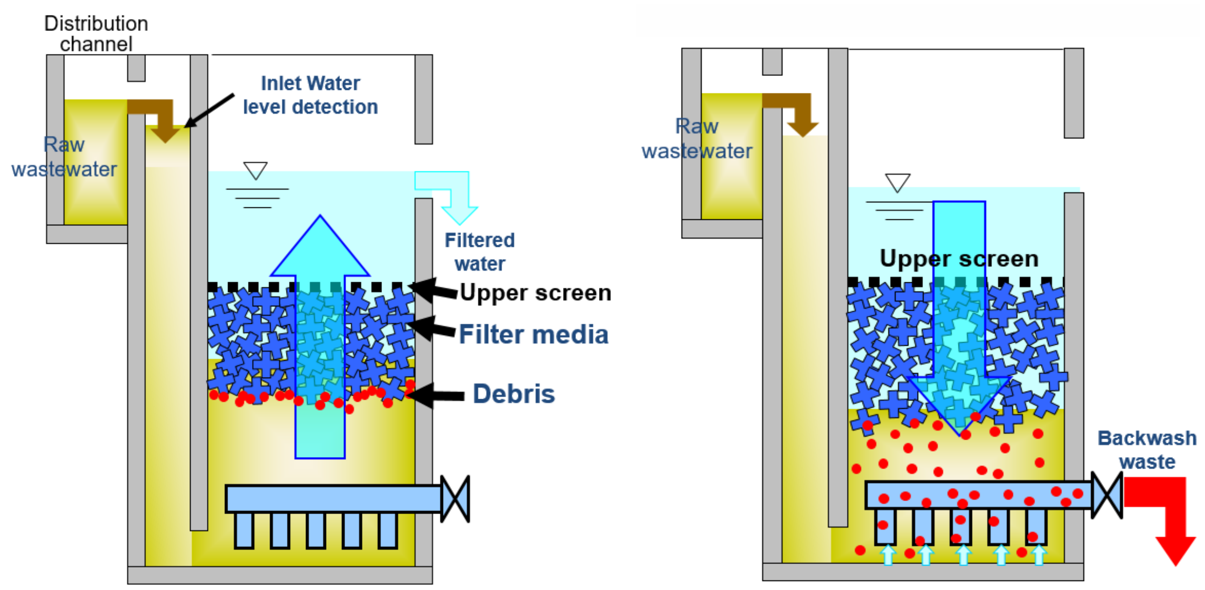


Figure 16: The treatment concept of the high rate filter, (Inrigo Water AS, 2016)

The filter capacity is dependent on the filter area, not the depth of the filter. It has a capacity of 40 m^3/m^2 per hour. The test container at Hoffselva has a filter area of 0.5 m^2, which equals to a capacity of 20 m^3 per hour. The frequency of backwashes depends on the filthiness of the water. In the beginning of the storm, the water tends to be filthier and contain more debris than later in the storm event. This leads to faster clogging of the filter and thereby a higher frequency of backwashes in the beginning. The filtration solution will still continue to filter the water; it does not have to stop in order to backwash. Figure 17 displays how the backwash frequency varies over time.

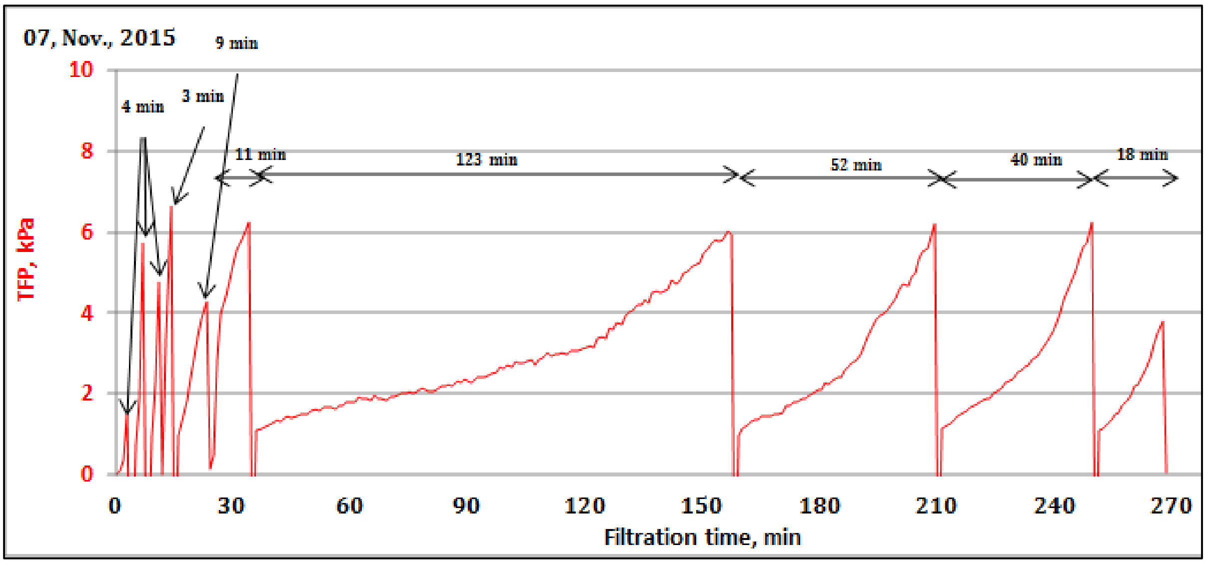


Figure 17: Backwash frequency (Inrigo Water AS, 2016)

To find the removal rate of pollutants, measurements from the inlet and outlet of the container have been compared. The compared constituents are suspended solids (SS), chemical oxygen demand (COD), Zinc (Zn), Copper (Cu), Chromium (Cr), Aluminum (Al), Nitrogen (N), Phosphorus (P), and turbidity. During a CSO event there are several measurement samples that are compared. Figure 18 below shows some samples that were taken during a CSO event.

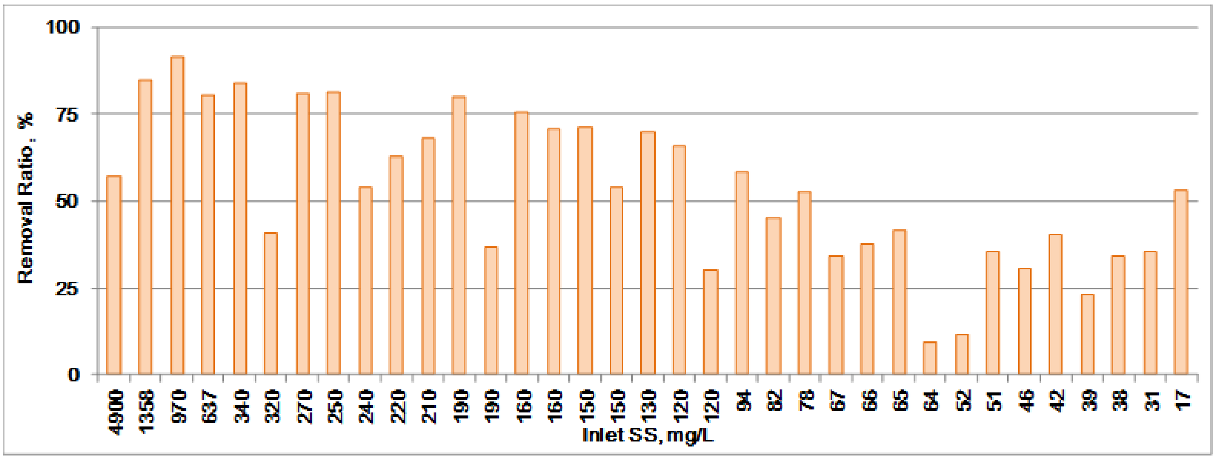


Figure 18: Removal ratio of SS (Inrigo Water AS, 2016)

The filter works as a primary treatment solution that can remove the main portion of the pollutants. We can see that the removal rate is very high in the beginning of the event. This might be due to the first flush where bigger particles are filtrated. Since many of the pollutants tend to be attached to these particles, the removal rate is higher in the beginning. The removal ratio varies over time and to determine the total removal ratio it is necessary to look at the whole event as one. As an example: SS concentration in = 386 mg/L, filter capacity of 20 m3/m2 per hour, duration of 1 hour, filter size of 0.5 m2 → Total SS in = 7.66 kg. If the measured concentration of SS out = 169.5 mg/L → Total SS out = 3.39 kg. Then the removal rate is then simply (7.66-3.39) / 7.66 = 56 % removal ratio.

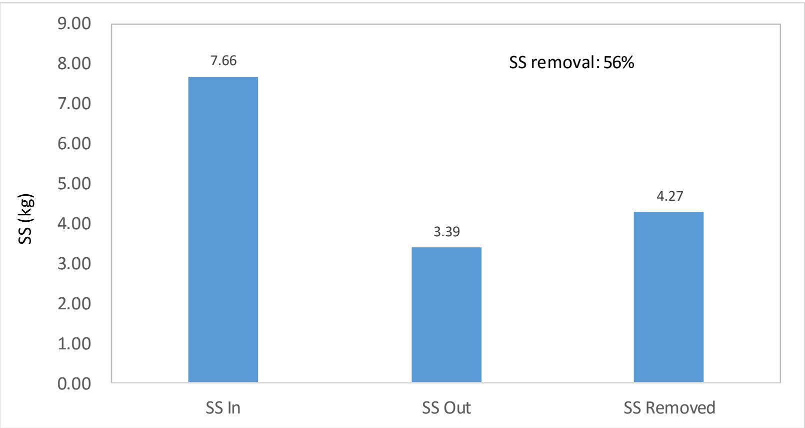


Figure 19: Removal rate example

Table 9: Summarized removal ratio (Inrigo Water AS, 2016)

Parameter	Number of CSO events	Removal ratio
SS	6	56 %
COD	6	47 %
Al	6	48 %
Zn	6	48 %
Cu	6	58 %
Cr	6	31 %
Total Nitrogen	1	6.3 %
Total Phosphorus	1	15 %

2.4 Hydrology

Hydrology is broadly defined as the geoscience that describes and predicts the occurrence, circulation, and distribution of the water of the earth and its atmosphere. In principle, it can be divided into the global hydrologic cycle and the land phase of the hydrologic cycle. The most relevant in this thesis is in the land phase, which is about the movement of water substance on and under the earths land surfaces (Dingman, 2008).

The hydrological cycle is the principle of that water is not lost in the system, but goes in an endless loop. Water evaporates into the atmosphere, water leaves the atmosphere and falls to earth as precipitation, precipitation become surface water or percolates into the water table and groundwater, and water is then transferred back to the sea through rivers and groundwater. The principles of the hydrological cycle are illustrated in Figure 20 below.

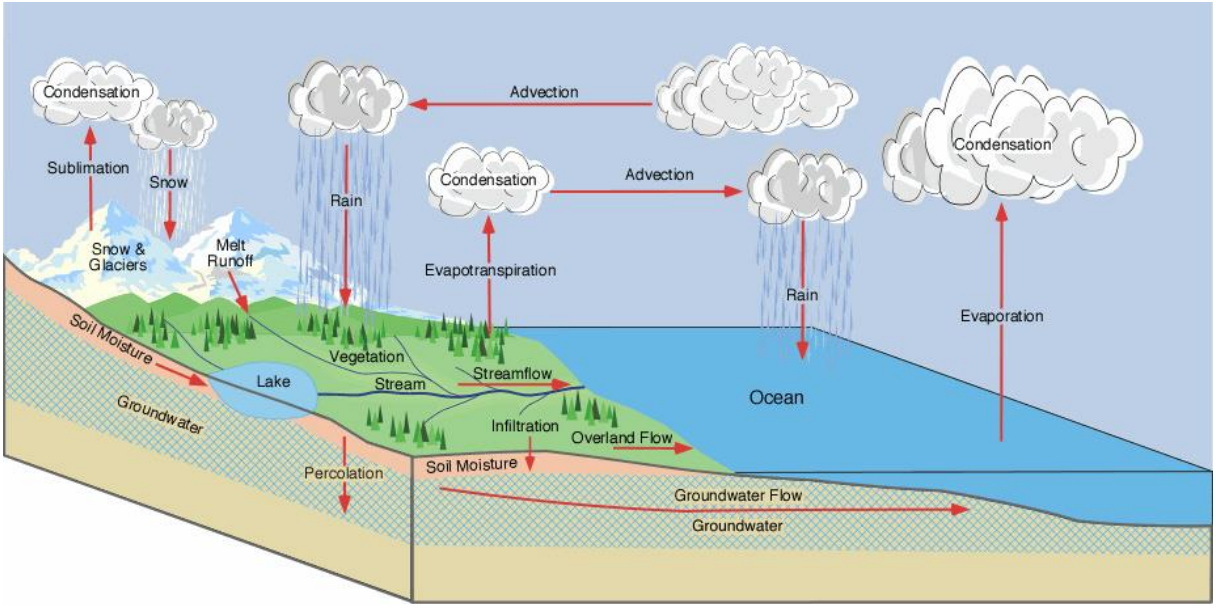


Figure 20: The hydrological cycle (Jones, 2009)

The mathematical expression for the hydrological cycle builds on the basic conservation. The basic conservation is a generalization of the conservation of mass, Newton's first law of motion, and the first law of thermodynamics (Dingman, 2008). In compressed form, the conservation equation can be written as:

$$Amount\ In - Amount\ Out = Change\ in\ Storage \qquad \text{Eq. 1}$$

When Eq. 1 is applied to the mass of water moving through various portions of the hydrological cycles, it is called a water-balance equation. Hydrologists commonly apply the conservation equation in the form of a water-balance equation to a geographical region in order to establish the basic hydrological characteristics of the region. The geographical region is often called a catchment. A catchment is defined as the area that appears on the basis topography to contribute all the water that passes through a given cross section of a stream (Dingman, 2008).

The regional water balance is the water-balance equation applied to a catchment. Figure 21 shows the schematic of the conceptual regional water balance.

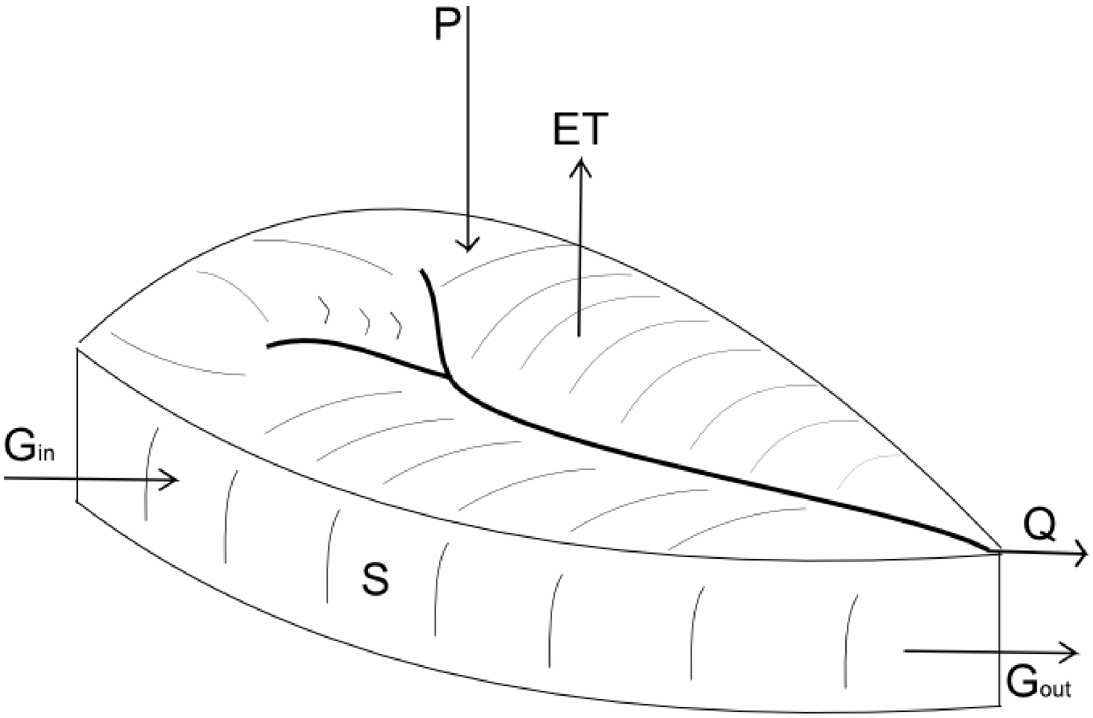


Figure 21: Schematic of a catchment with the components of the regional water balance

For the catchment shown in Figure 21, the water-balance equation can be written as:

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \qquad \text{Eq. 2}$$

Where:

P	=	Precipitation
ET	=	Evapotranspiration
Q	=	Stream outflow
G_{in}	=	Ground-water inflow
G_{out}	=	Ground-water outflow
ΔS	=	Change in storage

The runoff from a catchment is a function of a complex series of processes. Some of the precipitation that falls within the catchment will evaporate, trees and other vegetation will intercept some, some precipitation will group up in ponds and some will generate surface runoff. The quantitative description of the fresh water movement on the land phase of the earth is called hydrological modelling. Through the years, hydrological models have been developed and used as a simplified representation of a real world hydrological system.

2.4.1 Urban hydrology

Urban hydrology is the part of the hydrological cycle that is related to the urban areas. It is about the hydrological effect of change in land use which happens during urbanization of land. In natural landscape, the infiltration capacity is greater than in urban areas due to the perviousness of the soil and ground cover. The surface in urban areas are often impervious such as asphalt, concrete and buildings that will generate more surface runoff because the infiltration capacity is much lower. To describe the relationship between precipitation and runoff, the runoff coefficient is used. A runoff coefficient, c, varies from 0 to 1.0. Asphalt has a runoff coefficient of about c=0.8 which means that 80 % of the precipitation will generate surface runoff and the remaining 20 % will infiltrate or be intercepted in the ground. The runoff coefficient depends on the slope of the terrain, surface properties, time of rain event, intensity of rainfall and vegetation. Figure 22 illustrates the principle for the runoff coefficient.

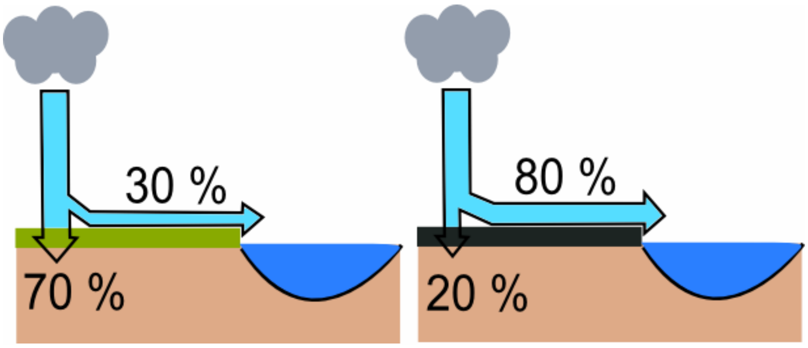


Figure 22: Runoff coefficient: "natural" on the left," urban" on the right

2.4.2 Precipitation data

In Norway there are several measurement stations for precipitation. They are publicly available through the Norwegian Meteorological Institute database. They have observations going back to 1957 with around 2000 stations. Through the years, many techniques have been applied to measure precipitation. A common technique to measure short time precipitation is the tipping bucket. The tipping bucket has a known volume and when it is full, it tips over and empty the bucket so it is ready to refill the bucket. With a time-logger for the time when it tips over and the known volume, it is possible to get a good record of the precipitation. A pluviograph gauge is also often used to measure short time precipitation. Both the pluviometer and tipping bucket can reach time resolutions of 1 -10 minutes. For coarser time resolution the weighing gauges is used. A weighing-recording gauge works by introducing the collected water in a vessel on a scale to measure the accumulated weight of water. The bucket/vessel in the stations have to be replaced manually.

For conventional gauges, the question of true precipitation is a concern. Heavy wind can disturb the results, water can splash out of the container, the height above ground can vary, water can evaporate and the orifice size may vary. According to Dingman (2008), tipping buckets often under-record during heavy rains, and the use of heating elements to record snowfall increase the evaporation. Weighing gauges is also said to have reduced sensitivity as the weight of collected water increases.

Precipitation data are usually measured at a few stations in or around the catchment of interest. It is a classical hydrological problem to determine the average precipitation in the catchment, based on the few measurement stations available. The objective is to find a precipitation data that will provide the correct runoff pattern in time and magnitude for the catchment of interest. In later years, radar data have been increasingly used to determine the precipitation.

2.4.3 Discharge data

The portion of precipitation, that is not evaporated or infiltrated, flows in streams which return it to the oceans to complete the hydrological cycle. Hydrologists faced with the practical problem of forecasting and predicting stream flow responses have developed a technique to separate the streamflow into two components: event flow and base flow (Dingman, 2008).

Event flow: Flow that is considered to be the direct response to a given water-input event. May also be called direct runoff, storm runoff, quick flow, or storm flow.

Base flow: flow that is not associated with a specific event, e.g. ground water and interflow

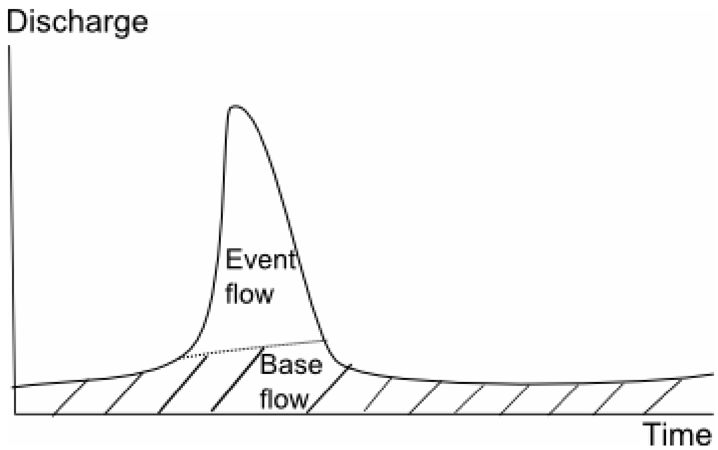


Figure 23: River response to rain event

If we were to look at the discharge in a conceptual modeling way, the input for river discharge can be divided in three components: surface runoff, interflow, and ground water. Interflow is the flow that moves downslope between the ground surface and the water table.

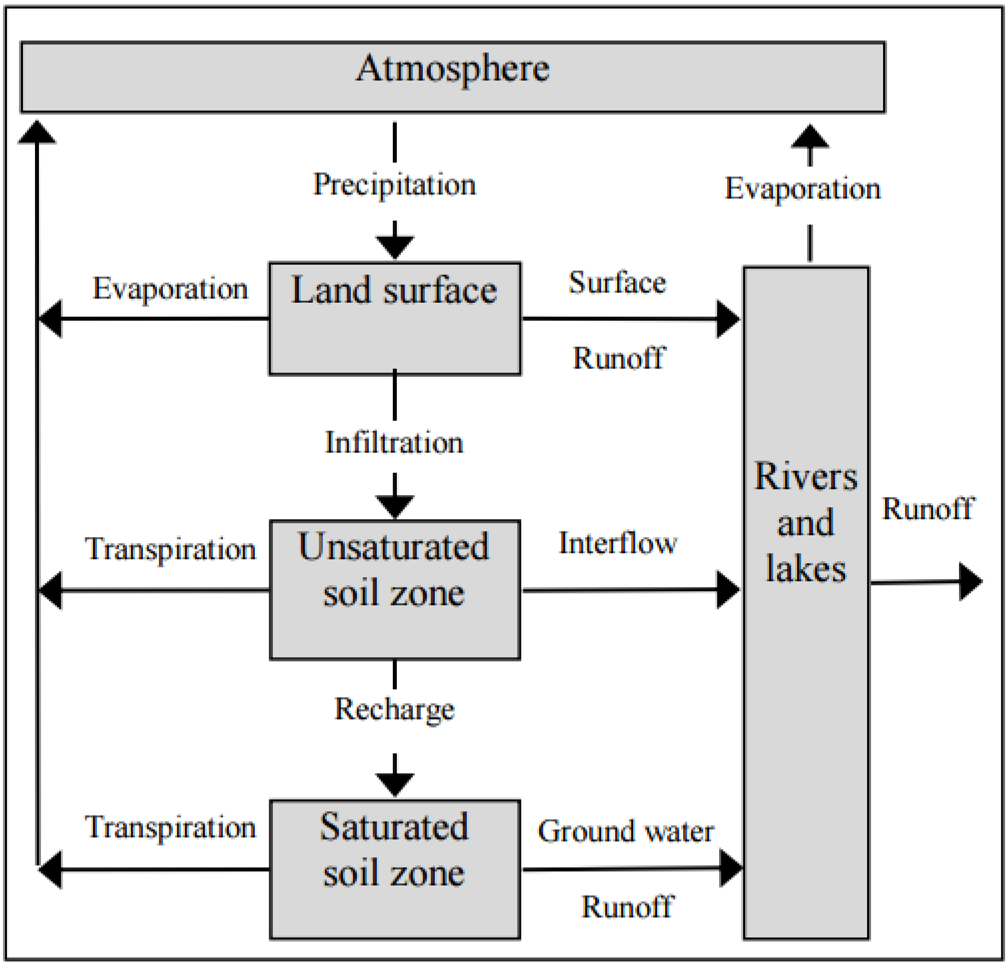


Figure 24: Conceptual modelling principle, by Singh 1988, (Rinde, 2015)

A graph of water input vs. time is called a hyetograph. Catchment response to a rain event can be characterized by measuring the stream discharge. A graph of stream discharge vs. time is called a streamflow hydrograph. By looking at the hydrograph and comparing it to the hyetograph it is possible to see how the catchment responds to rain events. The response varies with the time each drop of water uses to travel from where it strikes in the catchment, to the stream network, and the time from the stream it enters, to it gets to the point of measurement. A simple hydrograph contains four components: baseflow, the rising limb, the crest, and the falling limb. Definitions of terms used to describe hyetographs and response hydrographs have been obtained from Dingman (2008) and is shown in Figure 25.

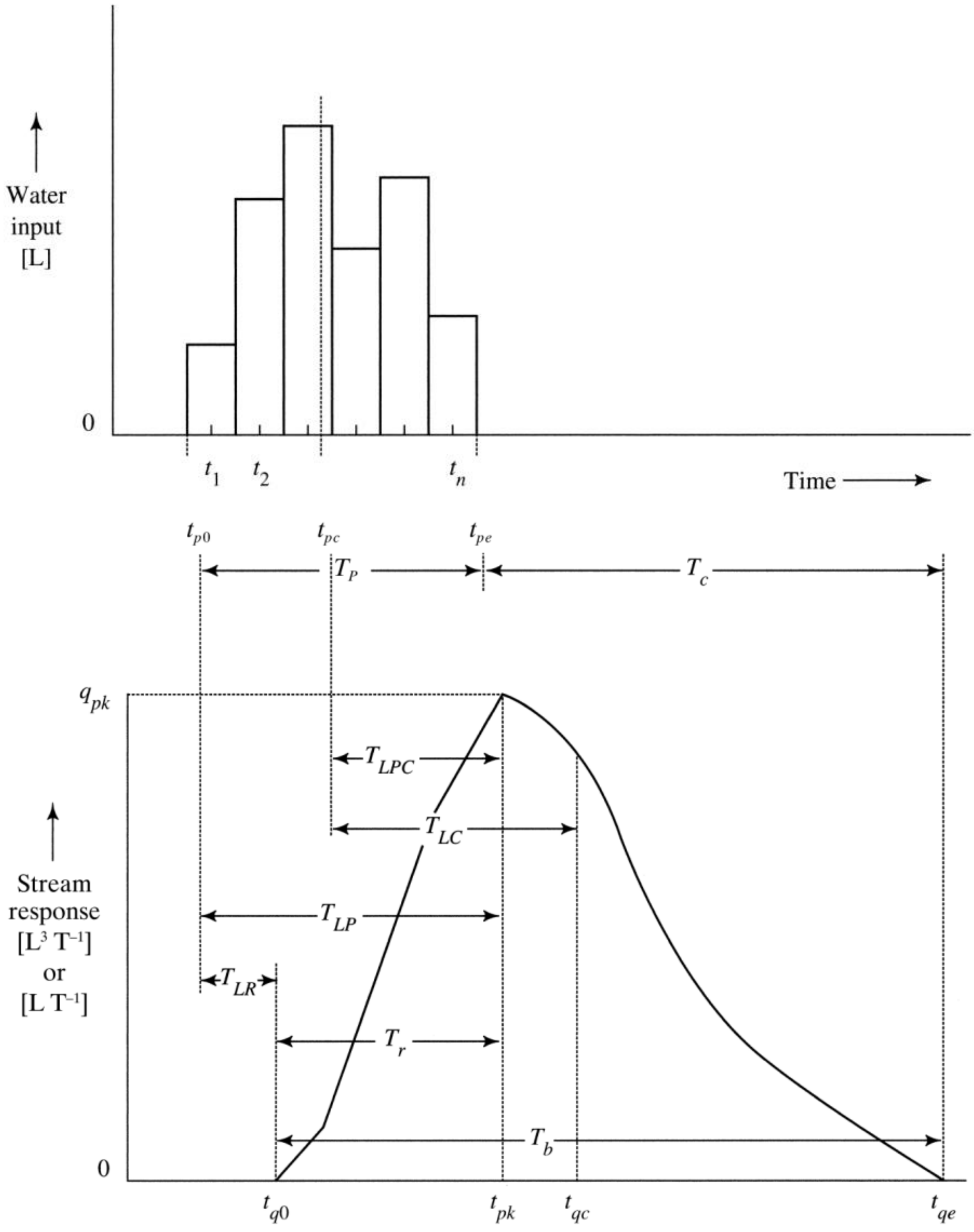


Figure 25: Terms used to describe hyetographs and response hydrographs

Definitions in Figure 25

t_{p0}	=	Beginning of effective water input	T_{LR}	=	Response lag
t_{pc}	=	Centroid of effective water input	T_r	=	Time of rise
t_{pe}	=	End of effective water input	T_{LP}	=	Lag-to-peak

t_{q0}	=	Beginning of hydrograph rise	T_{LPC}	=	Centroid lag-to-peak
t_{pk}	=	Time of peak discharge	T_{LC}	=	Centroid lag
t_{qc}	=	Centroid of response hydrograph	T_b	=	Time base
t_{qe}	=	End of response	T_c	=	Time of concentration
T_P	=	Duration of effective water input	T_{eq}	=	Time to equilibrium

A hydrodynamic model program, as HEC-RAS used in this thesis, requires inflow discharge series to route the water through a river system. Discharge measurement stations are often available in limited numbers for the catchment of interest. What is often done, is to scale and compare discharge series in catchments using statistical relations.

Based on Ingeniørhydrologi – bind 1 (Tveit and Norges tekniske høgskole Institutt for, 1977), the following factors are important when it comes to scale and compare discharge series in catchments:

Catchment area: will influence response time and hydrograph shape. Scaling from large to small catchments tend to lose the “sharpness” in the hydrograph of a small catchment. The opposite, from small to large, may lead to faster runoff than what we naturally have in a large catchment.

Specific runoff: describes the runoff generation of the catchment. Scaling should be avoided if there are large differences in specific runoff.

Distance: It is important that the scaling catchment and the catchment of interest are within the same runoff regime, e.g. not one coastal and one inland.

Weather pattern: Make sure both catchments are dominated by the same weather pattern. A deviation in weather pattern may influence the total runoff and temporal distribution of runoff.

Elevation: Both catchments should have similar elevation distribution. The elevation controls precipitation patterns and snow accumulation and melt

Surface type: influence runoff generation through the production of excess rainfall. Both catchments should have similar surface type.

Catchment form and lake percentage: Parameters like width/length, slope and lake percentage controls the runoff pattern and distribution.

If the study catchment is a part of the catchment with observations, we can scale the remainder of the main catchment and then compare the sum of scaled with the observations. Figure 26 is an illustration where the study sight is a part of the catchment.

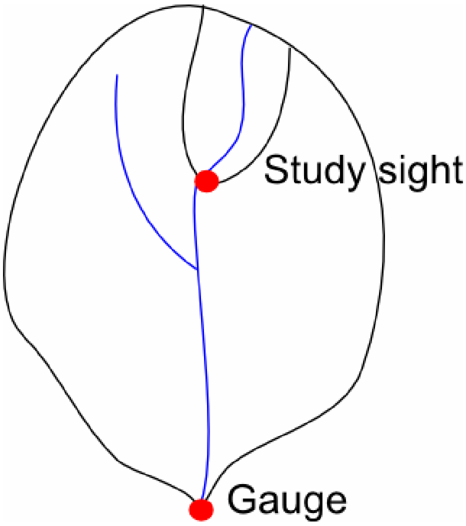


Figure 26: Study catchment within gauged catchment

In this thesis the situation can be related to the two discharge measurement stations available, “Oslo VAV” and “Log A”. By looking at Figure 27, the “study sight” is related to sub-catchment number 10 and the station “Log A”, while the “gauge” is related to the whole catchment and the “Oslo VAV” station.

“Oslo VAV” is located south, almost at the outlet of the river Hoffselva. It has detailed measurements of discharge in 5 min intervals. “Log A” is located at Skådalsbekken, right before Skådalsbekken merges with Styggdalsbekken. The measurement station is a Global Water WL16U with pressure sensor as a water level logger. It was installed as temporary measurement station in Autumn 2014 and 2015 fir the DESSIN project and recorded water levels in 5 min intervals. The discharges were obtained from a preliminary gauge-discharge relationship based on discharge measurements in Autumn 2014. Control measurements conducted by SINTEF Energy Research showed that the rating curve for Log A was stable and could be used for calculations of measurements in 2015 as well.

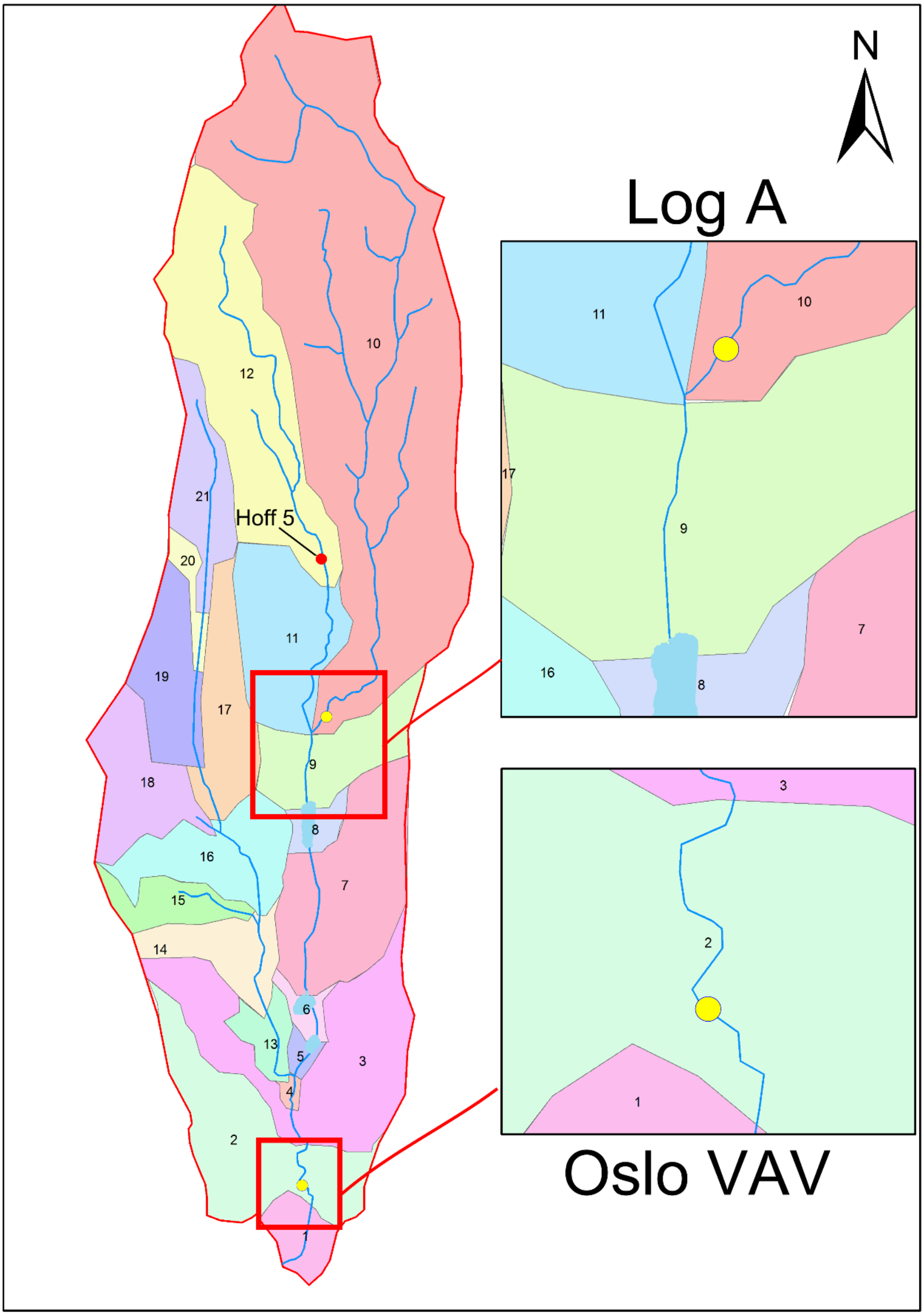


Figure 27: Location of discharge stations

At the very beginning of this thesis it was assumed that Oslo VAV had a rainfall-runoff-model to calculate the surface runoff and contributions to river discharge in the river. This was not the case. However, it was chosen to use the available information from the discharge measurement stations to estimate the river discharge. Based on data from the two stations, a mathematical relation between specific discharge at Log A and Oslo VAV was established to estimate the discharge at the outlet points for each sub-catchment. The mathematical relation was created by Postdoctoral fellow Ashenafi Seifu Gragne, from the Department of Hydraulic and Environmental Engineering at NTNU.

The catchment was divided into 21 sub-catchments. 21 points of discharge interest were defined along the river and each point was assigned a runoff catchment with use of the NEVINA catchment tool created by NVE. Since the runoff catchments represents the upstream area contributing flow to the selected point, it was necessary to clip the catchments in ArcMap. The result is shown in Figure 27.

As preparation for the mathematical relation, information about average slope and area of each sub catchment were calculated in ArcMap. The distances from each catchment to the measurement station "Oslo VAV" were also collected from Arc Map. The mathematical relation between specific discharge at Log A and Oslo VAV, done by Ashenafi Seifu Gragne, is shown below:

$$q_s = \frac{\tilde{q}}{\tilde{a}} = \left(\alpha \left(\frac{Q}{A}\right)^{\mu} + \beta \left(\frac{Q}{A}\right)^{\theta} s_i^{c_1} \bar{s}^{c_2} + \gamma \left(\frac{Q}{A}\right)^{\tau} L_i^{c_3} + \varepsilon \right) \qquad \text{Eq. 3}$$

$$q_i = q_s a_i = \frac{a_i}{\tilde{a}} \tilde{q} \qquad \text{Eq. 4}$$

Where:

q_s	=	Specific discharge for the gauged catchment (upstream Log A) [m/s]
$\tilde{q}$	=	Discharge from the gauged catchment (upstream Log A) [m3/s]
$\tilde{a}$	=	Area of the gauged catchment (upstream Log A) [m2]
q_i	=	Discharge of the ungauged sub-catchment [m3/s]
a_i	=	Area of the ungauged sub-catchment [m2]
s_i	=	Mean slope of the ungauged sub-catchment
L_i	=	Distance from the gauging station "Oslo VAV" to the ungauged sub-catchment [m]
A	=	Area for the entire catchment (upstream Oslo VAV) [m2]
$\bar{s}$	=	Mean slope for the entire catchment
Q	=	Discharge at the "Oslo VAV" station [m3/s]
c_1, c_2, c_3	=	Calibration parameters
$\alpha, \beta, \gamma, \mu, \theta, \tau, \varepsilon$	=	Calibration parameters

To simplify Eq. 3 can be rewritten as:

$$q_s = \frac{\tilde{q}}{\tilde{a}} = \left(\alpha \left(\frac{Q}{A}\right)^{\mu} + \beta \left(\frac{Q}{A}\right)^{\theta} s_i^{c_1} \bar{s}^{c_2} + \gamma \left(\frac{Q}{A}\right)^{\tau} L_i^{c_3} + \varepsilon\right)$$

$$q_s = \frac{\tilde{q}}{\tilde{a}} = (q_1 + q_2 + q_3 + \varepsilon) \qquad \text{Eq. 5}$$

Where:

q_1 = Base flow component

q_2 = Quick flow component

q_3 = Interflow component

ε = Error correction component

The quick flow component takes the slope of the catchments into account by introducing the relation between the mean slopes for each of the catchments. The interflow component takes the distance from the gauged station into account because there is a time lag. The calibration parameters are calibrated based on the relations between the two gauged catchments connected to “Log A” and “Oslo VAV”. It is assumed that each sub-catchment has the same response as the gauged catchment connected to “Log A”. In order to take the unique characteristics of each catchment into account, q2 and q3 is added to introduce the slope and distance for each sub-catchment.

A measure of the fit between the computed and observed discharges is called a calibration criterion or objective function. The goal of the calibration is to find those values for the model parameters that fit the calibration criterion. The calibration is done with an algorithm. In this case the shuffled complex evolution (SCE-UA) has been used for calibration and the Nash-Sutcliffe Efficiency (NES) has been used as an objective function.

The shuffled complex evolution algorithm combines the strengths of the controlled random search algorithms with the strategy of competitive evolution and the concept of complex shuffling (Song et al., 2012).

The Nash-Sutcliffe Efficiency object function has been used with focus on replicating the discharge peaks in the computed discharge. NSE is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”). It indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y^{obs} - Y^{mean})^2}\right] \qquad \text{Eq. 6}$$

Where:

Y_i^{obs}	=	The observed discharge
Y_i^{sim}	=	The simulated discharge
Y_i^{mean}	=	The mean observed discharge
n	=	Total number of observation
i	=	The observation number

Nash-Sutcliffe ranges between - ∞ and 1.0, with NSE = 1 being the optimal value. Values between 0 and 1 are generally acceptable levels of performance. NSE = 1 corresponds to a perfect match of modeled discharge and observed discharge. The calibration results in this thesis had an average Nash-Sutcliffe number of 0.95, which is a very good fit.

2.5 Modeling programs

This sub-chapter gives an introduction to the programs that have been used in this thesis. General usage of the programs and the underlying theory behind them are also introduced.

2.5.1 MIKE URBAN

2.5.1.1 About, usage

MIKE URBAN is a GIS-based modeling system developed by the Danish consulting and software organization DHI (Danish Hydraulic Institute). MIKE URBAN is a flexible system for modeling and design of water distribution networks and collection systems for wastewater and stormwater. MIKE URBAN is based on a database of storing network as well as hydraulic modeling data. The database is based on the ESRI (Environmental Systems Research Institute) GeoDatabase (DHI, 2015).

2.5.1.2 Theory concepts

MIKE URBAN has the opportunity to model runoff with two modules: DHIs own engine MOUSE or SWMM5 which is produced by the Canadian company CHI water. MIKE URBAN is also a deterministic model, which means input to the model are free of random variation so the model will always yield the same output if the input is the same.

MOUSE is a powerful and comprehensive engine for modelling complex hydrology. It models, advanced hydraulics in both open and closed conduits, water quality and sediment transport for urban drainage systems, storm water sewers and sanitary sewers. Typical application of MOUSE can e.g. include studies of combined sewer overflows.

SWMM (Storm Water Management Model) is an engine for storm water modelling. SWMM allows for the hydrodynamic simulation of flows and water levels in urban storm drainage and wastewater collection networks. In this thesis, the MOUSE engine is used for modeling.

2.5.1.3 Hydraulic network modeling with MOUSE

The MOUSE pipe flow model is a computational tool for simulations of unsteady flow in pipe networks with alternating free surface and pressurized flow conditions. The computation is based on an implicit, finite difference numerical solution of basic 1-D, free surface flow equations (Saint Venant) (DHI, 2004).

Solving the full Saint-Venant equation is done where there is rapid change in the water depth over time. The approach to solving the Saint-Venant equation is more involved than solving the kinematic wave equation. There exist two groups for solving the Saint-Venant equation: explicit methods and implicit methods. In MIKE URBAN, computations of the unsteady flow in the links are done with the dynamic wave equation. The dynamic wave is the term used to describe the full 1-D Saint –Venant equation (Olsen, 2012).

$$F_g - F_b - F_p - F_m = m\vec{a}$$

$$\rho g y B \Delta x I_0 - \rho g y I_f B \Delta x - \rho g \frac{dy}{dx} \Delta x (By) - \rho U B \Delta x y \frac{dU}{dx} = \rho y B \Delta x \frac{dU}{dt}$$

Eq. 7

Where:

F_g = Gravity component

F_b = Bed shear stress

F_p = Pressure gradient

F_m = Momentum term

This can be simplified further to the famous Saint-Venant equation:

$$g(I_0 - I_f) - g\frac{dy}{dx} = U\frac{dU}{dx} + \frac{dU}{dt} \qquad \text{Eq. 8}$$

Where:

I_0	=	Bed slope
I_f	=	Friction slope
g	=	Acceleration of gravity
U	=	Average velocity
t	=	Time
x,y	=	Spatial variables

Some places we have steep, partly full pipelines where the flow conditions are mainly governed by the balance between gravity forces and friction forces. The inertia and pressure terms in the momentum equation are less dominant, accelerations are small and the flow is almost uniform, so that the kinematic wave is a reasonable approach. However, there are numerical errors with the numerical solution of the kinematic wave equations that will produce a diffusive (dampened) wave motion. If the pressure term is included in the equation of momentum, then a damping term will automatically be included in the equations. By retaining the pressure term ($\partial y/\partial x$) in the computation, it is possible to implement the downstream boundary condition and thus consider backwater effects (DHI, 2004).

Kinematic: $g(I_0 - I_f) = 0$

Diffusive: $g\frac{\partial y}{\partial x} - g(I_0 - I_f) = 0$ Eq. 9

A MIKE URBAN model consists of the following hydraulic elements:

- Nodes and structures: manholes, basins, storage nodes, outlets
- Links: pipes and canals
- Weirs
- Orifices
- Stormwater inlets
- Pumps
- Valves

In all pipes and canals the computational grid is set up in alternating sequence of h- and Q-points. In these grid points the discharge Q, and water level h are computed at each time step.

The links (pipes and canals) is set up with a h-grid point at each end of the link where the link connects to the nodes in the network. The nodes will only have a single computational point where the water level H is computed. See Figure 28.

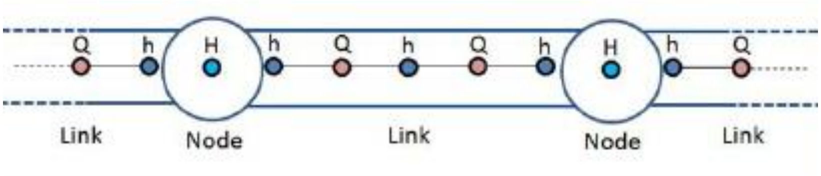


Figure 28: The computational grid (DHI, 2015)

At the nodes, the water level is computed based on the water level at the previous time step and the flow contributions during the time step from each connected pipe and external connected flow. The water level is only calculated at the nodes.

2.5.1.4 Rainfall-Runoff Modelling with MOUSE

In order to model surface storm runoff and infiltration on urban and semi-rural catchments a precipitation-runoff model has to be set up. In MIKE URBAN you have to define catchments and their connection to the network. A hydrological model has to be selected and precipitation has to be given as input. Optionally temperature and evapotranspiration can also be given. The figure under show the flow of information in hydrological modeling (DHI, 2015).

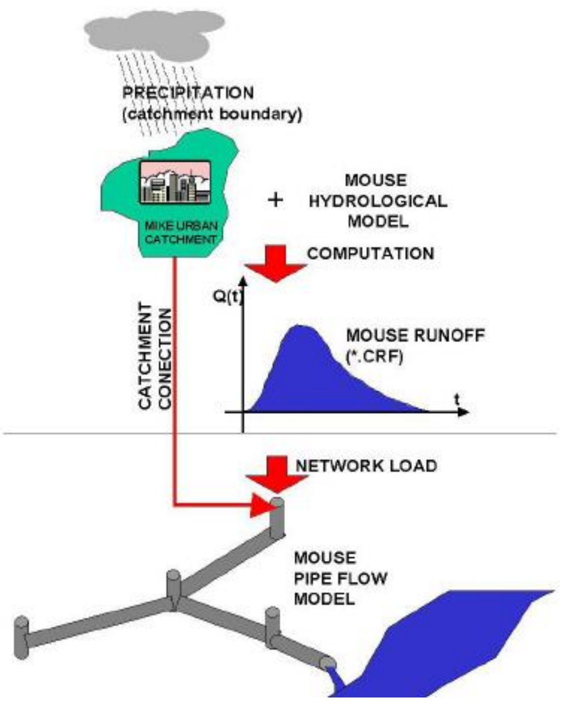


Figure 29: Information flow in MIKE URBAN

By dividing the catchment into MU (MIKE URBAN) catchments, we get a spatial discretization of the hydrological model. In order to transfer the runoff generated on the catchment surfaces into the collection network, the MU MOUSE model must include catchment connection of the catchment outlet to the collection network. Hydrological models for urban catchments include two distinct classes of models: surface runoff model and continuous hydrological models (DHI, 2015).

In the existing MIKE URBAN model from Oslo VAV, a surface runoff model is used. These models are the most common in urban runoff analysis, where only the surface runoff is computed. This implies discontinuous runoff hydrographs where flow starts as a result of rainfall and ceased back to zero again after the end of rainfall. These models are suitable for relatively densely urbanized catchments with dominant amount of runoff generated on impervious surfaces. In the existing model, and in this thesis, the Time-Area Method is chosen as hydrological model (DHI, 2015).

The Time-Area Method is a simple surface runoff model with minimum data requirements. The runoff computation is based on a simple treatment of hydrological losses and the runoff routing by the so-called time-area curve. In comparison to the rational formula, the time-area method takes into count the delay in runoff peaks from the different sub catchments. In the time-area method the closest surfaces contribute first, more distant surfaces later. It uses the time-area diagram to produce not only peak design flow, but also a flow hydrograph. The parameters that has to be set are time of concentration, initial loss, reduction factor and imperviousness of the catchment. In the existing model the time of concentration is calculated by assuming a flow velocity of 1 m/s in pipes and a drainage time of 5 minutes from the outer point of the catchment to the pipe network. It is assumed an initial loss of 0.6 mm, which is standard value in urban hydrological modeling to simulate "wetness" of dense areas. The model also assumes a reduction factor of 0.9 that means that 90 % of the impervious areas are directly connected to the network.

2.5.1.5 Boundary conditions

The model needs boundary conditions in form of water loads (rainfall, infiltration, wastewater etc.) The main characteristic of these "load" boundary conditions is that they contain a "transport medium"- water. Boundary conditions other than water loads are fully defined by the boundary condition variable itself, i.e. no additional item is possible to be associated with them. These are water levels, air temperature, evapotranspiration etc. MOUSE uses three groups of boundary conditions:

- Catchment loads and meteorological boundary conditions: temperature, evapotranspiration, wastewater loads, precipitation is used in the model for this thesis
- Network loads: wastewater production in form of dry weather flow (DWF)
- External water levels: none were used in this model

2.5.1.6 Simulation

In order to run a simulation, we have to run two kind of simulations: runoff simulation and network simulation. The runoff simulation will be used as a base input for the network simulation. The runoff simulation simulates the runoff generation based on the catchment loads. The network simulation simulates the behavior of the network when the runoff simulation result file is applied to the model.

2.5.2 HEC-RAS

2.5.2.1 About, usage

HEC-RAS is an abbreviation for Hydrological Engineering Center – River Analysis System. It is a free software for hydraulic modelling of water flow, in both one and two –dimensions, through natural rivers and other channels. The HEC-RAS system contains four one-dimensional river analysis components: steady flow water surface profile computations, unsteady flow simulation, movable boundary sediment transport computations, and water quality analysis (Brunner, 2016b).

In this thesis, the one-dimensional hydraulic flow computation and water quality computation components have been used.

Steady flow

This component of the modeling system is intended for calculating water surface profiles for steady gradually varied flow. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regime. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction, with the Manning's equation, and contraction/expansion with the friction coefficient multiplied by the change in velocity head. In situations where the water surface change rapidly, like hydraulic jumps, the momentum equation is used (Brunner, 2016a).

Unsteady flow

This component is capable of simulating one-dimensional unsteady flow through a full network of open channels. It uses the momentum equation and the continuity equation to determine flow and stage at each cross-section. This unsteady flow component was developed primarily for subcritical flow regime calculations. The hydraulic calculations for cross-sections, bridges, culverts and other hydraulic structures that were developed for the steady flow were incorporated into the unsteady flow module. In addition, the unsteady flow has the ability to model storage areas and hydraulic connections between storage areas, as well as between stream reaches (Brunner, 2016a).

Water quality analysis

This component of the modeling system is intended to allow the user to perform water quality analyses. HEC-RAS can perform temperature analyses and transport of limited number of water quality constituents. The current water quality constituents are: algae, dissolved oxygen, carbonaceous biological oxygen demand, dissolved orthophosphate, dissolved organic phosphorus, dissolved ammonium nitrate, dissolved nitrite nitrogen, dissolved nitrate nitrogen and dissolved organic nitrogen. A plan view of the river schematic may be color coded to describe spatial distribution of model results (Brunner, 2016a).

2.5.2.2 Required geometry inputs

The basic geometric data for the river system schematic are: cross section data, reach lengths, energy loss coefficients, stream junction information, bridges, culverts, spillways, weirs, etc. The river system schematic defines how the various river reaches are connected, and establish a naming for referencing the other data.

Cross sections are located at intervals along a stream to characterize the flow carrying capability and its adjacent floodplain. The smaller interval of cross sections thus higher accuracy of the real world river geometry is achieved. The cross section geometry is described by entering the station and elevation (X-Y data) from left to right, with respect to looking in the downstream direction. The program assumes that higher numbers are upstream and lower numbers are downstream. Other data are required for each cross section is downstream reach lengths, roughness coefficients, and contraction and expansion coefficients.

Reach lengths are referred to as the measured distance between cross sections. The reach lengths for the left overbank, right overbank and channel are specified on the cross section editor. Often these three length will be of similar value, but sometimes like in river bends the difference can be bigger. In these cases, a discharge weighted reach length is determined based on the discharge of each segment. For the channel (middle of the river) the reach lengths are typically measured along the thalweg (the deepest part of the river). While the reach lengths for the left and right overbank is measured along the anticipated path of the center of mass of the overbank flow.

Roughness coefficients “k” or Manning’s n values for friction loss are used to evaluate the energy loss. Selection of an appropriate value for Manning’s n is significant to the accuracy of the computed water surface profiles. The value of Manning’s n depends on a number of factors: surface roughness, vegetation, channel irregularities, channel alignment, scour and deposition, obstructions, size and shape of the channel, stage and discharge, seasonal changes, temperature, and suspended material and bedload (Brunner, 2016a). In general, the n values should be calibrated when observed water surface profile information is available. When this information is not available, n values are obtained from experimental data in similar conditions.

Contraction and expansion coefficients are needed because the contraction or expansion of flow, due to changes in cross sections are a common cause of energy losses. The coefficients are multiplied by the absolute difference in velocity heads between the current cross section and the next cross section downstream, which gives the energy loss caused by the transition.

2.5.2.3 Theory concepts

This chapter describes the theoretical basis for one-dimensional water surface profile calculations. Theoretical basis for one-dimensional flow calculations is that flow is only considered in the longitudinal direction (x-direction) along the river reach. It means lateral flow (y-direction) and vertical flow (z-direction) are neglected. The water surface is also considered to be horizontal across the river in the y-direction. This is a sufficient simplification because the lateral and vertical flow is considered very small compared to the flow in the longitudinal direction.

Steady flow

The basic computational element in HEC-RAS is the channel segment between two cross sections. Figure 30 shows the channel segment, the figure is adapted from (Rinde, 2015). To calculate flow one must specify geometry of upper and lower cross section, the distance between the cross sections and the roughness of the channel surface.

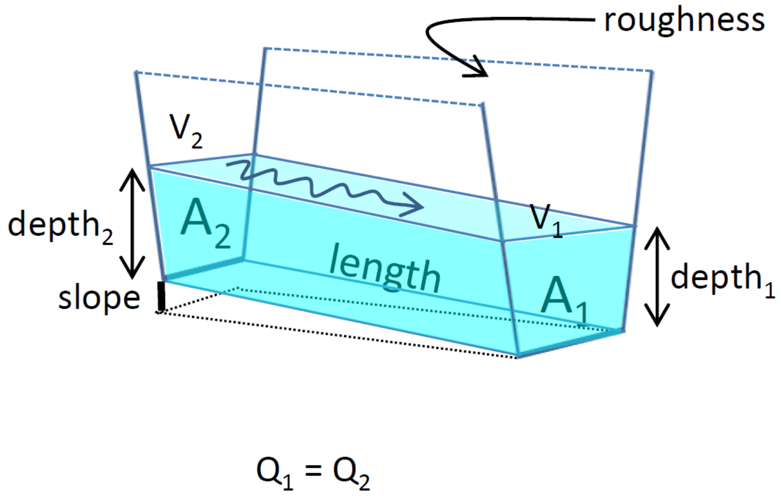


Figure 30: Channel segment between two cross sections

The water surface profiles are computed from one cross section to the next by solving the energy equation with an iterative procedure called the standard step method. The energy equation is shown in Eq. 10.

The energy equation is given as:

$$Z_2 + Y_2 + \frac{a_2 {V_2}^2}{2g} = Z_1 + Y_1 + \frac{a_1 {V_1}^2}{2g} + h_e \qquad \text{Eq. 10}$$

Where:

Z1,Z2	=	Elevation of the main channel inverts
V1,V2	=	Average velocities (Q/A)
a1,a2	=	Velocity weighting coefficients
g	=	Gravitational acceleration
he	=	Energy head loss

Figure 31 shows the terms in the energy equation adapted from the HEC-RAS reference manual.

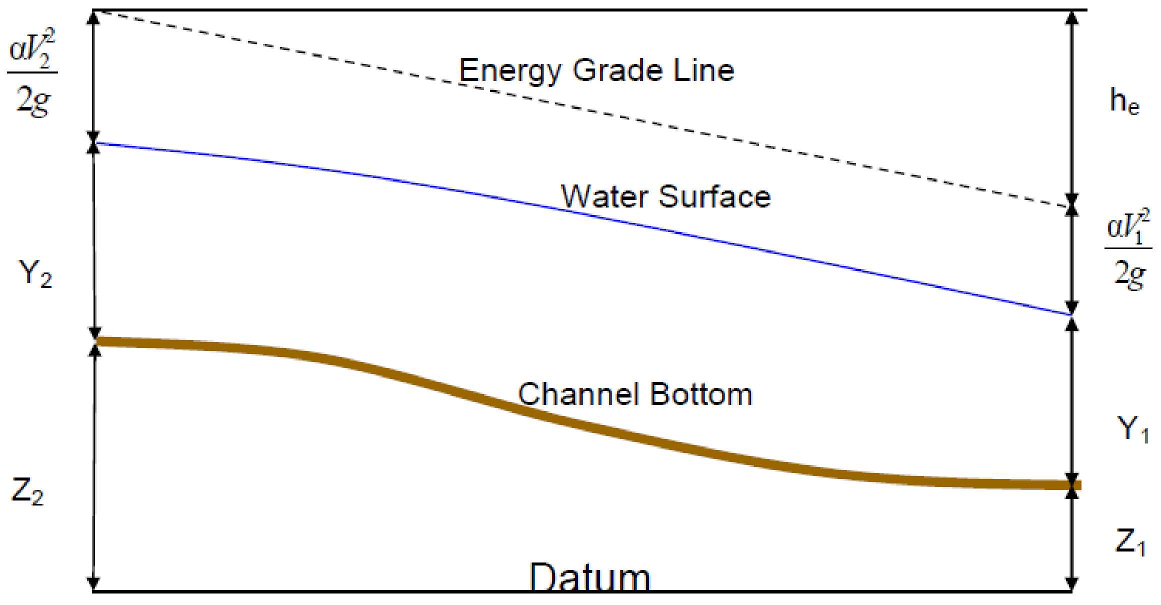


Figure 31: Representation of terms in the energy equation

The energy equation is only applicable to gradually varied flow situations, and in the transition from subcritical to supercritical, or the other way, we have a rapidly varying flow situation. In varying flow situations, like whenever the water surface passes through critical depth, the momentum equation must sometimes be used in order to obtain an answer (Rinde, 2015).

The momentum equation is given as:

$$\sum F_x = ma = Q\rho\Delta V_x \quad \textit{Eq. 11}$$

Where:

Q = Discharge

p = Density of water

dVx = Change in velocity

In order to compute the water surface profiles from one cross section to the next we have to solve the energy equation with an iterative procedure called the standard step method. To solve the energy equation, energy head loss (he in Figure 31) between the two cross sections must first be calculated. The total energy head loss consists of two components: energy friction loss and contraction-expansion loss.

The total energy loss is given as:

$$h_e = h_f + h_{ce} = \frac{n^2}{{R_h}^{4/3}} \times \frac{({V_1}^2 + {V_2}^2)}{2} \times \Delta x + c \left| \alpha_2 \frac{{V_2}^2}{2g} - \alpha_1 \frac{{V_1}^2}{2g} \right| \qquad \textit{Eq. 12}$$

When we put the total energy loss (Eq. 12) into the energy equation (Eq. 10) we get Eq. 13. The parts of the equation in bold text requires iterative calculation scheme and the iterative process depends on if we have subcritical, supercritical or mixed flow.

$$Z_2 + Y_2 + \boldsymbol{\frac{a_2 {V_2}^2}{2g}} = Z_1 + Y_1 + \frac{a_1 {V_1}^2}{2g} + \frac{n^2}{{R_h}^{4/3}} \times \frac{(\boldsymbol{{V_1}^2 + {V_2}^2})}{2} \times \Delta x + c \left| \boldsymbol{\alpha_2 \frac{{V_2}^2}{2g} - \alpha_1 \frac{{V_1}^2}{2g}} \right| \qquad \text{Eq. 13}$$

The iterative process called the standard step method, can be reviewed in detail in the reference manual (Brunner, 2016a).

Unsteady flow

As mentioned earlier, unsteady flow uses the momentum equation and the continuity equation to determine flow and stage at each cross-section. The physical laws of conservation of momentum (momentum eq.) and conservation of mass (continuity eq.) are expressed mathematically in the form of partial differential equation. The derivation of these equations are presented in the reference manual by Brunner (Brunner, 2016a).

The continuity equation (Eq. 14) and momentum equation (Eq. 15) are given in its final form below:

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_1 = 0 \qquad \text{Eq. 14}$$

Where:

Q = Flow

A_T = Total flow area

q_1 = Lateral inflow per unit length

t = Time

x = Distance

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \qquad \text{Eq. 15}$$

Where:

V = Velocity in the direction of flow

z = The elevation of the water surface

S_f = The friction slope

A = Cross-sectional area

Water quality calculations

The basis of the water quality model is the principle of mass conservation. HEC-RAS solves a 1D advection-dispersion transport module for each water quality constituent (Zhonglong Zhang 2014). The water quality module uses the QUICKEST-ULTIMATE explicit numerical scheme to solve the one-dimensional advection-dispersion equation.

In HEC-RAS the model organizes constituents and sources into three major groups: temperature modeling, nutrient modeling and arbitrary constituents. Temperature modeling computes heat energy sources and water temperature. Nutrient modeling simulates nutrients, dissolved oxygen, CBOD, and algae. Arbitrary constituents are simple tracers, configured by the user. Because most of the rate constants in the nutrient modeling are depending on the water temperature, nutrients modeling often require water temperature modeling (Brunner, 2016b).

The water quality module uses the river geometry from the hydraulic model. It divides the river into water quality cells in which the calculations are carried out. The water quality cells are initially established between the hydraulic cross sections and the computational points are always located at the center of a water quality cell. See Figure 32.

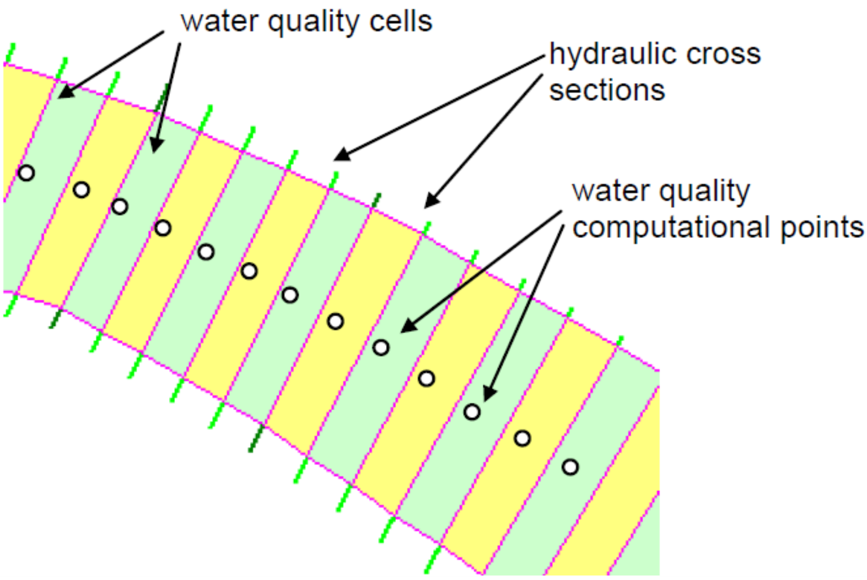


Figure 32: Water quality cells (green and yellow) in HEC-RAS

A very small water quality cell surrounded by larger cells is a challenging computational problem because the single small cell will force the model to choose a small time step. Smaller time steps lead to longer simulation times. It is possible to group water quality cells together into larges cells in places where small water cells occur.

Water temperature is an important factor for controlling water quality in rivers. Many water quality coefficients depend on the temperature. The temperature modeling uses a full energy budget approach. Model input requirements are hydrodynamic information and system geometry from the HEC-RAS unsteady flow model, as well as temperature at hydrodynamic boundaries, and meteorological data (e.g. solar radiation, air temperature, vapor pressure, wind speed). The change in water temperature with respect to time due to heat exchange at the water surface, is computed as follows according to (Zhonglong Zhang 2014):

$$SS_{Heat} = \frac{q_{net}}{\rho_w C_{pw}} \frac{A_s}{V} \qquad \text{Eq. 16}$$

Where:

SS_{Heat}	=	Heat source or sink term [°C/s]
q_{net}	=	Net heat flux [W/m^2]
ρ_w	=	Density of water [kg/m^3]
C_{pw}	=	Specific heat of water [J kg^{-1} °C^{-1}]
A_s	=	Area of the water quality cell [m^2]

The time step for the calculations in the water quality module is chosen to satisfy both Courant (C) and Peclet (a) constraints in order to enhance the model stability:

$$C_{us} = u_{us} \frac{\Delta t}{\Delta x} \leq 0.9 \qquad \text{Eq. 17}$$

Where:

C_{us} = Local Courant number [dimensionless]

u_{us} = Velocity at water quality cell face [m/s]

Δx = Length of water quality cell [m]

Δt = Time step [s]

$$\alpha_{us} = \Gamma_{us} \frac{\Delta t}{\Delta x^2} \leq 0.4 \qquad \text{Eq. 18}$$

Where:

α_{us} = Local Peclet number [dimensionless]

Γ_{us} = Dispersion coefficient at water quality cell face [m2/s]

To compute the optimal time step, the model code selects the smallest of the three values: the maximum time step that satisfies Eq. 17, the maximum time step that satisfies Eq. 18, and the user entered maximum allowable time step.

As mentioned earlier the water quality model uses the advection dispersion equation to determine concentrations at each computational node. HEC-RAS uses the QUICKEST (Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms) scheme developed by Leonard (1979) together with the ULTIMATE (Universal Limiter) algorithm (Leonard, 1991) to solve the advection-dispersion equation (Jensen et al., 2011). The Eq. 19 given below:

$$V^{n+1}\phi^{n+1} = V^n\phi^n + \Delta t\left[Q_{up}\phi^*_{up} - Q_{dn}\phi^*_{up} + \Gamma_{dn}A_{dn}\frac{\partial \phi^*}{\partial x_{dn}} - \Gamma_{up}A_{up}\frac{\partial \phi^*}{\partial x_{up}}\right] + \Delta t\frac{\partial \phi}{\partial t}SS \qquad \text{Eq. 19}$$

Where:

ϕ^{n+1} = Concentration at present time step [kg/m3]

ϕ^n = Concentration at previous time step [kg/m3]

ϕ^*_{up} = QUICKEST concentration at upstream face [kg/m3]

$\frac{\partial \phi^*}{\partial x_{up}}$	=	QUICKEST derivative at upstream face [kg/m4]
Γ_{up}	=	Upstream face dispersion coefficient [m2/s]
V^{n+1}	=	Volume pf the water quality cell at next time step [m3]
V^n	=	Volume of the water quality cell at current time step [m3]
Q_{up}	=	Upstream face flow [m3/s]
A_{up}	=	Cross sectional upstream face area [m2]
$\frac{\partial \phi}{\partial t}SS$	=	Cell energy budget terms [C/m3*s] or cell nutrient terms [kg/m3*s]

There are multiple variables as output when cell energy budget terms or cell energy budget terms are selected. See table 19-7 in the user manual for more details (Brunner, 2016b).

2.5.3 HEC-GeoRAS

HEC-GeoRAS is a GIS extension to process geospatial data for use in HEC-RAS. The extension allows the user to create a HEC-RAS import file containing geometric data from an existing digital terrain model (DTM). Once the hydraulic computations are completed in HEC-RAS, the water surface and velocity can be exported back into GIS using HEC-GeoRAS spatial analysis.

3 Methods and data used in the master thesis

This chapter describes the process of the work and which methods that were used during the master thesis. It is meant to give insight in the methods that have been used and which decisions that were made along the way.

3.1 Literature study

In the startup phase of the master thesis, a literature study was done. Relevant information about similar tasks and projects that includes much of the same theory, were found by searching in the online digital library Oria. Oria allows the user to search the library's printed and electronic collections of: books, articles, journals, theses, music, movies, and more. The thought behind the literature search was to find updated scientifically articles instead of older/outdated books in the physical library. The articles that were picked out, contained up to date research and are quality proved by common scientific forums.

In order to reduce the huge amount of hits on articles in the search for the different topics, truncation was used. E.g. instead of searching for "CSO", truncation was used to also include CSO, water quality, pollution, urban etc. in the search. This reduced the number of hits from 10 817 to 154 for this example. And on top of this, it was possible to sort from most popular (times sited) to pick out the articles that are most relevant to the topic. When a number of relevant articles were picked out, they were read through and a short summary was added and stored in the reference tool program EndNote.

3.2 ArcGIS: ArcMap

ArcMap has been an important tool in this thesis. The user interface is pretty similar to what is used in MIKE URBAN and HEC-RAS has its own GIS module. ArcMap has been used as a tool to combine and view results from MIKE URBAN and HEC-RAS in the same model and to get a better overview of the study area.

Oslo VAV provided the digital elevation model used in this thesis. The model has a 50 cm x 50 cm spatial resolution. It is made up of laser points in the southern part of the catchment and elevation contour lines in the northern part of the catchment. Because the southern part is made of laser point, the houses and buildings are also included in the model as elevations. The rivers in the digital elevation model do not have completely flat water surfaces because they are given from laser points, and there has been no correction to smooth out the water surfaces. It has not been made any corrections for the river surfaces in the catchment, other than the laser points. What is usually done, is to use the water surface and “burn” the rivers into the DEM, but this has not been done for this model.

3.3 Selection of software

MIKE URBAN was selected to model the activity from the CSOs because a MIKE URBAN model of the sewage network already existed. The existing model was established in MIKE URBAN in 2011, by the municipality of Oslo and DHI (Vike, 2011). The calibrated model was used to conduct a capacity analysis of the current sewer system, and to make an analysis of measures of improvement for the zone. Oslo VAV has modeling experts with experience from the MIKE URBAN model, and they were able to assist with supervision at their office in Oslo. DHI also makes student licenses to students at NTNU, which made it possible to work with the model without supervision as well.

HEC-RAS was selected based on the author of this thesis previous experience with HEC-RAS, and the fact that it is a free software which is widely used around the world. There is a broad network of forums etc. that can assist with support online on the internet, because it is a well-known free software. Supervision and support for the modeling in HEC-RAS was also available at the department of hydraulic and environmental engineering at NTNU. HEC-RAS provide the hydrodynamic and water quality modeling in this thesis.

3.4 Collection of data

Meteorological data

In this thesis most of the data are collected from the measurement station located at Blindern in Oslo. The station is situated at an elevation of 94 masl and is close to the catchment of Hoffselva. The closest station is Besserud, at an elevation of 240 masl. Blindern station has been an active weather station since 1968, while Besserud has been active since 1998. They both measure precipitation and air temperature, but Blindern has a pluviometer that measures down to minute time resolution. The MIKE URBAN modeling from 2011 also used meteorological data from Blindern when they calibrated the model.

The modelled areas range from sea level up to 500 m elevation. Given such wide range in topography it is likely that there will be some spatial variation in the rainfall from the low ground in the south to the higher areas in the north. The precipitation input was used to calculate the CSO activity and the CSOs are located in the lower part of the catchment in the urban areas. Based on this, Blindern station was found acceptable to use as representative precipitation for the catchment. Figure 33 shows the wide range in topography and the location of the measuring stations.

Meteorological data have been sampled from the Norwegian Meteorological Institute database for weather observations. Table 10 shows what kind of data that were sampled as input for this thesis.

Table 10: Meteorological data collected from eklima.no

Station	Measure	Time resolution
Blindern PLU	Precipitation	1 min
Blindern	Temperature	6 hours
Blindern	Air pressure	6 hours
Blindern	Evaporation	24 hours
Blindern	Air humidity	6 hours
Blindern	Wind	6 hours
Kjemibygget (Blindern)	Solar radiation	1 month

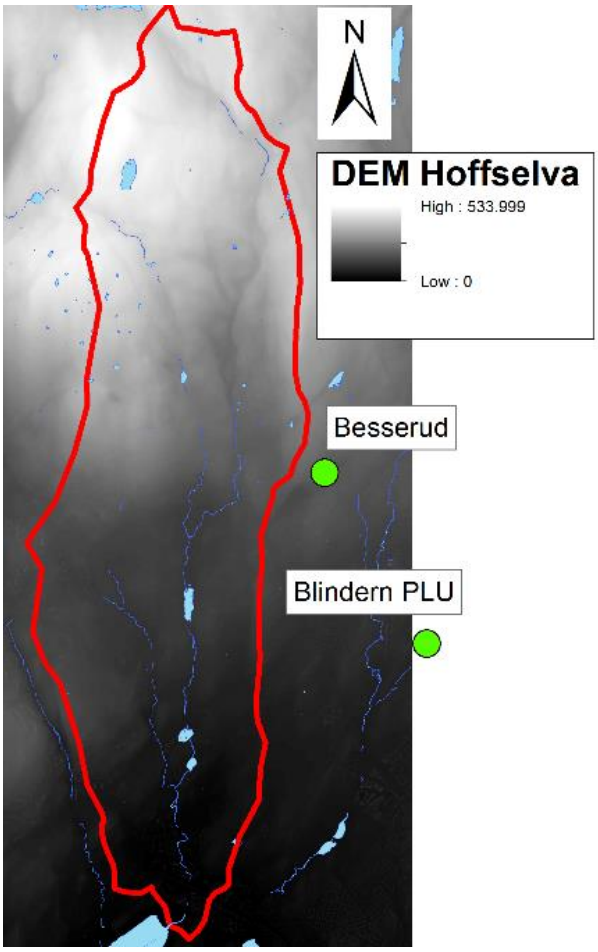


Figure 33: Location of the meteorological

Information and other relevant data

As this thesis is a part of a bigger project, it was necessary to retrieve information from previous project reports and documents that were of interest with respect to Hoffselva. SINTEF, NIVA and the municipality of Oslo have been very helpful with providing information of interest when it comes to inside information in this project. The web page of The Norwegian Resources and Energy Directorate (https://www.nve.no/) has been helpful with mapping tools to calculate runoff catchments etc. Map tools from Geological Survey of Norway (http://www.ngu.no/emne/karttjenester) were also helpful to find information about the geology of the area. In relation to the use of ArcMap, The Norwegian Mapping Authority (http://www.kartverket.no/Kart/) has been a valuable place to find relevant information for the catchment.

3.5 Modeling CSO spills: MIKE URBAN

3.5.1 Model setup

In 2011, as commissioned by the municipality of Oslo, a discharge model of the Hoffselva sewer catchment were established in MIKE URBAN. The model was built in MIKE URBAN and includes both combined sewer system and separate sewer system. The municipality of Oslo has made one part of the model themselves and the other part is done by DHI. The two parts are together turned into a model that covers the Hoffselva sewage network. The model is calibrated against measured data. Oslo's sub-model is calibrated against own monitoring data. DHI's sub-model is calibrated against measurement data from measurements campaign conducted by DHI (Vike, 2011).

In 2011 the calibrated model was used to conduct a capacity analysis of the current sewer system, and to make an analysis of measures of improvement for the zone. In this thesis the plan was to use the already build and calibrated model to produce CSO discharge volumes during different scenarios. Since the author of this thesis did not have any experience in working with MIKE URBAN it was decided to stay in Oslo for a week to get supervision in use of MIKE URBAN by the modeling experts at Oslo VAV. The plan was to run the finished model from 2011 with updated precipitation data and air temperature data for preselected periods. And in this way get CSO discharge volumes out as time series which then can be implied in HEC-RAS.

The catchment consists mainly of combined sewer and some places there are separate system. In the separate system zones, it is assumed that the stormwater is conveyed in stormwater pipes and into a watercourse nearby. The precipitation that falls inside the combined sewer zones are assumed to enter the combined sewer pipes and will contribute to the river discharge through combined sewer overflows.

The existing model's purpose was to look at the capacity of the existing sewer system, so it only considered the wastewater production from the separate system zones. It did not take into account the stormwater runoff production from the separate system zones. To consider this, a number of stormwater zones were added in the areas of separate system, and each zone were assigned to a fictive outlet by the river so the stormwater from these zones could be given as input to the river discharge.

It was expected that the stormwater pipes were taken into account from the beginning in the existing model, so it took a few days to make this additional changes to the model. To include the stormwater runoff from the separate system you have to specify stormwater-area, imperviousness, drainage manhole, drainage outlet and link from the stormwater-area to the outlet point by the river. An orthophoto was used to decide the percentage of imperviousness together with shape files of buildings and roads. The suggested imperviousness percentage were compared with the imperviousness of the neighboring cells from the calibrated model. Normally a 50-60 % imperviousness is used in dense urban areas, while it is usually below 40 % in the peri-urban areas.

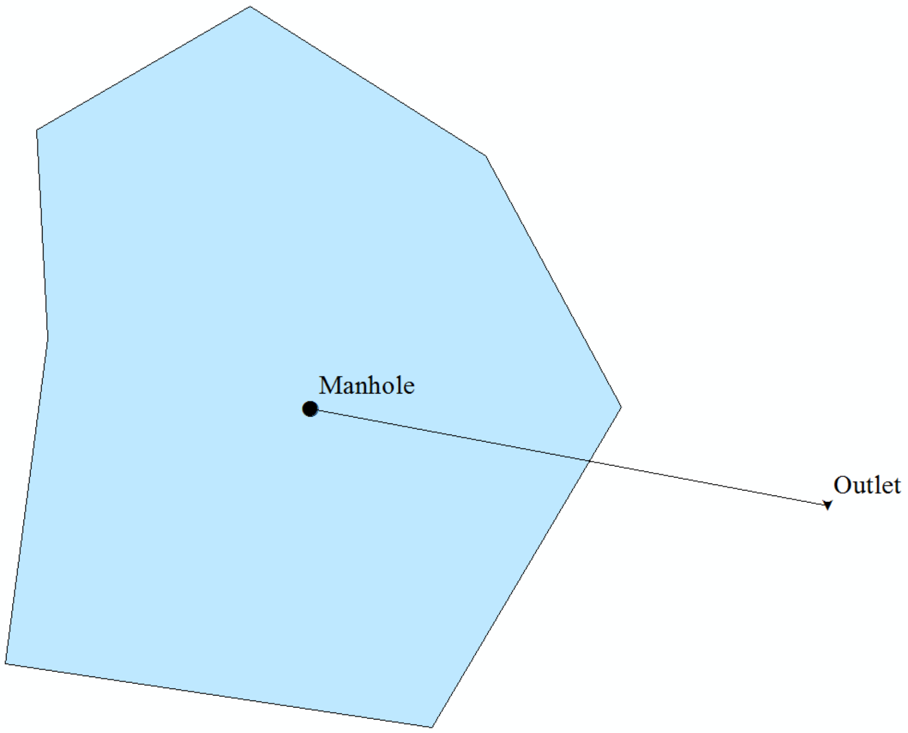


Figure 34: Components in the making of a catchment

Gemini VA is a professional system the municipalities use for the management and documentation of water and sewage network. Gemini VA is a system with an overview of the network that can contain information about technical data, geography, operating data and history of the system. Gemini VA was used to locate which stormwater pipes that have an outlet going into Hoffselva. By tracing the stormwater pipes flow direction backwards from the outlet it was possible to locate the separate systems that contribute to stormwater discharge in the river and the location of the outlets. Figure 35 shows a part of the catchments from the original model and Figure 36 shows the same part with stormwater areas that were added to the model.

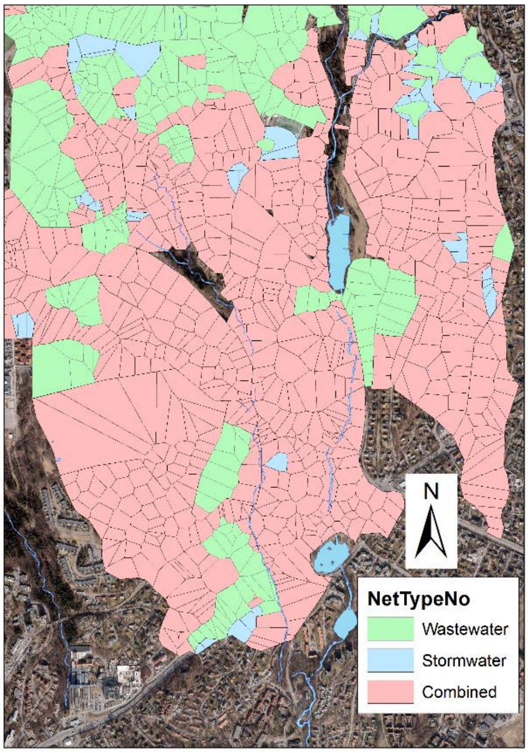


Figure 35: The original catchments in MIKE URBAN

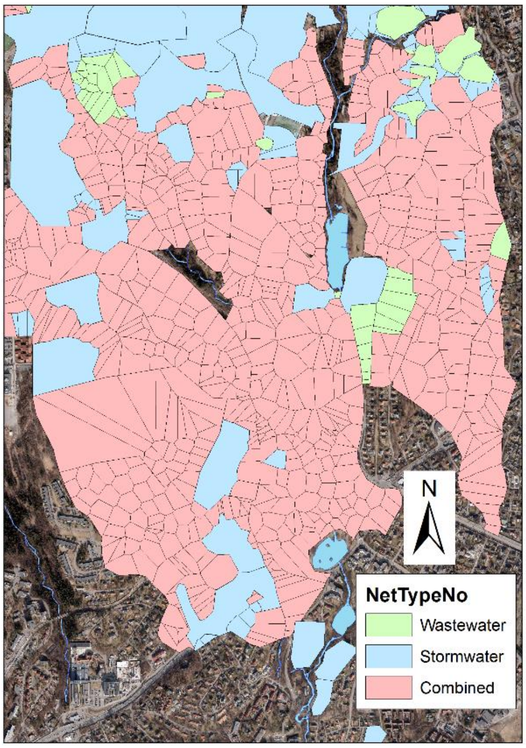
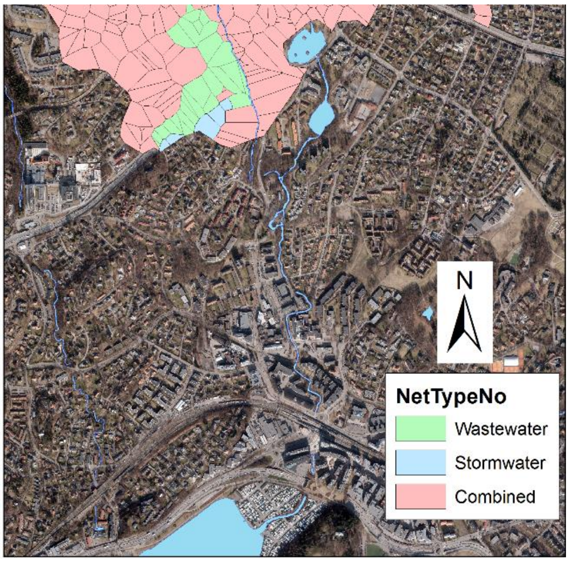


Figure 36: The added catchments in MIKE URBAN

As we can see, some of the separate systems (wastewater zones) are not covered by stormwater zones. This is because they are ineffective separate systems that convey the stormwater into a combined sewer system instead of reaching the river. By the use of GIS, it was possible to add information about where the old river used to flow, and how it looks like today, if it lays in pipes or of it flows in the open. This helps when it comes to the placement of the outlets and in understanding where the stormwater comes from. Some places the separate system leads the stormwater to outlets where it seems to be no river, but with the shape files it is possible to see where it contributes to the river discharge. The elevation of the outlets and manholes were taken from the digital terrain model.

The existing original model did not cover the lowest part in the urban areas around Skøyen, see Figure 37, so stormwater areas were also added to the model for this part. The same method has been used to determine which areas that contribute to stormwater discharge in the river as before, but this time Gemini VA was the only source to show which areas that were combined and which that were separate systems.



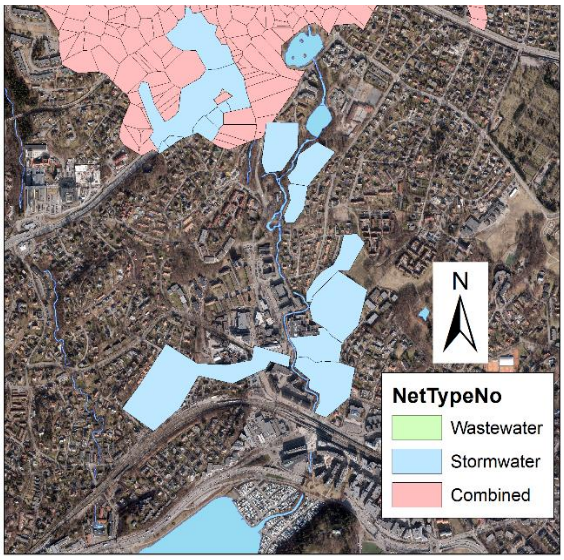


Figure 37: Lower part of Hoffselva before *Figure 38: Lower part of Hoffselva after*

When the network in the model was in place, it had to be tested. This was done by running a scenario that were done in the previous study in 2011. In the beginning, there were a few error messages that had to be sorted out, but after some time it ran without any errors. The next step was to update the input data for the model. In the preparation for the supervision, data about precipitation and air temperature were collected for the research periods Jun-Aug 2009, Sep-Dec 2014 and Sep-Dec 2015. Since MIKE URBAN needs a minimum of 6 months of precipitation in advance of the simulation period to recreate the initial conditions, a precipitation file and an air temperature file for 2008-2015 were collected from the meteorological station at Blindern. The existing evaporation file was updated to 2015. In order to enter the data in MIKE URBAN, the files had to be converted from csv/txt files and into dfs0 files which MIKE URBAN uses.

There are two ways of doing this: with the time series editor in MIKE URBAN or with Mike Zero. The time series editor was not able to read the input files in the way that was wanted, so we had to try with Mike View instead. Mike View sorted out the data in the right way, but the author only had a demo license so it was not able to save more than 50 time steps. To help out with the problem DHI, the producer of MIKE URBAN, was contacted and they helped out with converting the files to the right dfs0 format.

3.5.2 Scenario

The periods of interest were June-August 2009, September-December 2014 and September-December 2015. After some simulations, it became clear that it would take a lot of computer power, time and storage space if we were to simulate all these periods. It was made an attempt to simulate just one week, but just this took about 3 hours and produced a result file of 7 GB. Because the size of the file it caused MIKE URBAN to crash when trying to open it. It was decided pick out rain events of a couple of days, because the CSO's are expected only to be active during the heavy rain periods. After consultation with the supervisor it was decided to focus on one specific rain event in October 2014. The selected period is a 9 days' period from 18- 27 October. In this period, we had good data available for calibration and several observations in form of video clips and pictures from the rain event. The discharge values were available for every 5 minutes from the Oslo VAV station. They were found to have large deviations for some periods, but not for the selected time period.

Figure 39 shows the precipitation data from Blindern station during the 9-days rain period in 2014, as it comes from eklima. It uses a pluviometer, so data is stored for each time the tipping bucket is emptied. The figure shows a dense data registration due to the tipping bucket registration of data.

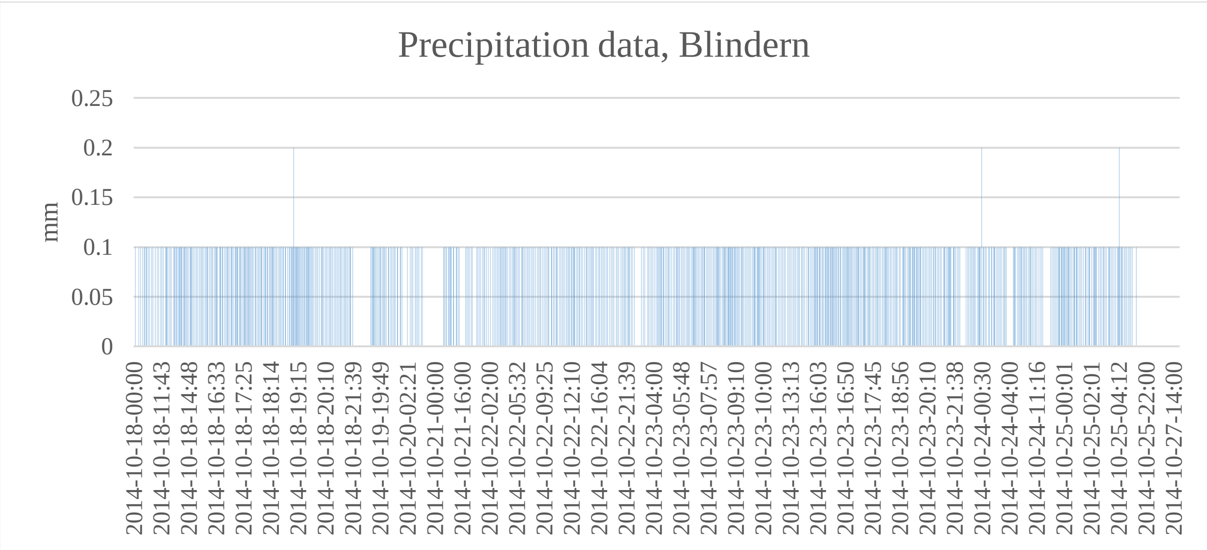


Figure 39: Rainfall intensity pluviometer at Blindern 2014

In order to say something about the intensity of the rain and how often it occurs, the precipitation intensity was calculated. The Norwegian Meteorological Institute has statistical tool that calculates the probability frequency for precipitation at a given station. It calculated the maximum precipitation intensity in the period 18.10 – 27.10.2014, for different storm durations, and compared it with the IDF-curves of the Blindern station. The precipitation intensity is plotted against the IDF-curves in Figure 40.

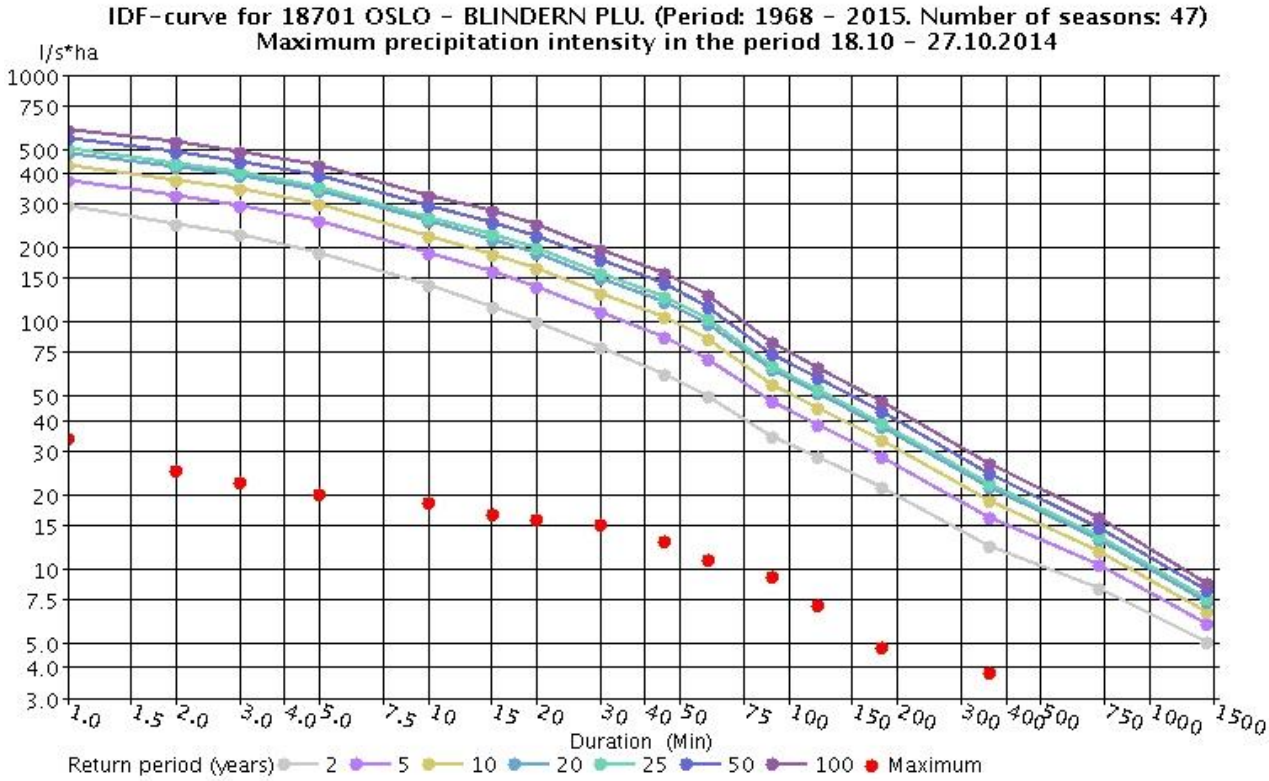


Figure 40: IDF-curves vs. calculated precipitation intensities (eklima.no, 2016)

The calculated precipitation intensity for the chosen scenario (as red dots in the figure) shows that the rain event is well below a return period of 1 year. The return period for the rain event indicates a rainfall which might occur several times in a year.

3.5.3 CSO locations

The CSO activity, that has been simulated, is based on the existing model of by Oslo VAV. The model does not include the whole catchment of Hoffselva, and thereby not all of the CSOs. Figure 41 shows the CSOs that are included in the MIKE URBAN model in orange color. The grey CSOs in the south are not included in the MIKE URBAN model. In total, the model consists of 26 CSOs: 17 stormwater overflows, 4 emergency overflows for pumping stations, and 5 dividing overflows.

The CSOs, which are not included in the model, are outside the modeled sewer network. Table 11 shows the CSO activity during 2012. A common characteristic for the catchment is that the CSO capacity problems of the sewage system accumulates further south in the catchment. As we can see the CSO in grey are pretty active and should be considered a concern regarding the water quality in the fjord and the lowest part of the river.

Table 11: Overflow events for CSOs in grey color (Vannmiljø, 2012)

CSO	Overflow events (2012)	Sum duration in minutes
HO 1	2	90
HO 2	0	0
HO 3	2	30
HO 62	1	22
HO 66	15	185
HO 69	10	1144

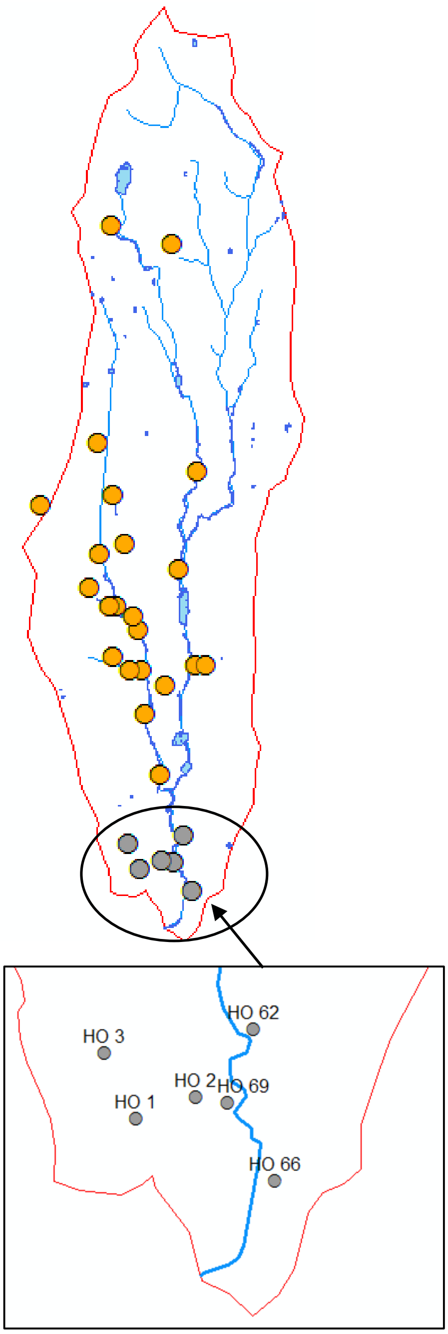


Figure 41: CSO locations, (orange is included in the model)

3.5.4 CSO results

The results from the modeling of CSO spills in MIKE URBAN showed that three of the CSOs were active during the selected scenario. The three active CSOs are located in the southern part of the catchment and discharge to the tributary river Makrellbekken, as shown in Figure 42. During the scenario period of 18. October - 27. October, there were four CSO events.

Figure 42: Active CSOs

The most active CSO is HO6Ma with an accumulated spill volume of 691 m3, during the whole scenario period. It also has the highest spill discharge rate of 90.5 l/s.

Table 12: Accumulated spill and highest spill discharge during the whole scenario

CSO	Accumulated spill volume	Max. spill discharge
HO11Ma	8.5 m^3	6.6 l/s
HO9Ma	34.3 m^3	5.9 l/s
HO6Ma	691.2 m^3	90.5 l/s

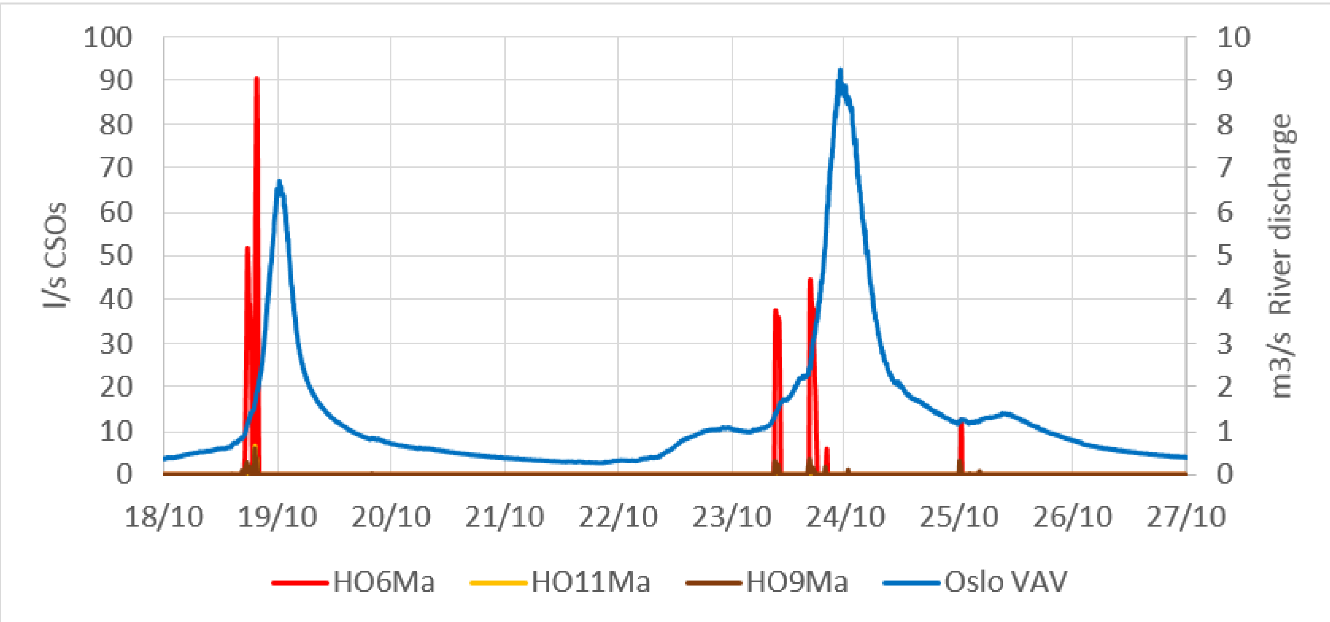


Figure 43: Modelled CSO event

Figure 44 shows one of the CSO events. The discharge graphs are made from the results in MIKE URBAN. The result for the rest of the CSO events can be reviewed in attachment 3.

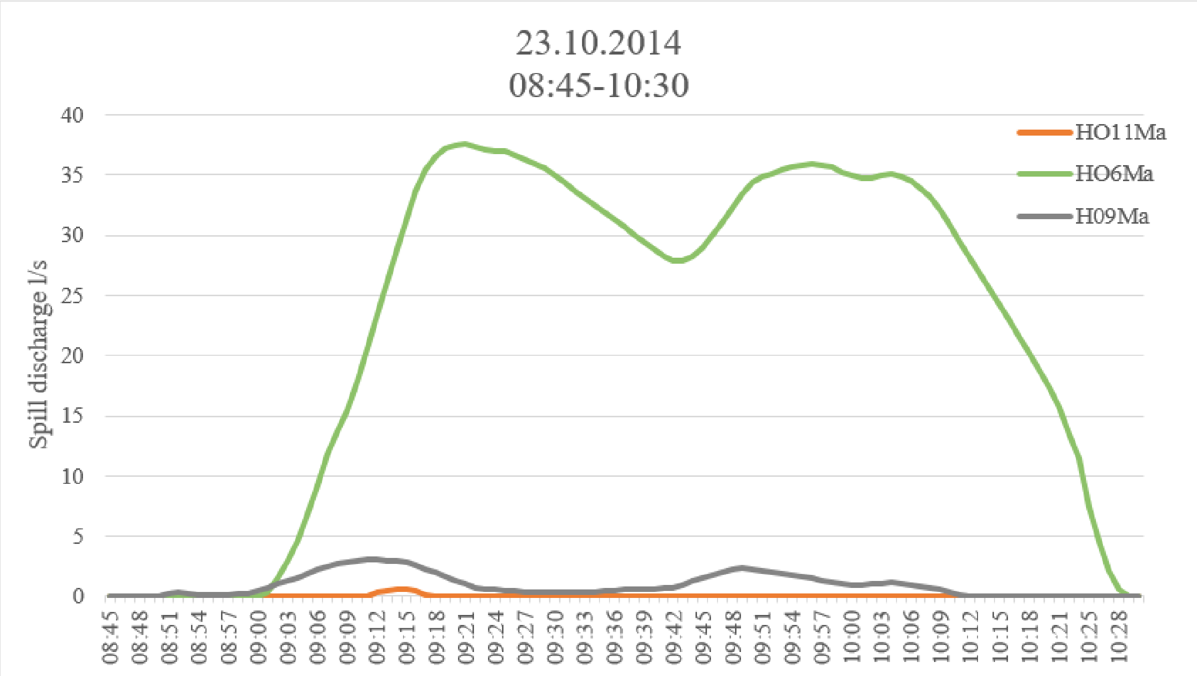


Figure 44: Modelled CSO event on 23. October 2014

3.6 Modeling hydrodynamics: HEC-RAS

3.6.1 Model setup

HEC-GeoRAS was used to make the river network for HEC-RAS. With HEC-GeoRAS different RAS layers were made in ArcMap and extracted as geometric data. Some layers are required while others are optional, the layers that were created in this case, were the stream centerlines, banks lines, flow paths, storage areas, cross section cut lines and land use.

The stream centerline layer was the first layer to be created. The stream centerline is used to establish the river reach network. The river network must be digitized in the direction of the flow with reach endpoints coincident at junctions.

Bank lines are used to distinguish the main channel from the overbank floodplain areas. Compared to the main channel, overbank areas are often assigned higher values of Manning’s n to account for more roughness caused by vegetation. The bank lines help to locate the bank points in the cross sections editor when they are extracted to HEC-RAS.

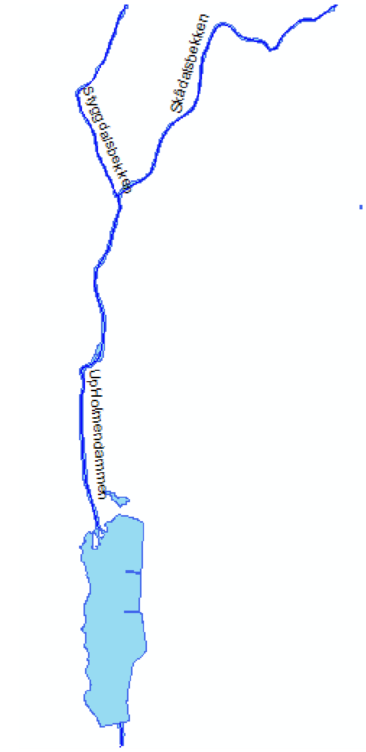


Figure 45: Centerlines for each river reach

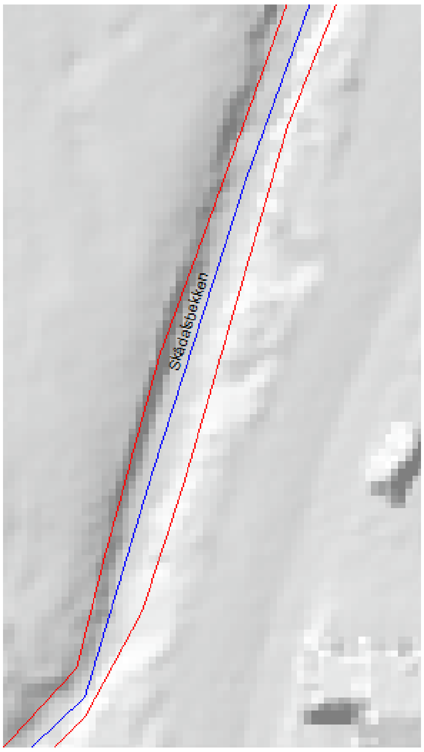


Figure 46: Centerline (blue) and banks (red) with hillshade in the background

The location of the centerlines and bank lines have been determined from the water surface shape file and by looking at the hillshade layer with the elevation contour lines. Hillshade is a shaded relief from a surface raster, in this case the DEM delivered by Oslo VAV. It considers the illumination source angle and shadows and in this way it gives a better visual perspective of the terrain. The centerlines are assumed to be in the middle of the water surface layer and the bank lines are assumed to be on the edge of the water surface layer.

Flowpath lines are used to determine the downstream reach lengths between cross-sections in the main channel and over bank areas. In this case, only the flowpath centerline was used. The flow path centerlines are assumed to lie approximately in the center of the main channel so they can be used as flow path centerlines. Since the overbank flowpaths are not specified, the overbank flowpath length will be assigned the value from the channel flowpath length as default.

Cross sections cutlines are used to extract the elevation data from the terrain to create a profile across channel flow. To create the cross sections, it is important that they are digitized perpendicular to the direction of flow. They must span over the entire flood extent to be modeled, and they always have to be digitized from left to right when looking in the downstream direction. It is used a 12-meter width of the cross sections and 20 meter intervals between each cross section. With HEC-GeoRAS, reach/river name, station number along the centerline, bank stations and downstream reach lengths will all be extracted from the drawn centerlines, bank lines, channel flow path and DEM.

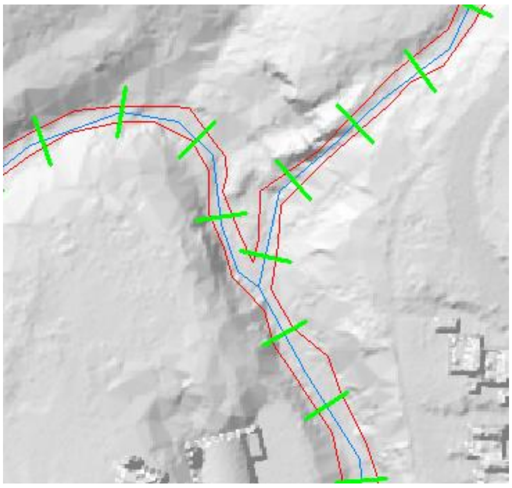


Figure 47: Cross section cutlines added (in green)

The final task before exporting the GIS data to HEC-RAS geometry file, is to assign the Manning's n value to the cross sections. In HEC-GeoRAS, this is accomplished by using a land use feature class with Manning's n values stored for different land use types. In this case a polygon was made for each part of the river with approximately the same Manning's n values, and a value were assigned for the whole polygon. In this way, each cross section inside the polygon will get the same Manning n value. The Manning n values used within each polygon is estimated from satellite photos and pictures taken of the river at several locations, by looking at the vegetation and the size of the river. The n-values are determined with the values from Chow (1959), which most literature refers too. The uncertainty related to the n-values can be +/- 20 percent or more.

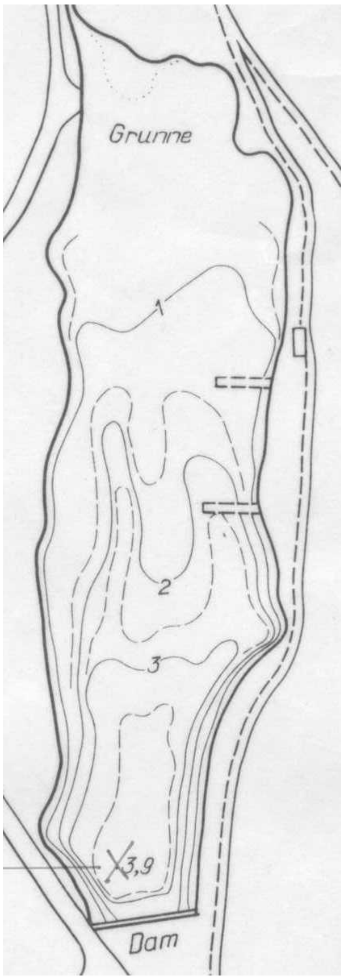
Figure 48: Land use polygons added

Table 13: Mean values of the Manning coefficient n for water flow in open channels (Dingman, 2008)

Type of channel and description	**Min.**	**Normal**	**Max.**
Natural streams, main channels			
Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
Clean, straight, full stage, no rifts or deep pool, but more stones and weeds	0.030	0.035	0.040
Clean, winding, some pools and shoals	0.033	0.040	0.045
Clean, winding, some pools and shoals, but some weeds and stones	0.035	0.045	0.050
Same as above, but with more stones	0.045	0.050	0.060
Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
Very weedy reaches, deep pools or floodways with heavy stand and timber and underbrush	0.075	0.100	0.150
Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
Bottom: cobbles with large boulders	0.040	0.050	0.070
Closed conduits flowing partly full			
Concrete: culvert, straight and free of debris	0.010	0.011	0.013
Concrete: culvert with bends, connections, and some debris	0.011	0.013	0.014

Storage areas are used to model floodplain detention storage where the simulated water surface will be horizontal. A storage area is used to define an area in which water can flow into and out of. Storage areas are not reflected in the cross-sectional geometry. Storage areas can be added in HEC-GeoRAS by drawing a polygon for the storage area and describe it by using elevation range, elevation-volume data or terrain point extraction. In this thesis the elevation-volume data method is used to describe the storage volume of Holmendammen.

The elevation-volume data calculates elevation-volume curve for the storage area from the minimum elevation to the maximum elevation. With a sketch of the bathymetry of Holmendammen, from 1979, it was possible to use ArcMap and find the areas for each depth and then to calculate the volume in relation to the depth. The water surface elevation is assumed to be 107.8 masl, the same elevation which is given by the digital elevation model. See Figure 49.



Depth [m]	Area [m2]	Acc.Volume [m3]	Elevation [masl]
3.9	21 583	0	107.8
3.5	17 249	369	108.2
3	12 078	1 822	108.7
2.5	8 973	4 391	109.2
2	6 306	8 211	109.7
1.5	3 968	13 473	110.2
1	1 845	20 805	110.7
0	1	40 221	111.7

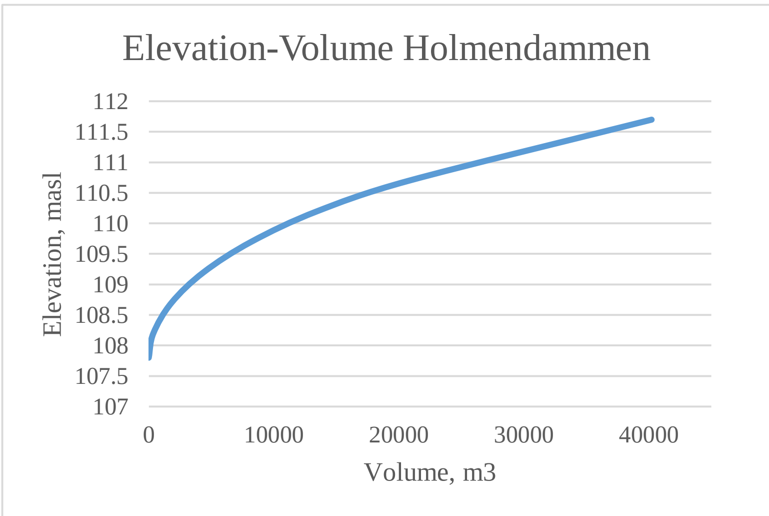


Figure 49: Elevation-Volume curve for Holmendammen

Export of data

As described, the basic river geometry was created in ArcMap with the HEC-GeoRAS extension. River centerline, bank lines, flow paths, cross sections, storage areas, n-values and river names were created. The data were exported into GIS format files (xml and SDF files) that HEC-RAS is able to import. Figure 50 shows how it looked like in ArcMap before export and how it looked like after import in HEC-RAS.

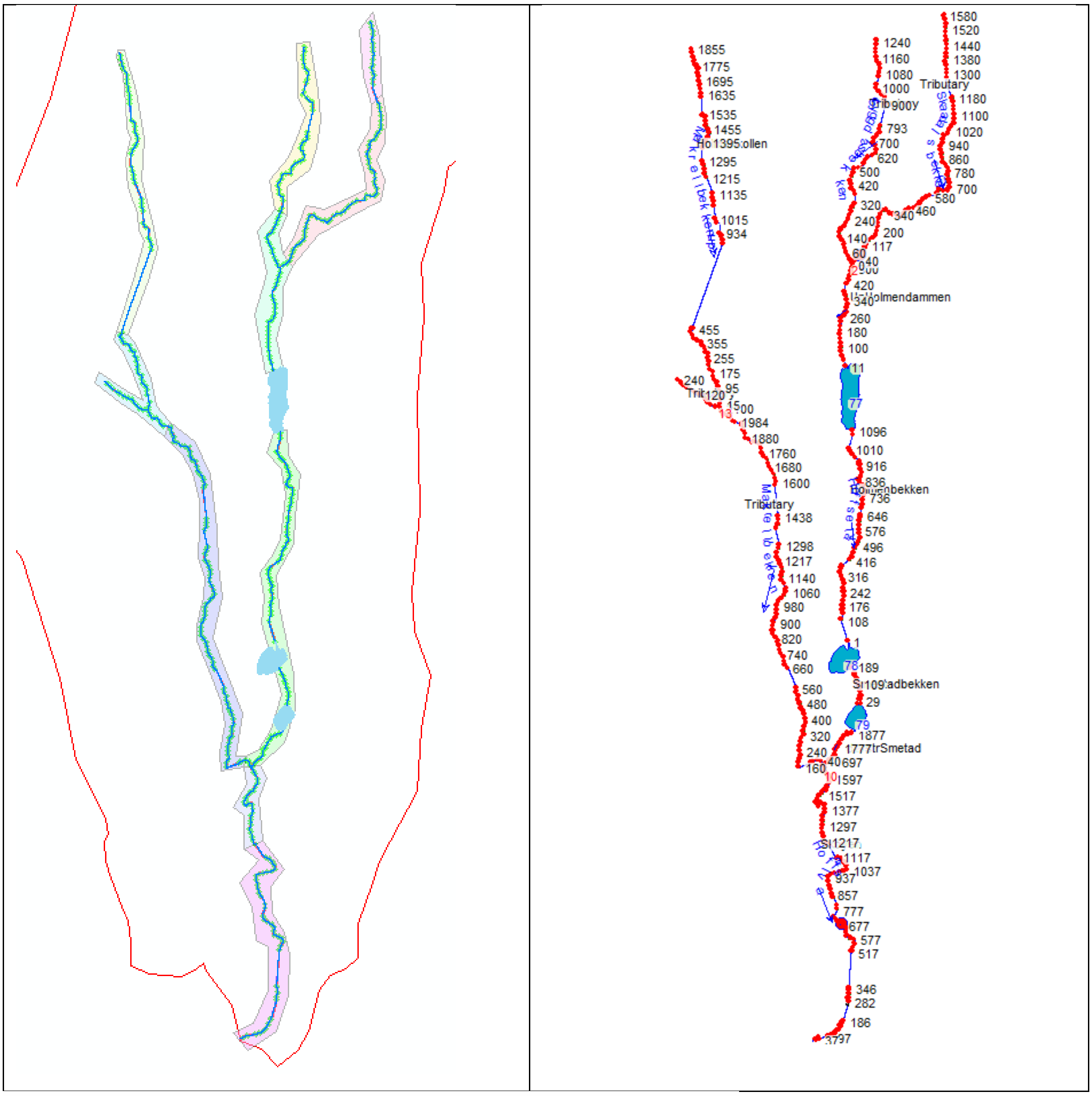


Figure 50: Export of data: ArcMap on the left, HEC-RAS on the right

Preparing the model

Hoffselva consists of many culverts. The HEC-RAS model in this thesis is not supposed to simulate flood events, so the culverts are neglected as they are assumed to not have a bottleneck effect on the flow in the river. A case study of flood risk conducted by SINTEF (Nie, 2011) on behalf of Statens vegvesen, were used to assign the culverts under the road E18. The study showed that it was a bit complicated culvert crossing under the road, consisting of three different type of culverts. From the sketches it looked like the first 24.7 meters consists of two circular culverts with a diameter of 3.0 m and 1.8 m. Next part of the culvert crossing the two culverts combine into on circular pipe with a diameter of 2.7 m for 30.5 meters before it ends up in a 3.0 m circular pipe for the last 21.7 meters. As a simplification the culvert can be set to a circular pipe with a diameter of 3.0 meters for the whole length of the culvert. The tunnel underneath Skøyen railway station can also be added to the model with the same geometrical data as in report (Nie, 2011).

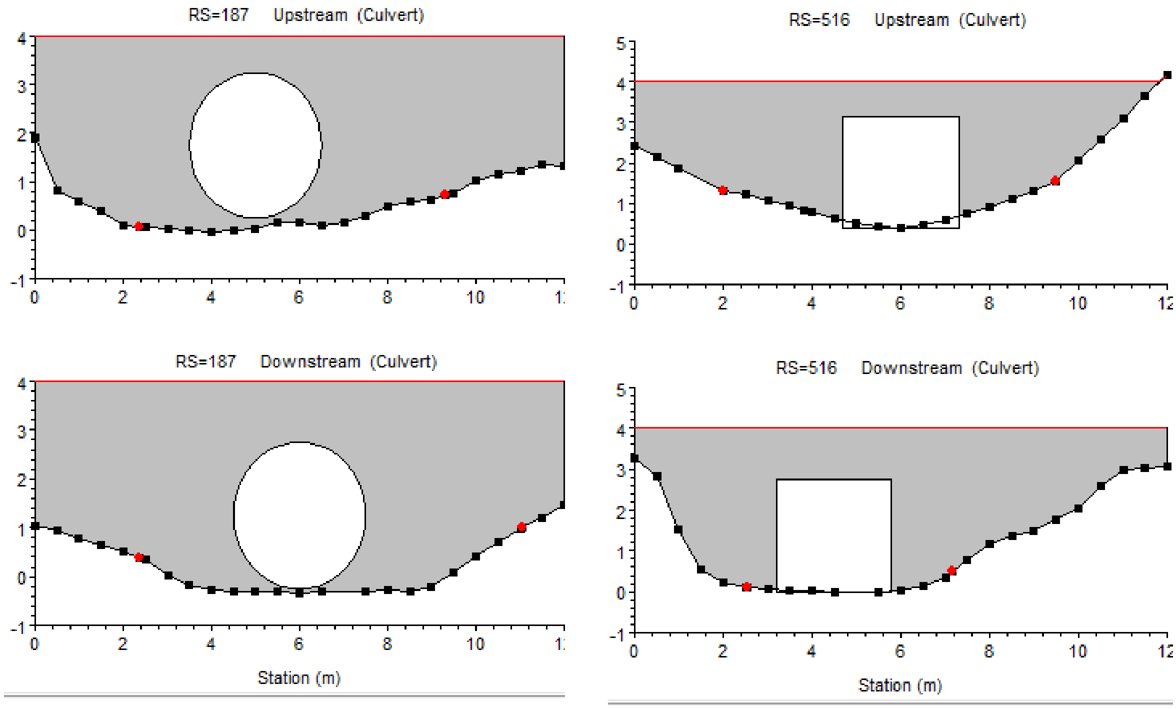


Figure 51: Culverts which can be added to the model at Skøyen

The smaller culverts are neglected in this model, because the author did not have information about the geometrics and because they are assumed to not have a great impact on the water quality. In CSO modelling the lower discharges are important because then the dilution effect is small and the pollution effect is greater than in a flood event where the wastewater is highly diluted. Under normal rain conditions the capacity of the culverts will not be exceeded and there will not be a bottleneck effect that will have an impact on the water quality. Figure 52 shows a typical neglected culvert/bridge where the river is assumed to be the same as in the previous cross section.

Figure 52: Examples of neglected culverts

As most of the culverts are neglected, cross section interpolation can be used to maintain the approximate distance interval of 20 meters between the cross sections.

In order to control the cross-section, a steady flow simulation was done to establish the water levels in the cross section during a given discharge. Based on the established hydrographs for discharge and measured discharges, a specific discharge was given as boundary condition upstream of each reach. The results were used to correct the cross-section so the width of the cross section is wide enough to contain the whole water stage area. Figure 53 shows an example of how the cross sections looked like in the steady flow simulation.

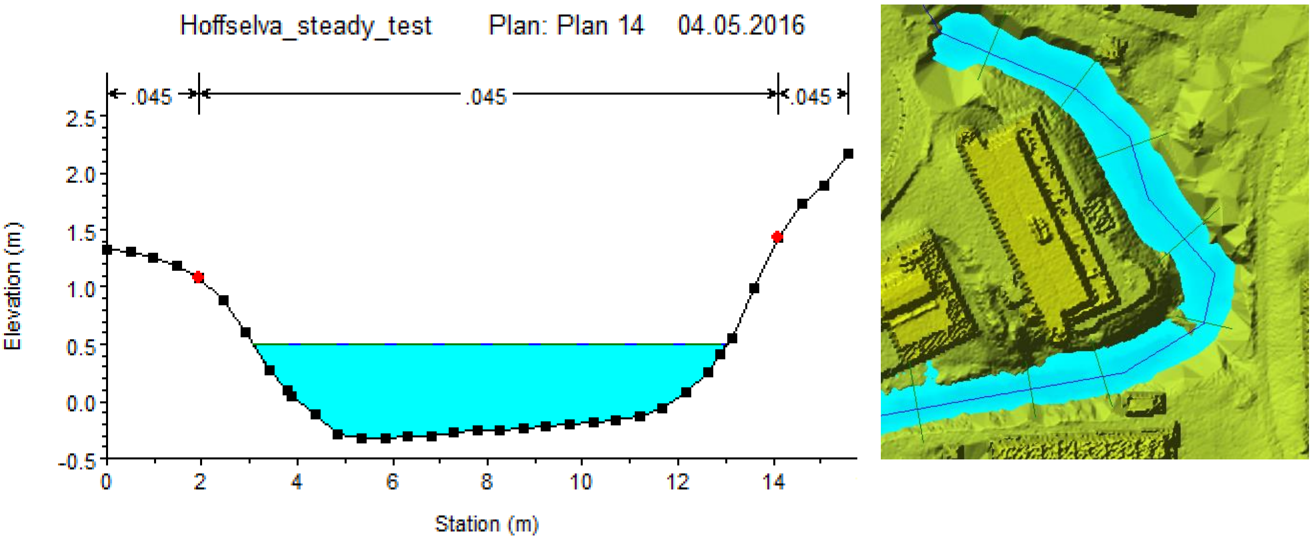
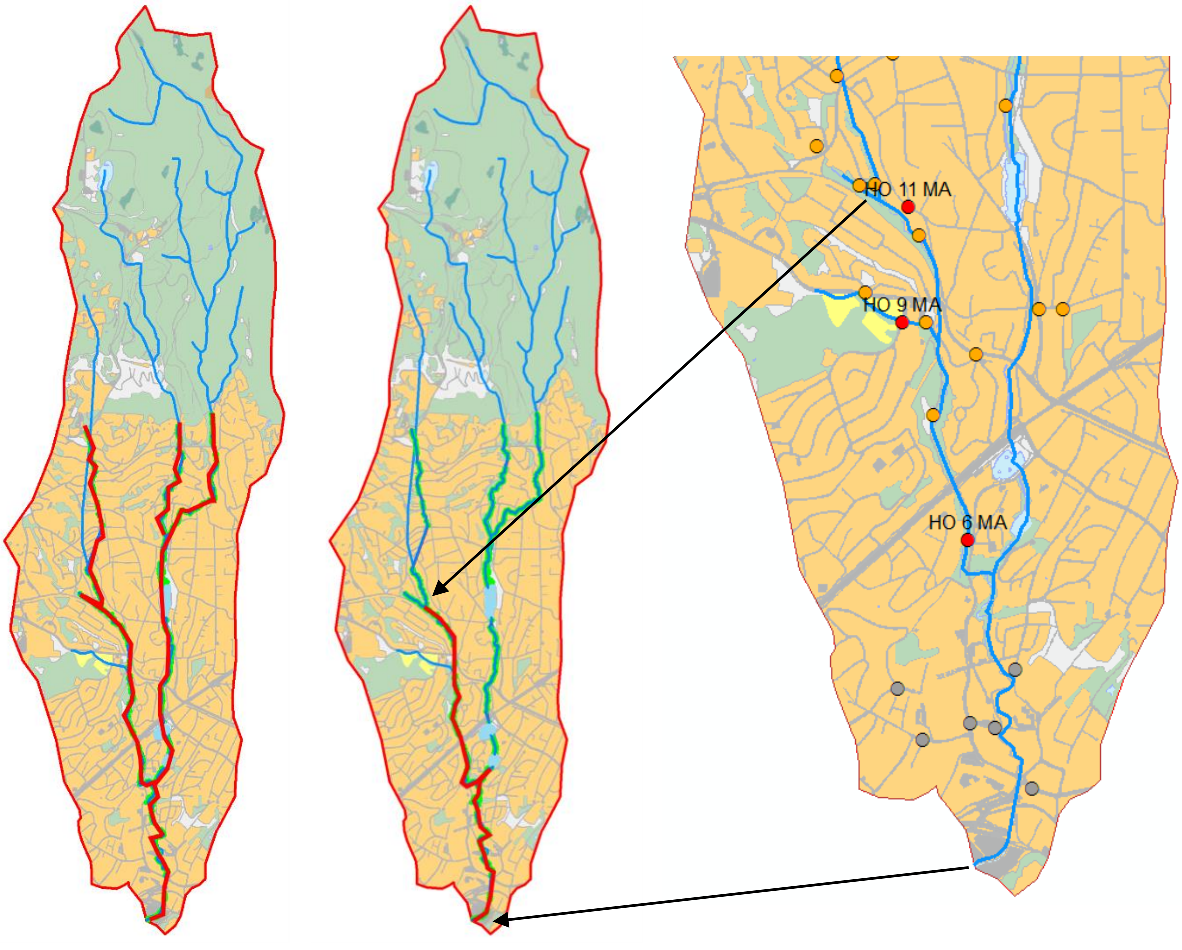


Figure 53: Steady flow test

3.6.2 Unsteady- flow simulation

In order to perform a water quality simulation varying over time, a completed, calibrated unsteady hydraulic model must be available. The unsteady simulation uses the same river geometry as in the steady simulation, but with different boundary conditions. The Hoffselva river contains three storage areas. To implement their effect in the river system, it would be necessary to get more information about the outlet connection of each storage area. For the selected period from 18-27. October only three of the CSOs were active. Based on the task to simulate the effect from the CSOs and the fact that they are located south in river system, it was chosen to reduce the model area to the river lengths of interest. See Figure 54 below.



a) b) c)

Figure 54: a) steady model, b) unsteady model c) Active CSOs

For the unsteady flow calculations, an inflow hydrograph is needed as boundary condition input. Due to lack of discharge measurements along the river, an estimation of discharge was needed. In this thesis, it was chosen to use the established mathematical relation, described in chapter 2.4.3.

Unsteady flow is significantly more complex and requires more data than steady flow. The unsteady model is very sensitive when it comes to numerical instability during unsteady analyses. The advantage with unsteady simulation is the possibility of entering hydrographs as boundary conditions. In this way it is possible to route the water throughout the river during an actual rain event.

To begin with, the reaches of interest (shown in Figure 54), were imported to the unsteady model. Hydrograph curves of the upstream catchments, from the statistical calculation (2.4.3), were combined into one common hydrograph, and used as inflow boundary conditions. See Figure 55.

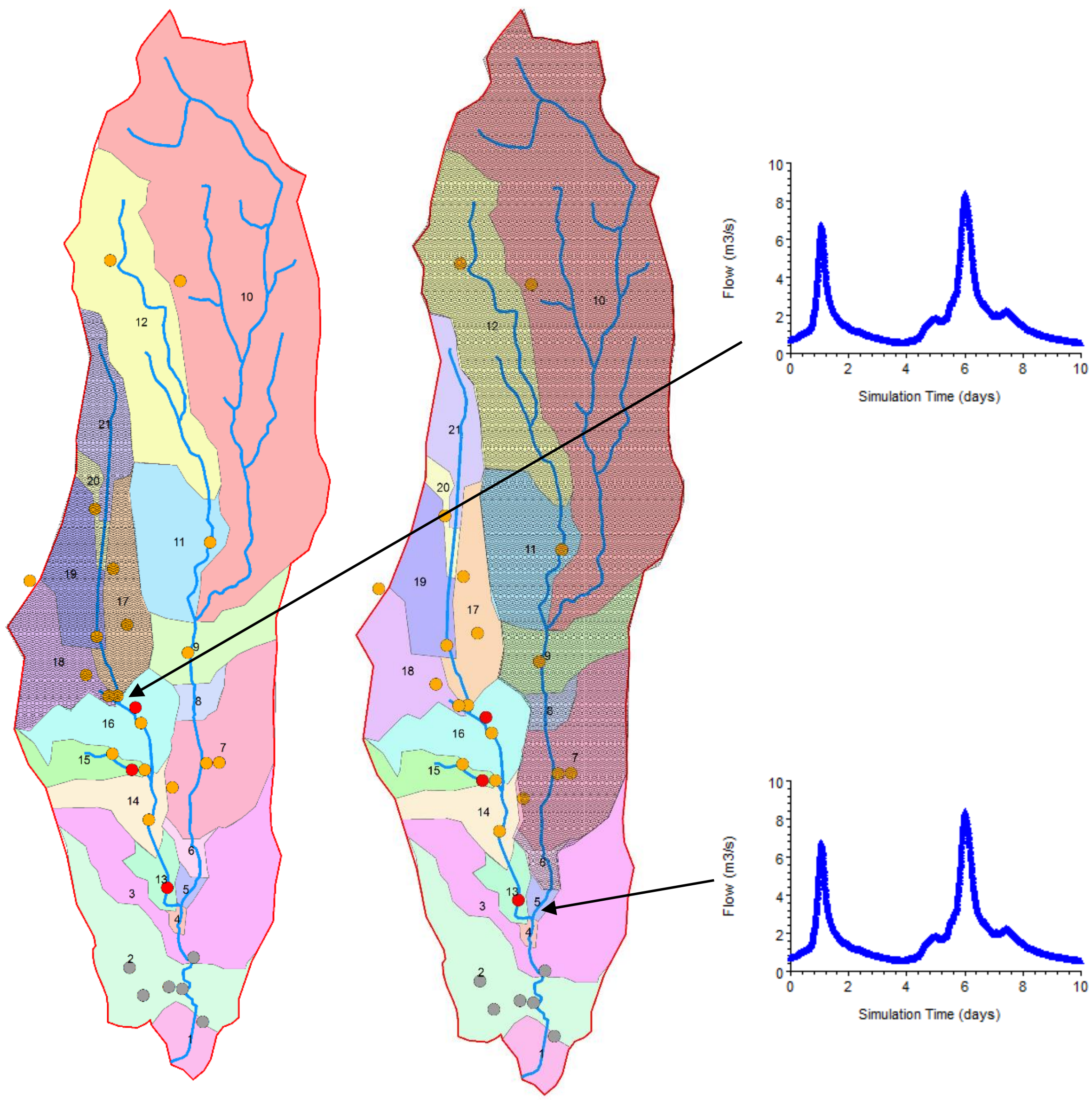


Figure 55: Boundary conditions input for the first unsteady model

The original idea was to use the hydrograph from each sub-catchment as input along the river. This could have been done with the lateral inflow boundary conditions if we had an unsteady model of the whole river system. The hydrographs that have been used as inflow at the upper cross section in the simplified model, are hydrographs where each time step have been summed up for all of the sub-catchments upstream of the cross section. This is a very easy simplification, as in the real world they would have some delay factor because of the distance to the boundary condition cross section. This error is partly shown in the results later and discussed in chapter 4.2.

The time period for the unsteady simulation was set to 18 Oct 2014 – 27 Oct 2014 to replicate the flow in the river during the selected rain event. A stage hydrograph was used as downstream boundary condition. The stage hydrograph describes the stage of the water. In this case, it was used as a boundary condition for the downstream cross section by the fjord. The observed tidal water, in Oslo, varied from 32 – 152 cm during the simulation period. In this thesis it was decided to not focus on the tidal rise of water as it is not considered as an import factor with regard to the low intensity of the rain event. The water stage was set to 0 m stage to simulate the water level of the fjord in the model. The stage hydrograph is considered the most stable downstream boundary condition. However, the stage hydrograph boundary condition caused the model to yield unrealistic high water surface elevations. Instead a Normal depth boundary condition had to be used. A normal depth will be calculated for each profile based on the user-entered slope. If the energy slope is unknown, like in this case, the slope of the water surface can be used. The slope was set to I = 0.01. The initial flow conditions were set to 1 m3/s water flow. This is the basic setup for the unsteady simulation. Attempts were made to run the model, but as expected error after error message occurred. Several measures were applied in order to increase the numerical stability of the computation to get the model to run without any errors.

The first measure to improve the stability was to make changes in the preprocessor. The preprocessor creates hydraulic property tables for the main channel, and the floodplain. The hydraulic tables for the cross sections must be high enough to capture all possible water surface elevations. If the computed water surface goes above what is specified in the table, it can often cause the model to go unstable. Each hydraulic property table contains a minimum of 21 points in the vertical direction for each cross section. The points were set to the maximum value of 500 so the table will have enough detail to accurately depict changes in area, conveyance, and storage with respect to elevation. The increment decides the spacing between the points and was set to 0.03. The starting elevation was set to the minimum channel elevation, meaning the computation starts at the bottom of each cross section. In this way the hydraulic table parameters cover all of the possible water surface elevations by checking with the maximum water elevation in the steady flow simulation. The hydraulic tables were changed in the geometric data editor in the **HTab parameter** (**H**ydraulic **Tab**le Parameters).

The next step was to remove some parts of the reach downstream of Smestaddammen due to a waterfall that caused instability to the model. The reach was added to the model to get the side river inflow effect from the Hoffselva river upstream of Skøyen. Instead of having the reach, it was decided to add the inflow as lateral inflow in the cross section where Makrellbekken and Hoffselva merge. Still the model gave error message for instability problems in the calculations. Attempts were made to fix the problem by increasing the Manning's n numbers and by adding more interpolated cross section to reduce the distance between the cross sections. The number of points in the cross section were also reduced to make less complex cross sections to compute. After several attempts with different computational time steps, it was decided to build the model piece by piece, starting down by the fjord and building the model in the upstream direction.

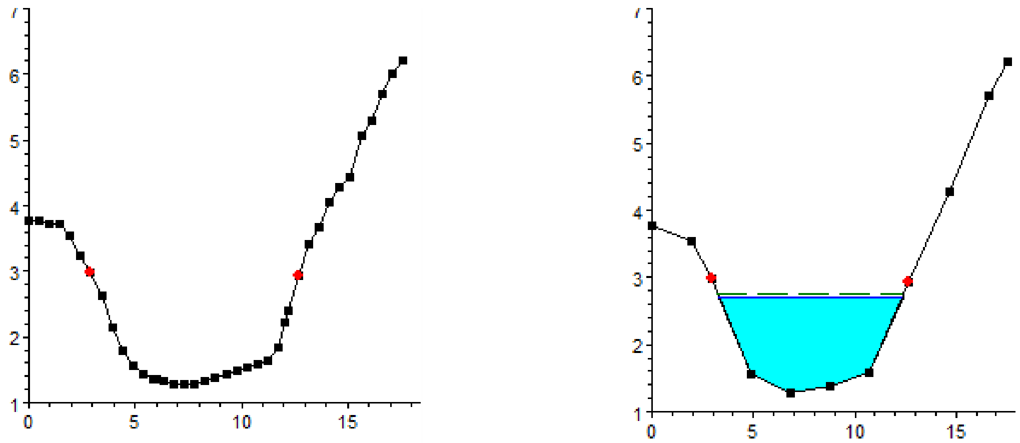


Figure 56: Cross section 737 before and after reduction of point in the cross section

The piece by piece method works out by successfully running the unsteady simulation for a small part of the river and then add more and more of the river geometry to the model as the model runs without errors. Some of the main challenges with modeling Hoffselva and Makrellbekken, are the slope of the river, many small waterfalls, and the flow/water depth is very low especially in the upper parts of Makrellbekken. All them are factors which contribute to instability in the model. Figure 57 shows the longitudinal profile plot of Makrellbekken. It goes from an elevation of 105 masl in the most upstream cross section to an elevation of 14 masl in the most downstream cross section. With a distance of 2085 meters, the slope from bottom to top cross section is I = 0.044. Some places there are even steeper slopes and a few waterfalls.

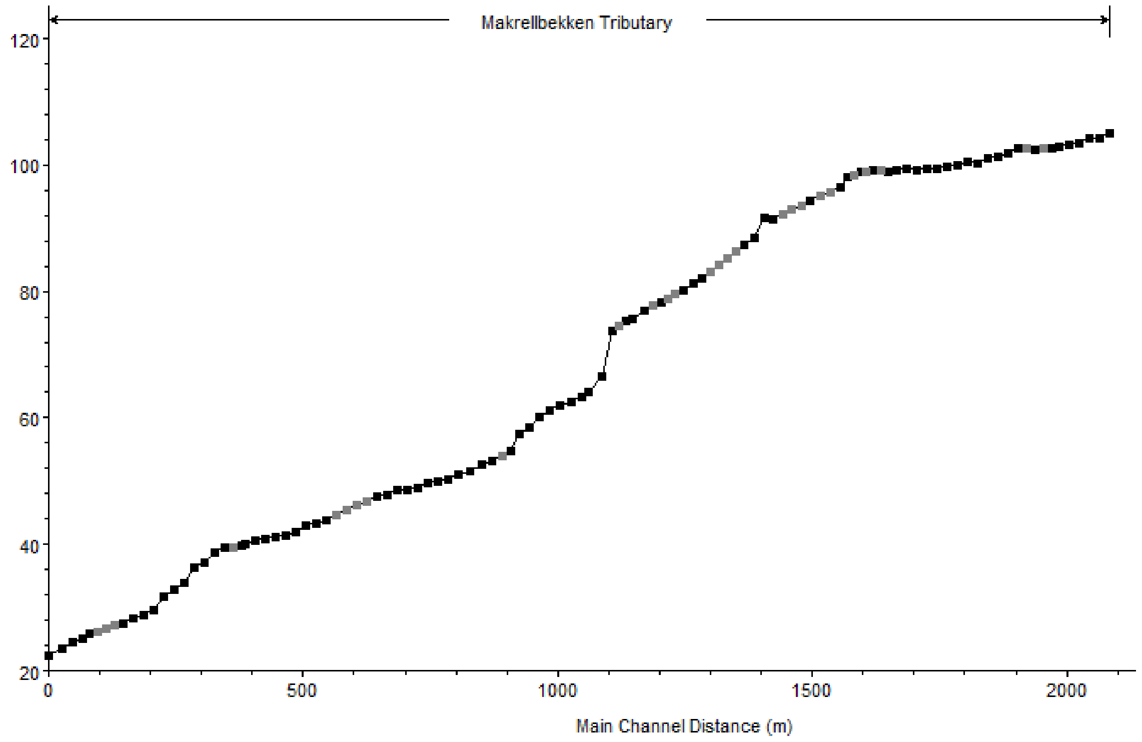


Figure 57: Longitudinal plot of Makrellbekken

The longitudinal plot of Hoffselva, through Skøyen, shows a much smoother slope. However, there is a waterfall right before the urban part of the catchment which also cause instability.

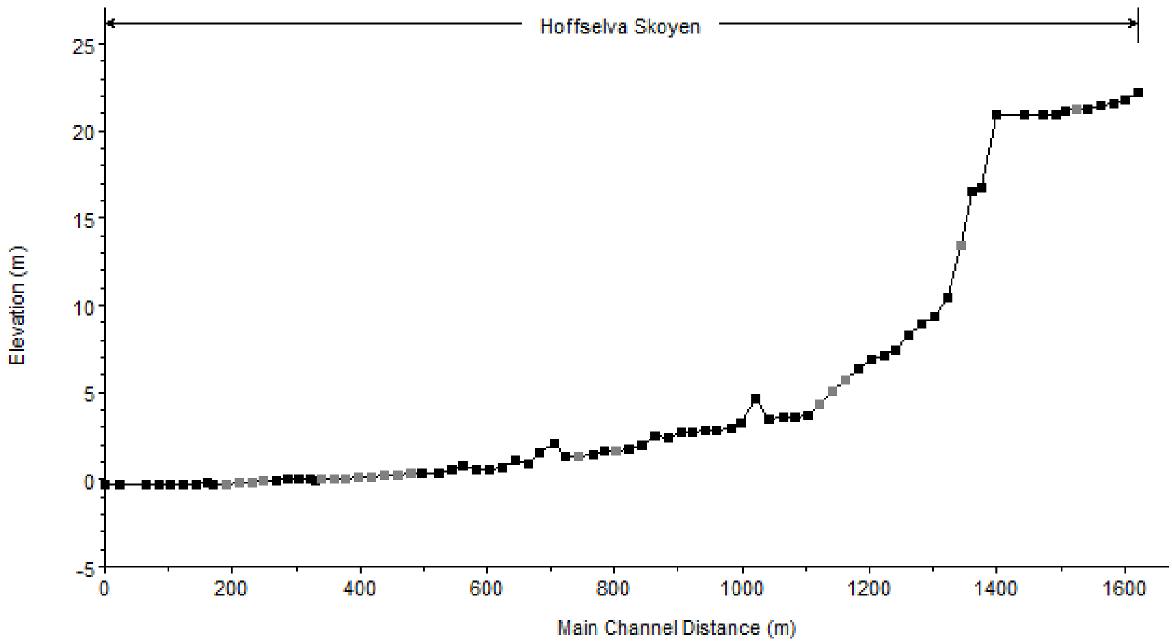


Figure 58: Longitudinal plot of Hoffselva through Skøyen

With regard to the complexity and experience of simulating the model so far, it was decided to simplify the model further. Since the most active CSO (HO6Ma) makes up 94.2 % of the total spill volume during the rain event, it was decided to only make the unsteady model part by part up to the cross section where HO6Ma discharge spill into the river. In this way a lot of work with including the rest of the Makrellbekken was avoided.

When the unsteady model was build part by part, inline structures were used to stabilize the waterfalls. Some of the cross sections had too high elevations (see Figure 58), they were fixed to match the neighbor cross sections elevations.

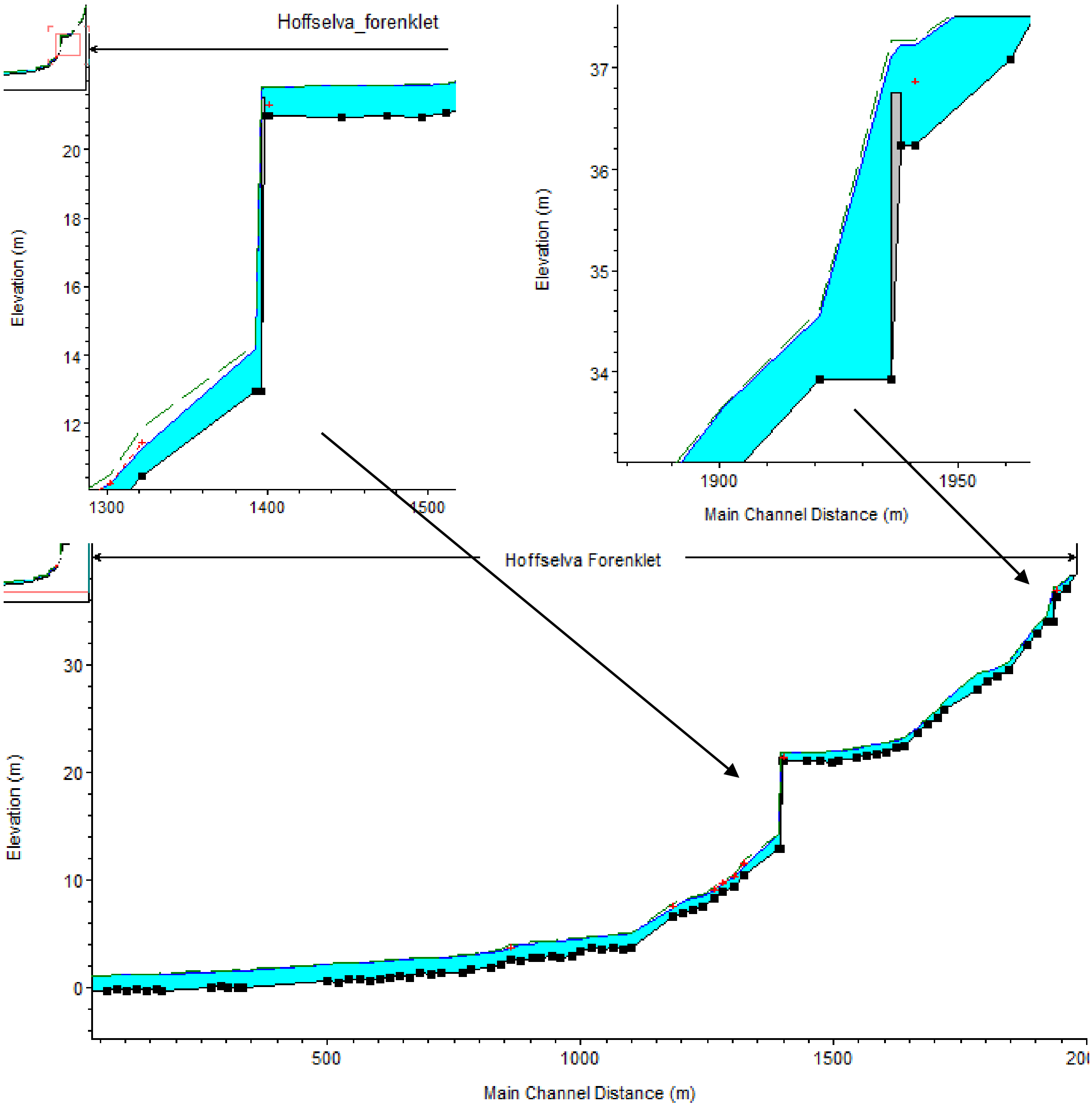


Figure 59: Longitudinal plot of the final unsteady model, with the inline structures

The inflow boundary conditions were updated with data from the statistical model and the remaining sub-catchments were added as lateral inflows.

Table 14: Summary of boundary conditions

Cross section	River	Boundary condition	Comment
1977	Makrellbekken	Flow hydrograph	Aggregated hydrograph of the upstream sub-catchments in Makrellbekken
1637	Hoffselva	Lateral inflow hydrograph	Aggregated hydrograph of the upstream sub-catchments in Hoffselva
1337	Hoffselva	Lateral inflow hydrograph	Inflow from sub-catchment 4
1080	Hoffselva	Lateral inflow hydrograph	Inflow from sub-catchment 3
513	Hoffselva	Lateral inflow hydrograph	Inflow from sub-catchment 2
14	Hoffselva	Normal depth	Boundary condition of the fjord

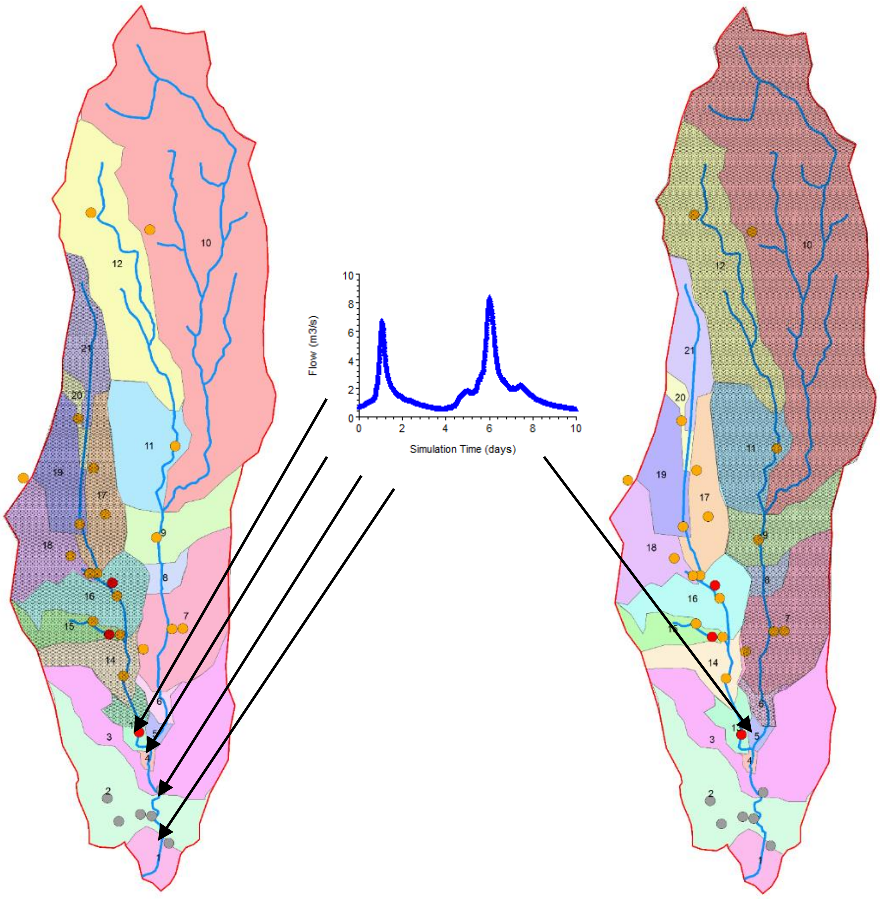


Figure 60: Boundary conditions for the final unsteady model

3.6.3 Unsteady simulation results

In the HEC-RAS model, the Oslo VAV measurement station is located at cross section 718. Oslo VAV has hydrographs of the flow in the river at this point in 5 min time resolution. When the observed flow data from Oslo VAV are plotted against the simulated flow hydrograph in cross section 718, we get the comparison shown in Figure 61.

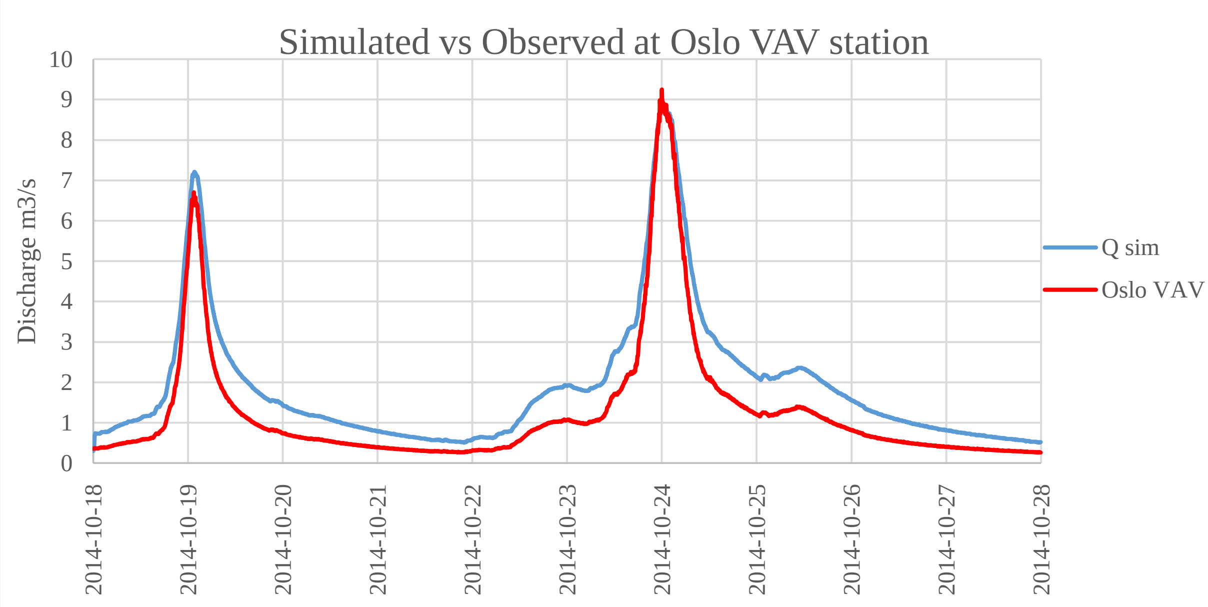


Figure 61: Simulated discharge versus observed discharge

As we can see the simulated values match the measured values at the peaks, but before and after the peaks the simulated values are a bit higher than the observed. Considering the uncertainties with the input data and the model, discussed in chapter 0, it was decided to calibrate the model to fit the observed values. Since the values have a good match in the peaks, a calibration function (Eq. 20) was developed.

		$$Q_{i,c} = Q_i \pm X\% * \frac{Q_m - Q_i}{Q_m}$$	Eq. 20
Where:			
$Q_{i,c}$	=	Calibrated discharge at timestep i	
Q_i	=	Discharge at timestep i	
Q_m	=	Maximum discharge for the whole discharge time series	
X	=	Calibration parameter	

The calibration parameter can be both positive and negative, depending on if the time series needs to be upscaled or downscaled. In the peaks, the discharge will be almost similar to the maximum discharge, and the formula will yield a very little change in the values. The calibration function was applied to the inflow hydrograph at the top of Makrellbekken and to the lateral inflow hydrograph from Hoffselva upstream Skøyen. The calibration of the hydrographs gave a lower discharge input to the model which caused the model to become even more unstable. Due to the terrain in the catchment the model needs a certain flow in the river to become stable in the computations. As a minimum flow in the river, the minimum flow from the original flow hydrographs were used. Figure 62 shows how the inflow hydrograph at Makrellbekken looked like before and after calibration.

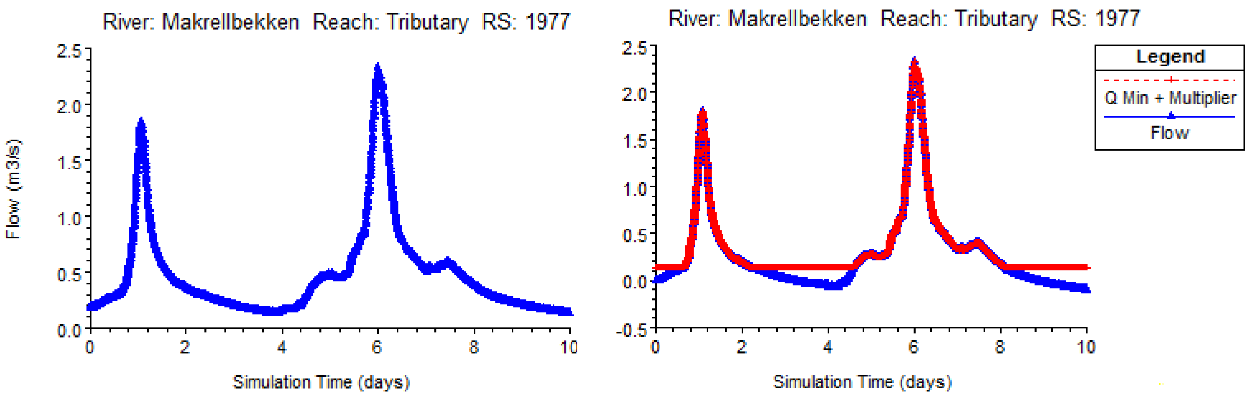


Figure 62: Inflow hydrograph at Makrellbekken before and after calibration

After trial and error with the calibration the final result was a simulated hydrograph that is visually well fitted against the one measured at the Oslo VAV station.

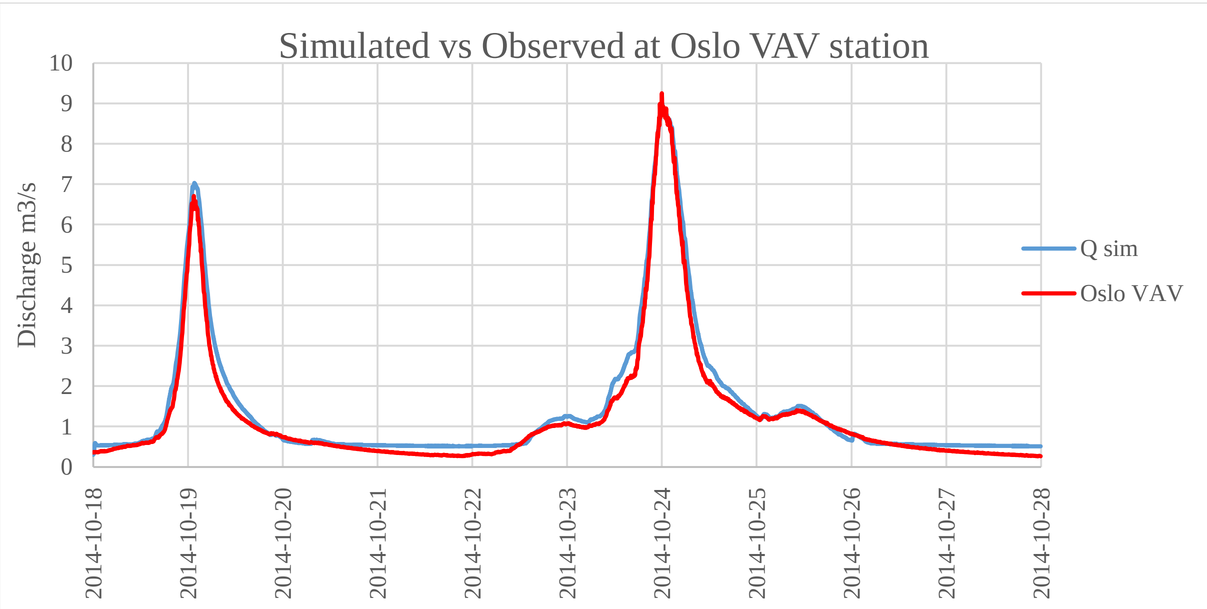


Figure 63: Calibrated model output hydrograph at cross section 718

3.7 Modeling water quality: HEC-RAS

3.7.1 Model setup

As mentioned earlier, a calibrated unsteady or steady hydraulic model is required to perform a water quality analysis in HEC-RAS. The hydrodynamic model computes water flow and water stage at all cross-sections at all time-steps. The water temperature model uses this information together with computed heat fluxes to solve the advection dispersion equation. In addition to the hydraulics plan from the steady or unsteady simulation, the water quality simulation requires entered water quality data. The data is entered in the water quality data window in HEC-RAS. The program asks for water temperature boundary conditions, initial water temperatures, dispersion coefficients, meteorology datasets etc. The data can be entered as tables or they can be given a constant value.

When the hydraulic plan from the unsteady flow calculation was used in the water quality simulation, an unknown error occurred. The author of this thesis tried to solve the problem through a network of people at NTNU and consulting companies, but with no luck. Since the error could not be fixed within the remaining time for the project, it was decided to add steady flow data and use the hydraulic plan from the steady flow calculations instead.

Water temperature: Water temperatures have to be assigned at all of the cross sections where boundary conditions were entered in the steady model. Water temperatures were available for the Oslo VAV station in cross section 718. It was assumed that the same temperatures can be used at different locations in the river as well.

Initial conditions: A water temperature of 6.75 Celsius was set as initial condition, because it is the first temperature registration in the data series for the selected period.

Dispersion coefficients: are set to the internally computed values by HEC-RAS, based on hydraulic variables at each face from the steady flow simulation.

Meteorology datasets
Atmospheric pressure: Time series in KPa collected from Blindern station
Air temperature: Time series in Celsius collected from Blindern station
Humidity: Time series in % Relative Humidity (RH) collected from Blindern station
Short wave radiation: Constant value of 130 W/m2 in October, data from the municipality
Cloudiness: Constant cloudiness fraction of 0.9, collected from NASA earth observatory
Wind speed: Time series in m/s (10 m above the ground), collected from Blindern station
Observed data: time series of water temperature, same as the water temperature data

The minimum cell length was set to 10 meter, which equals 97 water quality cells for the model. To replicate the flow conditions in the river, several river stations were added as flow change locations. The flow change locations are located at the pour point for the sub-catchments along the river. Two flow conditions were created. Scenario "Simulated flow" contains average flow values from the first simulated discharge, in Figure 61, during the CSO event. "Observed flow" contains flow values derived from the average observed flow for the CSO event.

Table 15: Steady flow data for the simplified water quality model

River station (cross section)	Simulated flow [m3/s]	Observed flow [m3/s]
1997	0.29	0.153
1677	1.783	0.84
1337	1.787	0.95
1080	1.957	1.039
513	2.087	1.108

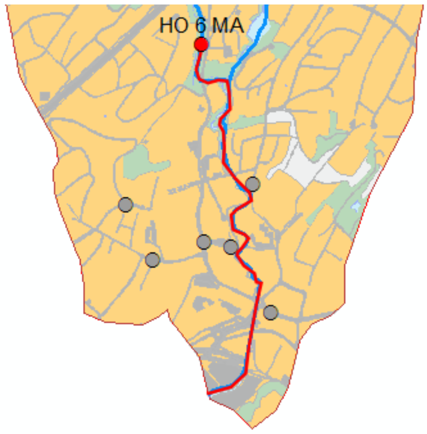


Figure 64: Simplified water quality model

3.7.2 Water quality simulation

In order to run the nutrient modeling, a functioning temperature model needs to be in place. The temperature model requires the meteorology datasets, given in the model setup chapter above. The maximum temperature during the simulation period is shown in Figure 65. As we can see from the figure, the water temperature does not change much. The figure displays the maximum daily water temperature, which occurred at 27. October.

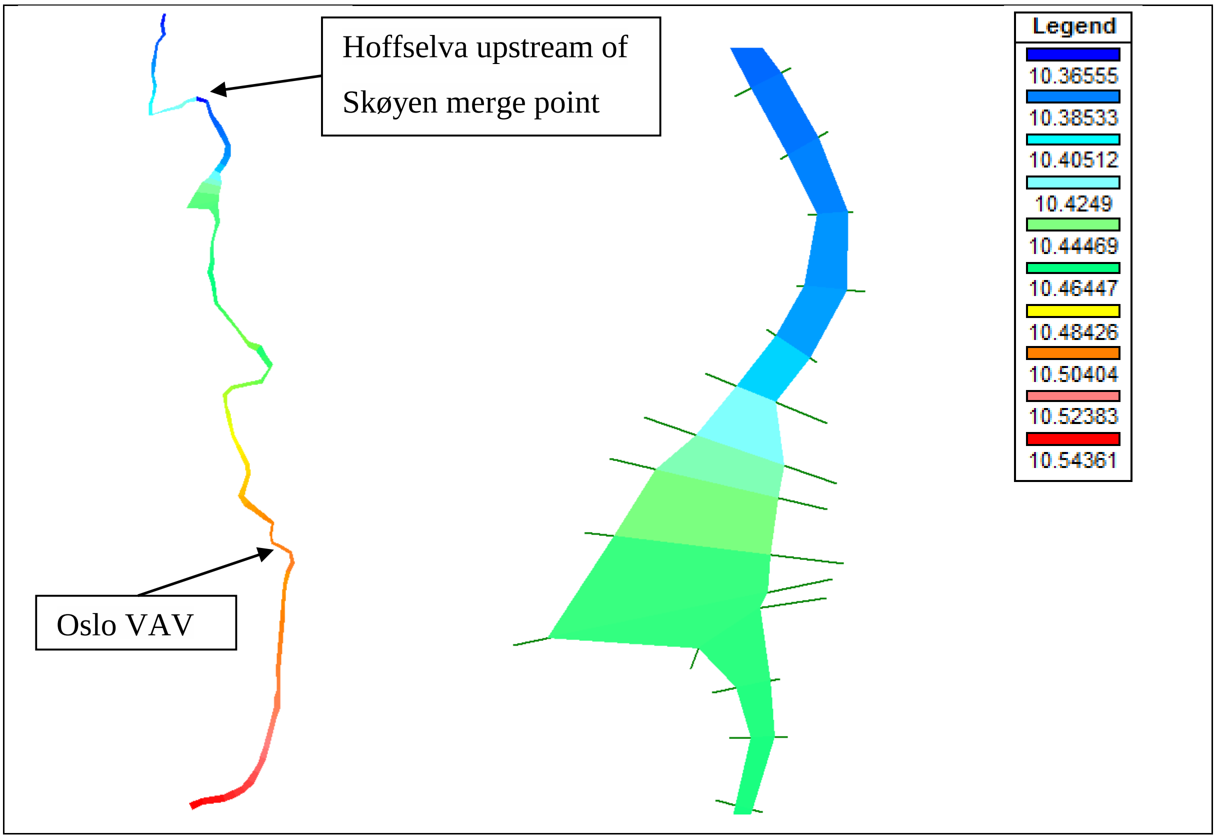


Figure 65: Temperature model

Non-conservative constituents are tied to biological or seasonal cycles and have short residence time. The nutrient modeling simulates the non-conservative parameters: nutrients, dissolved oxygen, CBOD, and algae. Because most of the rate constants in the nutrient model are temperature dependent, nutrients may not be modeled unless water temperature is simulated. In this thesis, information about conservative constituents such as suspended solids and turbidity were available. Conservative constituents occur in constant proportion or change very slowly through time, and have long residence time. To model the conservative constituents, it is possible to use the mass injection function in HEC-RAS. The mass injection gives the opportunity to introduce a quantity of mass rather than concentration into the model. Conservative constituents have to be entered as “arbitrary constituents”, which means they are independent of water temperature and nutrients.

Mass injection is useful for simulation of spills and for dye studies, when the problem requires the introduction of mass rather than concentration of a particular constituent (Brunner, 2016b). To simulate the CSO event, information about: location, time, mass, and duration of the spill have to be set. In addition, an initial concentration of the arbitrary constituent has to be set for the river.

When mass injection is used, the total amount in gram, is distributed over the duration for the spill event. This may be a good way to simulate the effect of a spill into a river where the concentration is constant throughout the spill event, but for CSO events this leads to an unrealistic distribution of concentration. As discussed in previous chapters, the concentrations are typically higher in the beginning of a CSO spill. To model simulate a more realistic CSO spill, a pollutograph was created. In this master thesis, it was chosen to model the amount of suspended solids in the river. This is because suspended solids is a conservative parameter and it has been proved to have good correlation with total Nitrogen, total Phosphorus, Nickel, and Lead in Hoffselva during the simulation period. The correlations are described in Table 16. Total Nitrogen and total Phosphorus are nutrients, which is considered as non-conservative parameters. In this thesis the nutrient modeling is simplified by using a conservative parameter (SS), which is converted to nutrients by using the correlation from measurements at Hoffselva. The pollutograph for the spill is based on the typical distribution of SS during CSO events measured by Inrigo Water.

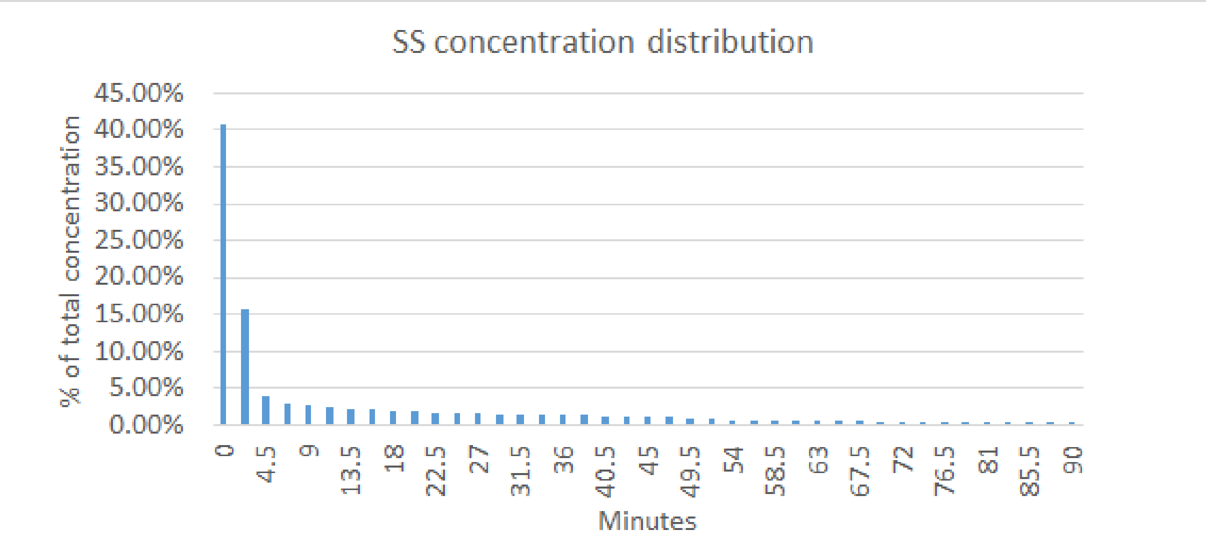


Figure 66: SS concentration distribution based on Inrigo Water measurements

NIVA (Norwegian Institute for Water Research) has measured data from the 23. October 2014, so it was decided to model the CSO event which occurred 09:00-10:30 on 23. October 2014 (Tryland et al., 2016). The CSO activity results from MIKE URBAN contains the discharges from the CSO during the event, but it does not contain information about the concentrations of suspended solids. In order to calculate the total amount of suspended solids in gram, which is needed as input to the mass injection, we need the concentrations of SS. In literature, the concentration of SS varies from study area to study area. Parameters such as soil use, population density, traffic intensity, rain event etc. varies and produce differences in concentrations.

It was chosen to use average values from previous measurements conducted in the Hoffselva treatment container. On 8. February in 2016, measurements of SS concentrations were done for a CSO event with approximately the same duration as the one simulated in this thesis. The concentrations varied from 41 to 1900 mg/L SS, which according to literature seems to be a normal finding in combined sewer systems during CSO events.

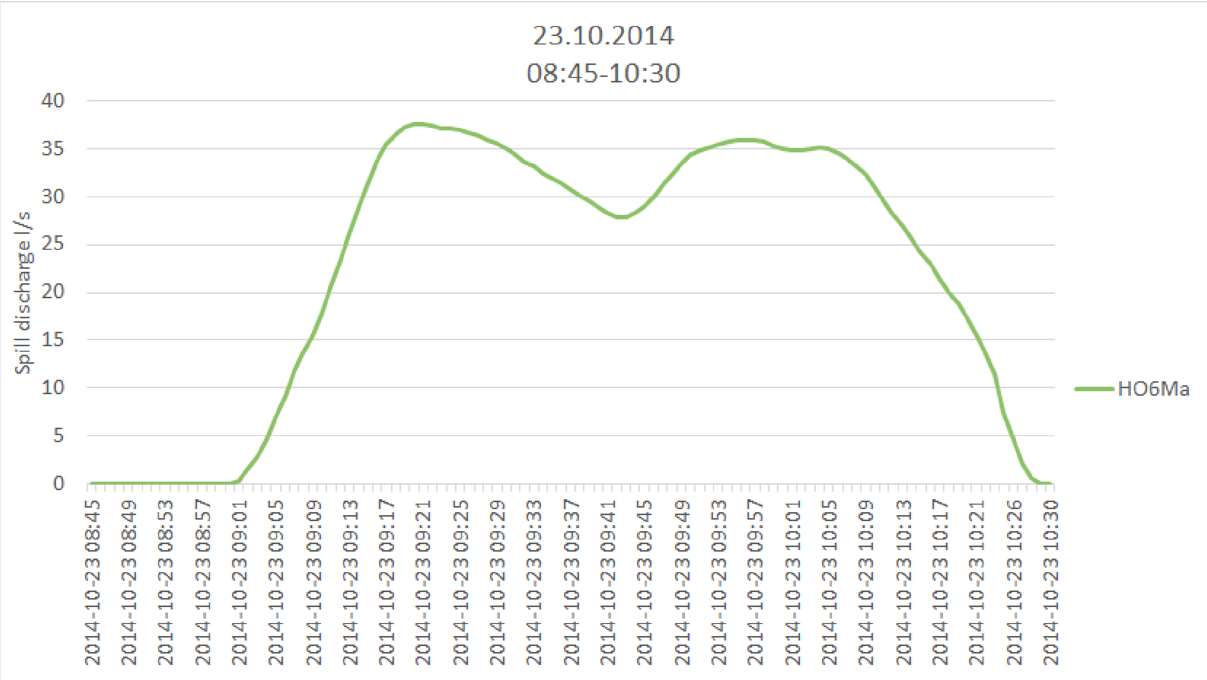


Figure 67: Selected CSO event

When the concentrations of SS were applied to the CSO event in Figure 67, the calculated total amount of suspended solids going into the filter became $SS_{inn} = 43$ Kg , and with a treatment rate of 56 % for suspended solids: $SS_{out} = 18.92$ Kg. The total SS was then distributed accordingly to Figure 66, and the pollutograph is shown in Figure 68 below.

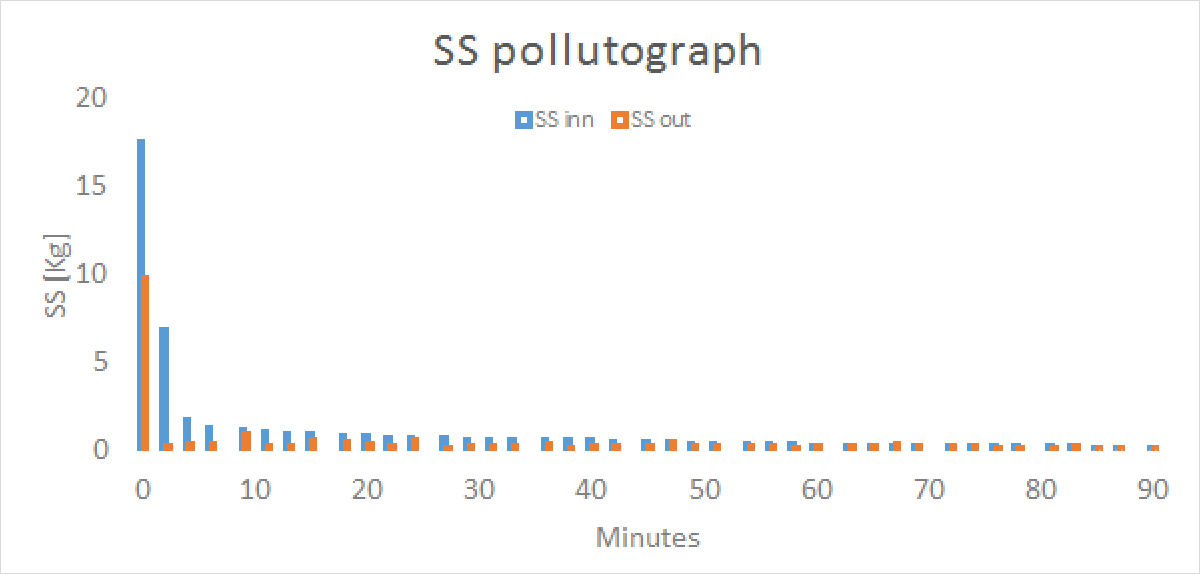


Figure 68: SS pollutograph for the CSO event

The pollutograph was implemented in the mass injection by adding several mass injections which overlap each other in time. In this way we get a more realistic shape of the suspended solids. Figure 69 below, shows how the shape of the spill from the CSO can be entered in HEC-RAS. The shape on the left is how the spill would have looked like if the total mass and time of the CSO event were entered. The figure on the right is how the spill looks like if the mass is distributed accordingly to Figure 68 by adding several mass injections.

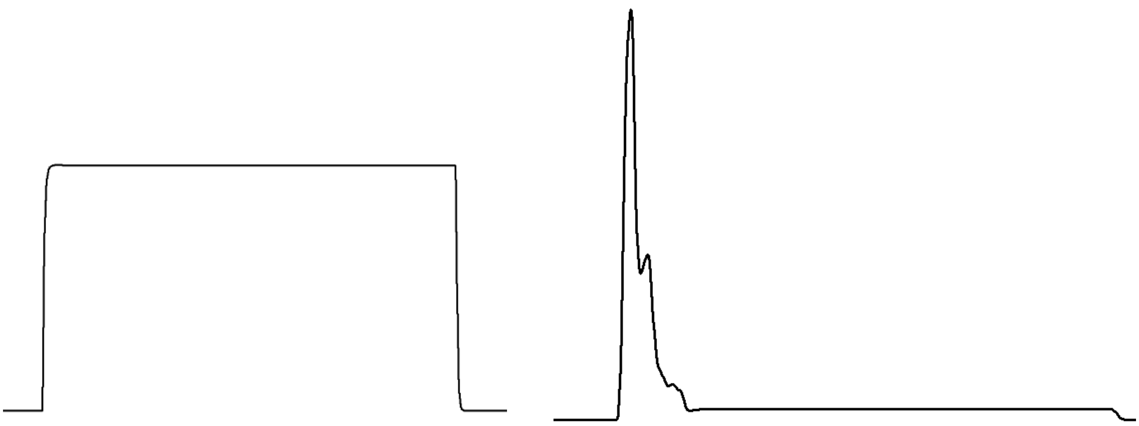


Figure 69: Mass injection shape with and without distribution

When the suspended solids are computed along the river, it does not say much about the water quality in the river. To get a measure of the water quality we need to convert the SS results into parameters which can be used to say something about the water quality. NIVA took samples from Hoffselva 23-24 October 2014 where they, among other parameters, measured the SS concentration, total Phosphorus concentration, total Nitrogen concentration, Lead concentration, and Nickel concentration. They found a strong linear regression between SS –

Tot P, SS- Tot N, SS- Pb, and SS-Ni (Tryland et al., 2016). Table 16 was created based on the measurement data provided by NIVA. The measurement data are collected from an auto sampler placed in the Oslo VAV station. The samples were taken each hour from 15:00 on 23. October until 04:00 on 24. October. The samples were merged into five mix samples (15-17, 18-20, 21-23, 24-02 and 03-04) and analyzed.

Table 16: Linear regression analysis results for Hoffselva 23-24 October 2014 (Tryland et al., 2016)

Correlation	Fit, R^2	Regression line function, y(x)= ax + b
SS – Tot P	0.94	a = 1.9252 b = 25.14
SS – Tot N	0.87	a = 6.6606 b = 1089.10
SS – Pb	0.89	a = 0.0449 b = 2.4943
SS – Ni	0.88	a = 0.0609 b = 1.4382

With a 95 % confidence interval, a value of R^2= 0.8 is considered as good correlation. This means that the concentrations of suspended solids can be converted by using the regression line function where x is SS in mg/l and y is the desired concentration in µg/L. The concentrations of total Phosphorus and total Nitrogen are related to the ecological state while Pb and Ni are related to the chemical state of the river. When these are compared with the threshold values in the Water Framework Directive, it is possible to say something about the water quality condition of the river.

When it comes to bathing water quality, there was no significant correlation between suspended solids and E. Coli. At least from the samples taken by NIVA in Hoffselva, there were no good correlation.

Scenarios

To evaluate the water quality in the river, four scenarios were created. There are many variables when it comes to simulating the water quality. The background concentrations in the river, concentrations of spills from CSOs, river flow, and the magnitude of the spill event may vary. It was chosen to simulate the event on 23 October and to keep the spill volume from the CSO event as a constant parameter. The scenarios were run with and without treatment by the use of SS concentrations shown in Figure 68. The concentrations were calculated from the CSO event, which occurred on 08. February 2016, by Inrigo Water. The parameters which vary in the scenarios are related to the condition of the river.

Table 17: Scenarios

Scenarios	River flow m3/s at Oslo VAV	Background concentration of SS in the river	Comment
Scenario 1	1.108 m3/s	5 mg/L	Low flow in the river and low background concentration
Scenario 2	1.108 m3/s	58 mg/L	Low flow in the river and high background concentration
Scenario 3	2.087 m3/s	5 mg/L	Higher flow in the river and low background concentration
Scenario 4	2.087 m3/s	58 mg/L	Higher flow in the river and high background concentration

As mentioned in chapter 0, Hoffselva is classified as “Clear” meaning SS < 10 mg/L. The background concentration of suspended solids was set to 5 mg/L in the river for the “low” background concentration. In the period before the simulated CSO event on 23. October, it had been raining for a longer period (150 mm the previous 3 weeks) but without heavy rain events. In wet periods there are a higher number of particles in the water due to surface runoff and erosion. The “high” background concentration is set to 58 mg/L and it is based on the average concentration of suspended solids from the samples taken by NIVA on the 23. October.

The simulation period lasts from 23OCT 06:00 – 23 OCT 15:00 to cover the hours before and after the CSO event which occurred in the time 09:00-10:30. The scenarios were ran with and without treatment of the CSO.

3.7.3 SS simulation results retrieved at the location of the Oslo VAV station

In this chapter the results from the simulations are shown for the cross section located closest to the Oslo VAV station. The borders between the different conditions, from Table 6, are plotted against the simulated results. The boundary between moderate and good condition is the most critical in the WFD context, because it is the main basis for setting environmental goals for natural water bodies. The boundary between moderate and good is named "Moderate/Good" in the figures.

Scenario 1 untreated

Scenario 1 is a scenario where the river condition is set to a low concentration (SS = 5 mg/L) and constant river flows based on the observed values at the time of the CSO event on 23. October.

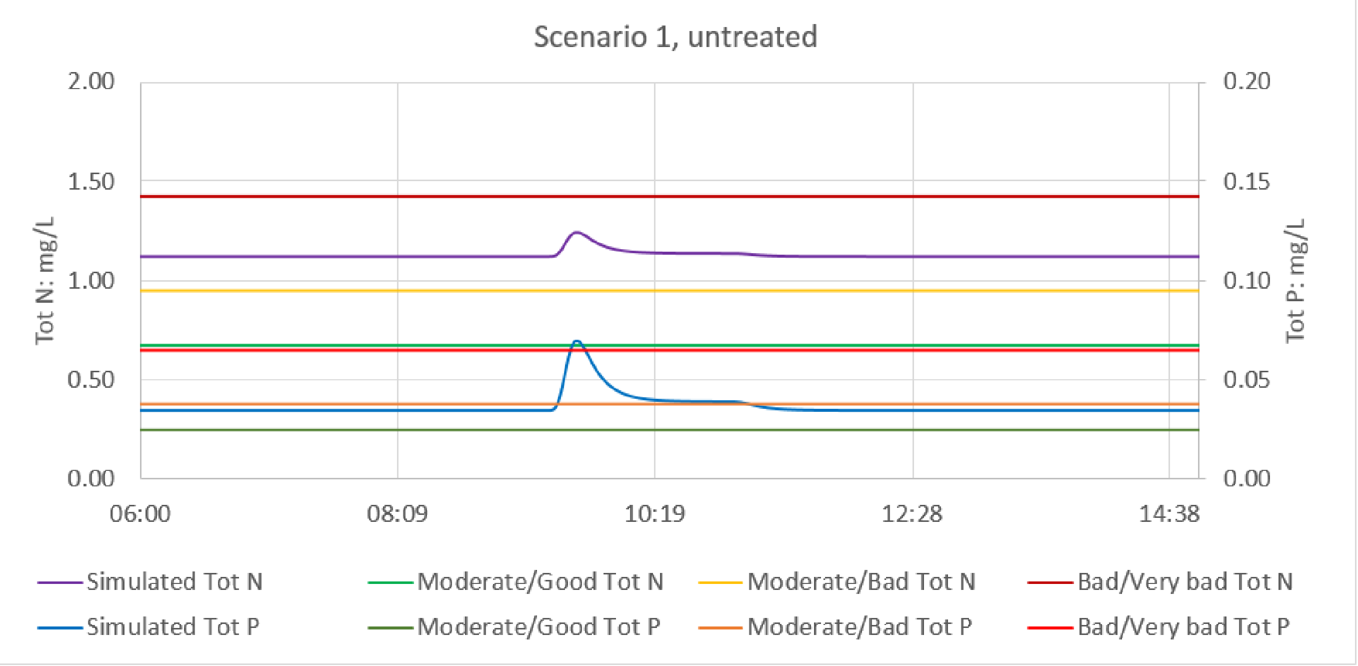


Figure 70: Scenario 1 untreated results

In this scenario the Tot P is in the condition class "Moderate" before and after the CSO spill, "Bad" during the spill event, and "Very bad" for a short moment at the peak moment of the spill. The Tot N concentration is classified as "Bad" during the whole simulation period.

Tot P maximum concentration: 0.0697 mg/L, Tot N maximum concentration: 1.2433 mg/L

Scenario 1 treated

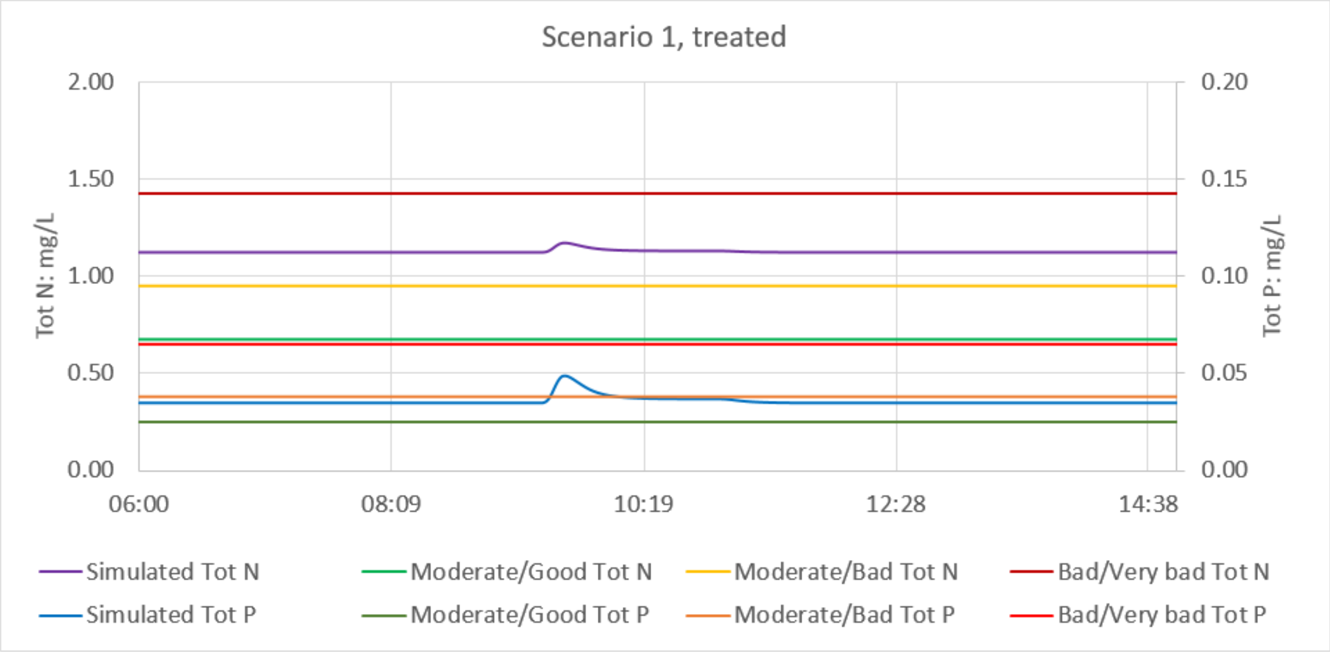


Figure 71: Scenario1 treated results

With treatment, the Tot P is in the condition class "Moderate" before the spill event and right after the highest peak. For a short moment the Tot P peak is in the "Bad" condition. The Tot N concentration is classified as "Bad" during the whole simulation period.

Tot P maximum concentration: 0.0487 mg/L, Tot N maximum concentration: 1.1707 mg/L

Scenario 2 untreated

Scenario 2 is a scenario where the river condition is set to a wet condition with precipitation in the days before the simulation period (SS = 58 mg/L) and with constant river flows based on the observed values at the time of the CSO event on 23. October.

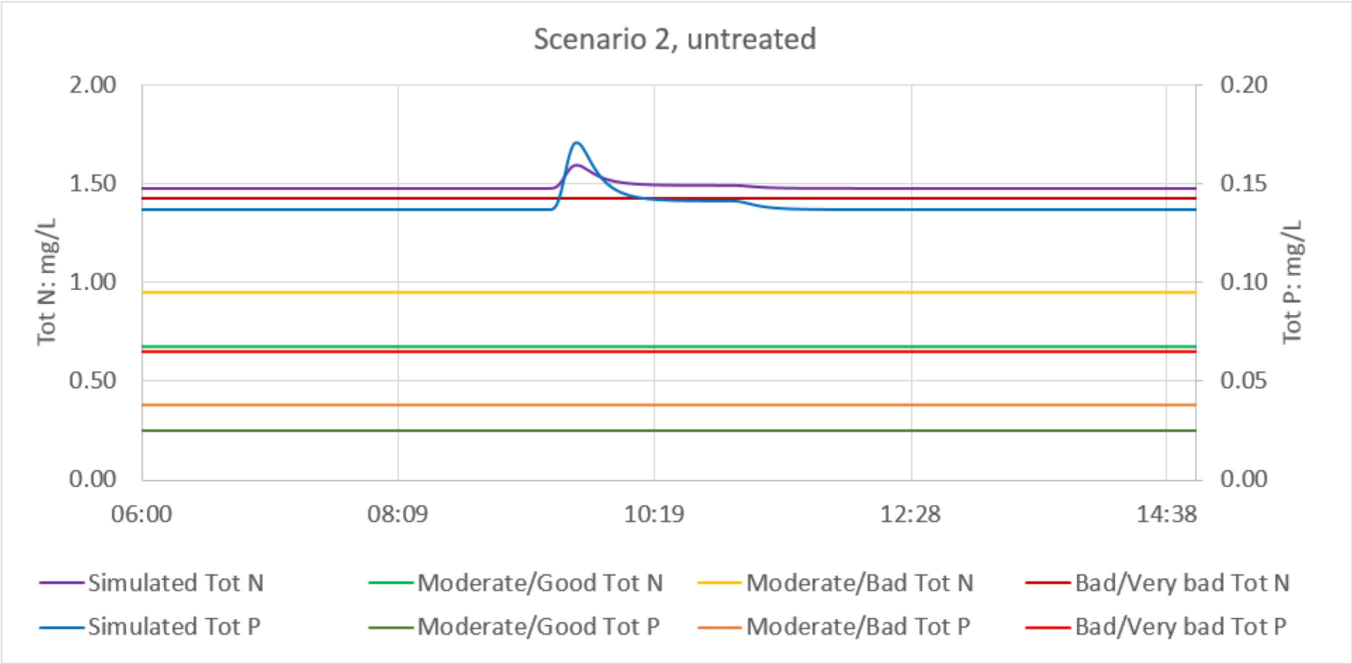


Figure 72: Scenario 2 untreated results

In this scenario the Tot P and Tot N are both in the condition class “Very bad” during the whole simulation period.

Tot P maximum concentration: 0.1706 mg/L, Tot N maximum concentration: 1.5924 mg/L

Scenario 2 treated

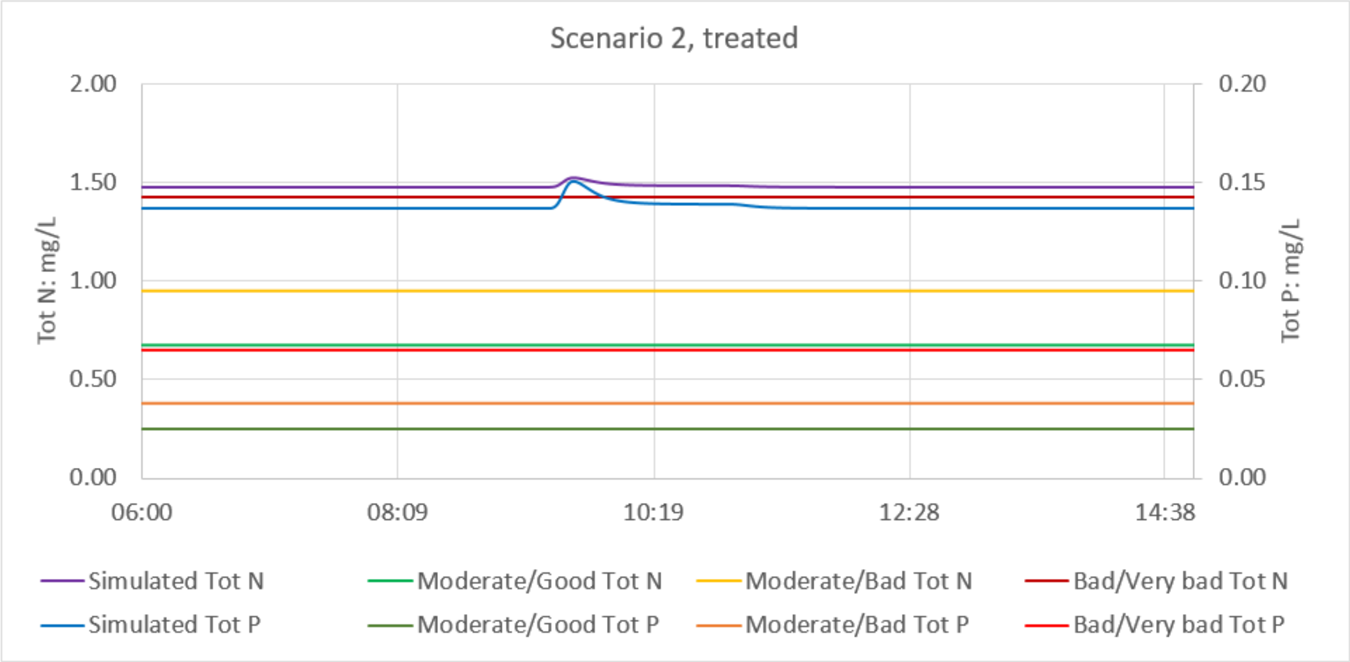


Figure 73: Scenario2 treated results

With treatment in this scenario, the Tot P and Tot N are both still in the condition class "Very bad" during the whole simulation period.

Tot P maximum concentration: 0.1504 mg/L, Tot N maximum concentration: 1.5225 mg/L

Scenario 3 untreated

Scenario 3 is a scenario where the river condition is set to a low background concentration (SS = 5 mg/L) and with constant river flows based on the simulated values at the time of the CSO event on 23. October.

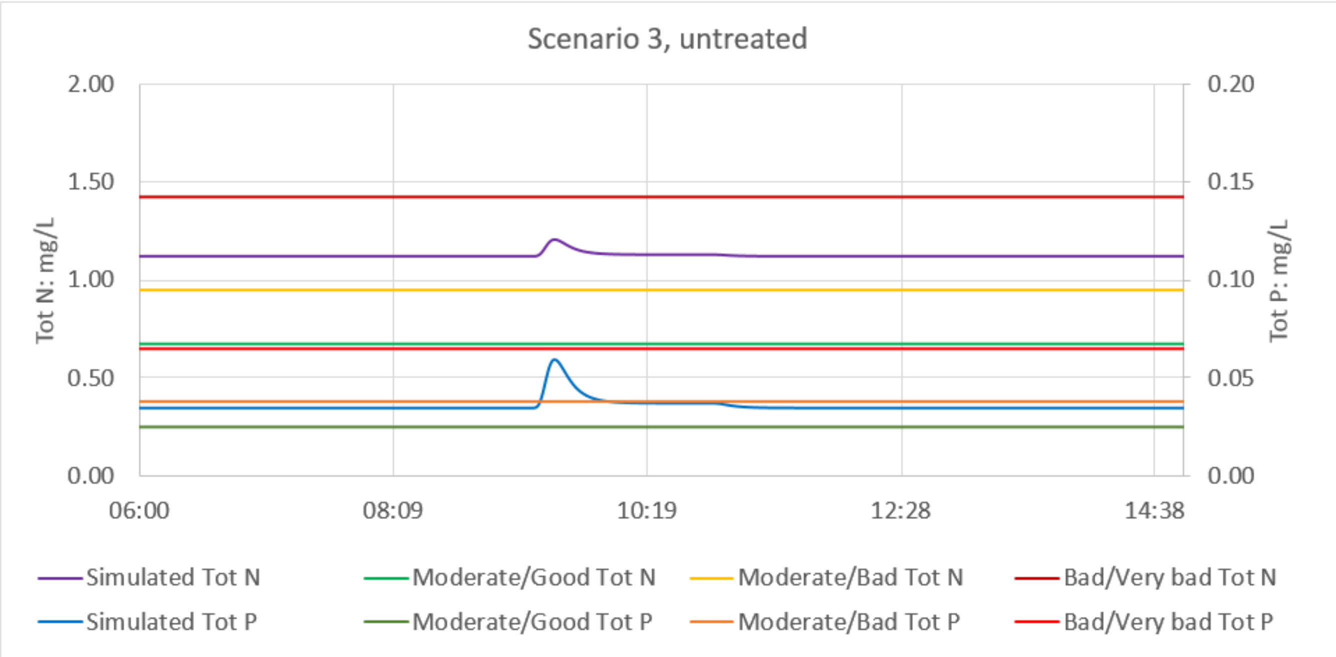


Figure 74: Scenario 3 untreated results

In this scenario the Tot P is in the condition class "Moderate" before and after the CSO spill, and "Bad" during the concentration peak. The Tot N concentration is classified as "Bad" during the whole simulation period.

Tot P maximum concentration: 0.0594 mg/L, Tot N maximum concentration: 1.2076 mg/L

Scenario 3 treated

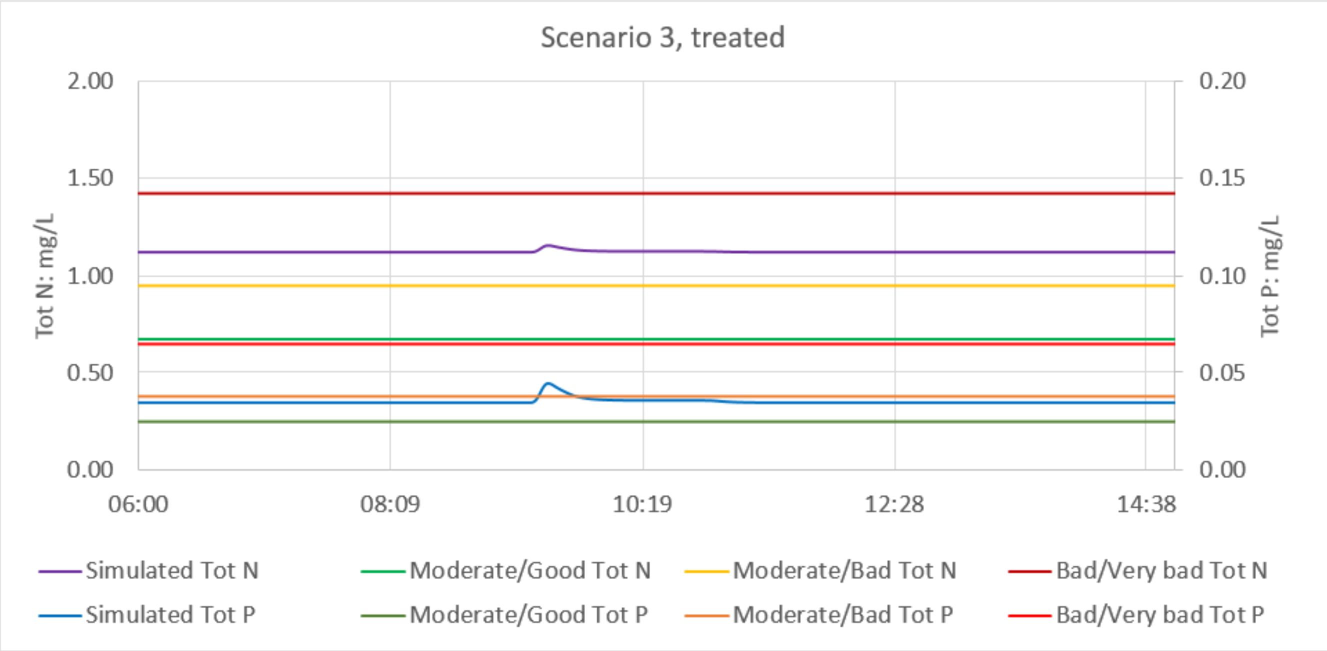


Figure 75: Scenario3 treated results

With treatment, Tot P is in the condition class "Moderate" before and after the CSO spill, and "Bad" during the concentration peak. The Tot N concentration is classified as "Bad" during the whole simulation period.

Tot P maximum concentration: 0.0446 mg/L, Tot N maximum concentration: 1.1565 mg/L

Scenario 4 untreated

Scenario 4 is a scenario where the river condition is set to a wet condition with precipitation in the days before the simulation period (SS = 58 mg/L) and with constant river flows based on the simulated values at the time of the CSO event on 23. October.

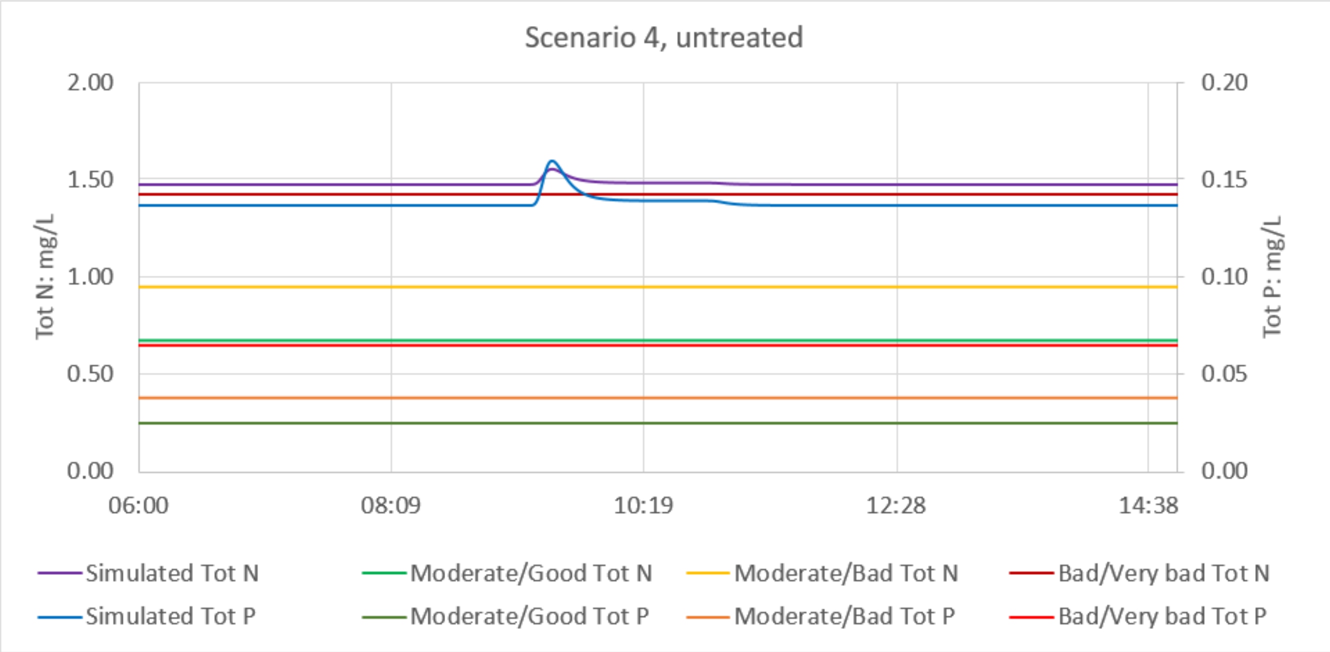


Figure 76: Scenario 4 untreated results

In this scenario the Tot P concentration is in the condition class "Very bad" during the whole simulation period. The Tot N concentration is also classified as "Very bad" during the whole simulation period.

Tot P maximum concentration: 0.1596 mg/L, Tot N maximum concentration: 1.5544 mg/L

Scenario 4 treated

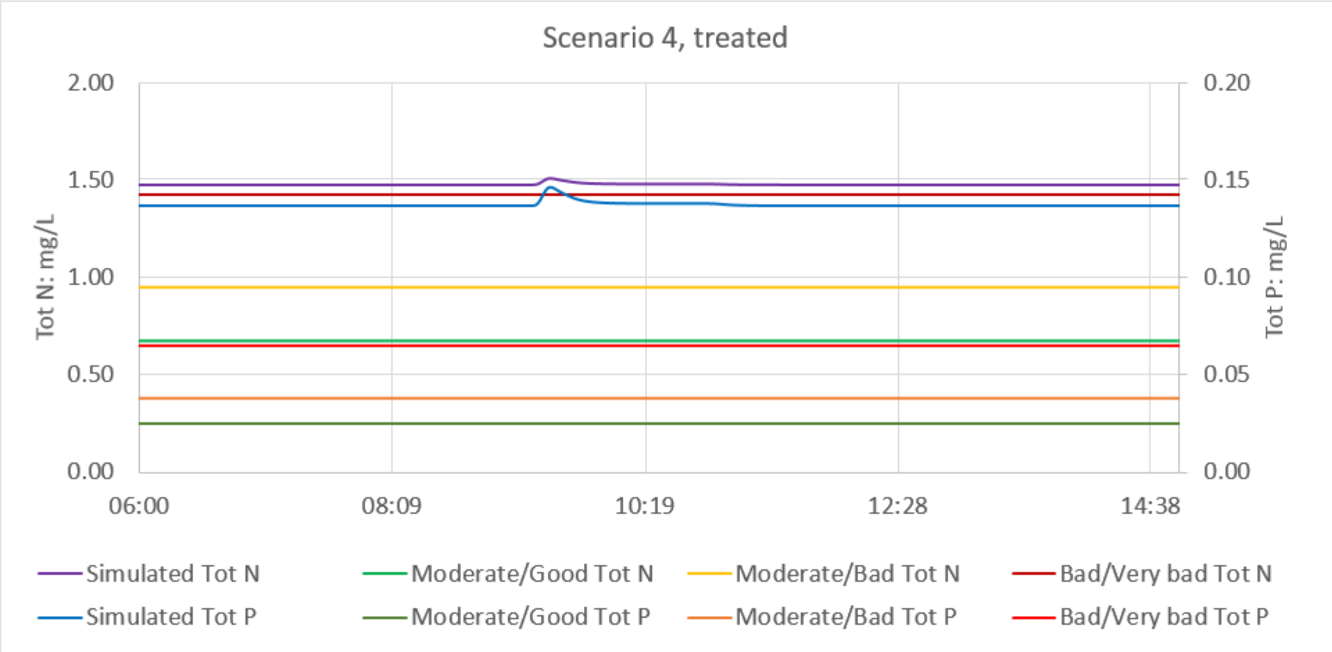


Figure 77: Scenario 4 treated results

Although the peaks have been reduced with the treatment, both Tot P and Tot N are classified as “very bad” for the whole simulation period.

Tot P maximum concentration: 0.1463 mg/L, Tot N maximum concentration: 1.5081 mg/L

The worst and best conditions achieved for Tot P and Tot N during the simulation period, are summarized in table below:

Table 18: Summarized results of conditions for the simulated ecological parameters in the river during the simulation period

Scenarios T = Treated U = untreated	Concentration of Tot P		Concentration of Tot N	
	Best condition	Worst condition	Best condition	Worst condition
Scenario 1U	Moderate	Very bad	Bad	Bad
Scenario 1T	Moderate	Bad	Bad	Bad
Scenario 2U	Very bad	Very bad	Very bad	Very bad
Scenario 2T	Very bad	Very bad	Very bad	Very bad
Scenario 3U	Moderate	Bad	Bad	Bad
Scenario 3T	Moderate	Bad	Bad	Bad
Scenario 4U	Very bad	Very bad	Very bad	Very bad
Scenario 4T	Very bad	Very bad	Very bad	Very bad

The chemical state is classified either as “Good” or “Bad”. It was chosen to summarize the results in a table because it is only one threshold value to plot against. Table 19 shows the concentrations which occurred during the simulation period when SS was converted to Pb and Ni.

Table 19: Summarized result for chemical parameters

Scenarios T = Treated U = untreated	Concentration of Pb [µg/L]		Concentration of Tot Ni [µg/L]	
	Initial concentration	Max. concentration	Initial concentration	Max. concentration
Scenario 1U	2.72	3.53	1.74	2.85
Scenario 1T	2.72	3.04	1.74	2.18
Scenario 2U	5.10	5.89	4.97	6.04
Scenario 2T	5.10	5.42	4.97	5.40
Scenario 3U	2.72	3.29	1.74	2.52
Scenario 3T	2.72	2.95	1.74	2.05
Scenario 4U	5.10	5.63	4.97	5.69
Scenario 4T	5.10	5.32	4.97	5.27

We can see the same pattern here, as for Tot P and Tot N. The initial conditions are the same with and without treatment, but the maximum concentrations are reduced with treatment. Figure 78 shows how the maximum simulated values are compared with the maximum EQS limits.

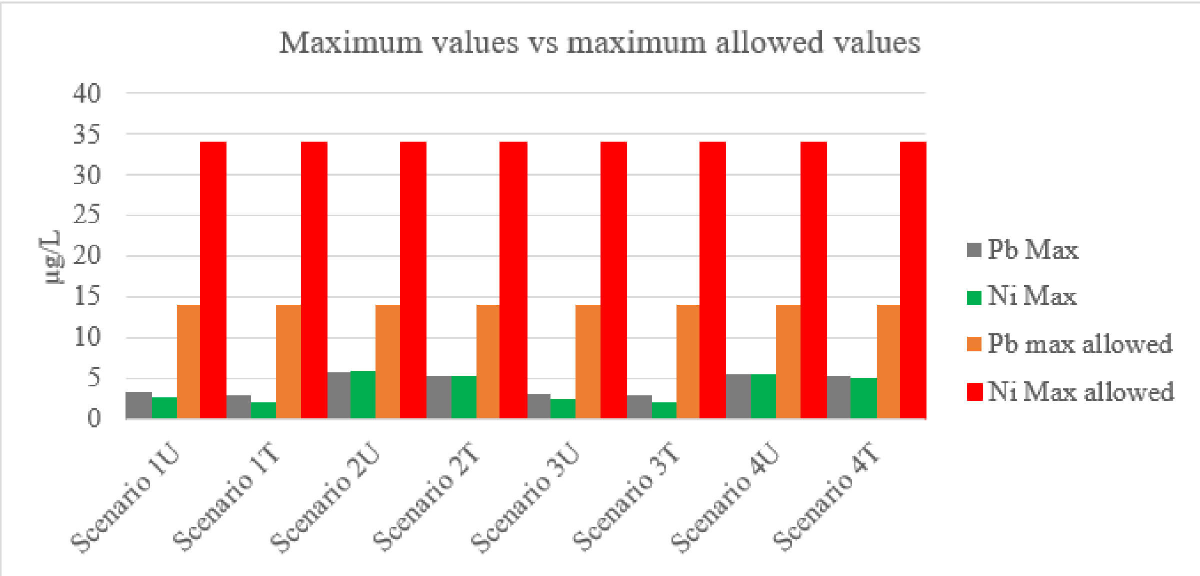


Figure 78: Maximum simulated values of Pb and Ni compared with EQS values

As we can see, the maximum concentrations of Pb and Ni are well below the threshold values during the simulation period. In Figure 79 the average annual values for Pb and Ni are compared with the initial conditions for the scenarios. We can see that the initial Ni concentrations are within the average threshold value for scenario 1U, 1T, 3U and 3T, but above the threshold in scenario 2U, 2T, 4U and 4T. The initial Pb concentrations are above the threshold values in all of the scenarios.

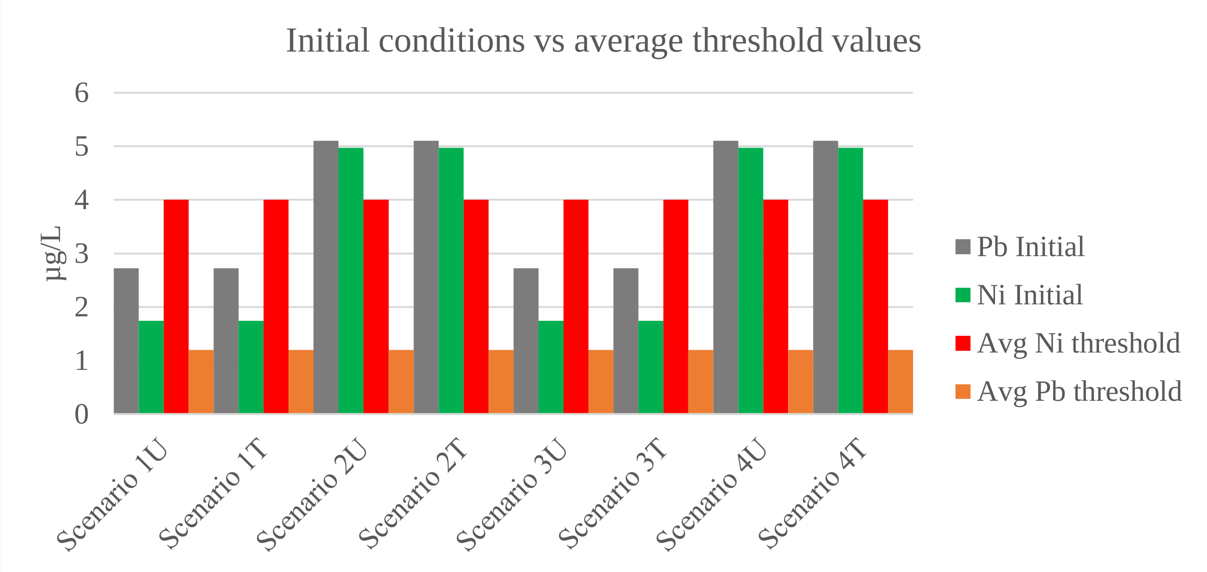
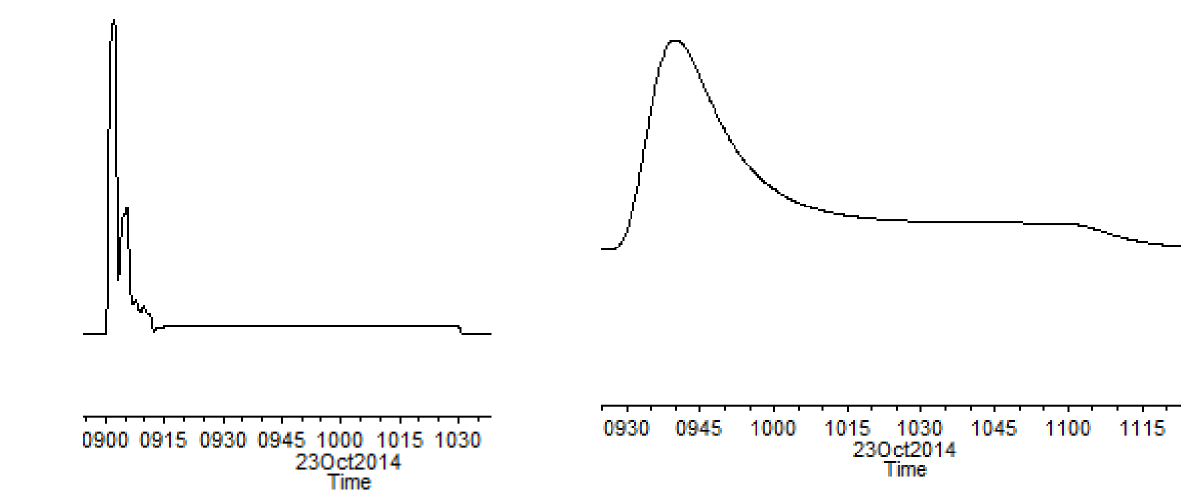


Figure 79: Initial conditions of Pb and Ni compared with EQS values

The time table shows that it takes approximately 40 minutes before the spill concentration peak, from HO6Ma, reaches the Oslo VAV station, and 60 minutes before it reaches the outlet at Bestumkilen. This yields an average transport velocity in the river of about 0.53 m/s. Figure 80 displays the movement of the SS concentration peak for one of the simulated scenarios. Which one is irrelevant, the point is to show the timing of the concentration peak.



a) Simulated suspended solids concentration at the HO6Ma location

b) Simulated suspended solids concentration at the "Oslo VAV" location

Figure 80: Travel time of the SS concentration peak during a CSO event

4 Discussion of the results and uncertainties

4.1 MIKE URBAN

The results from the MIKE URBAN simulation of CSO activities, showed that HO11Ma, H09Ma and HO6Ma were active during the selected time period. Judging from the IDF-curves, in chapter 3.5.2, this rain event was a pretty normal rain event that happens quite often. The CSO activity can also be justified by the report from the original use of the MIKE URBAN model in 2011 (Vike, 2011). In the report, 116 of the biggest rain events from the period 1967-2009 were used to simulate the CSO activity. The selected rain events represented different types of rain events. The results showed that HO11Ma, HO9Ma and HO6Ma were the most active CSOs.

Table 20: Selection of the model results from 2011 (Vike, 2011)

CSO	Number of CSO events	Comment
HO11Ma	428	Active in 111 of 116 rain events
HO9Ma	423	Active in 116 of 116 rain events
HO6Ma	425	Active in 116 of 116 rain events

Since the MIKE URBAN model was made in 2011, the results seem to make sense. But during the selected period Peggy Zinke (the supervisor of this thesis), had several pictures and videos which showed activity from a CSO upstream of Holmendammen (HO64Ma). The observations clearly show active CSOs, but which the MIKE URBAN model showed as inactive during the simulation. This might have to do something with that the model was calibrated against previous results (before 2011) and the fact that the selected rain event occurred in 2014.

The report related to the original MIKE URBAN model (Vike, 2011), contains analysis of measures of improvement for the CSO spills. It could be a possibility that some of the measures suggested in the report have been fulfilled during 2011-2014 and it could have an impact on the results from the model. In an e-mail, from Per Ole Israelsen at Oslo VAV, they confirm to their knowledge that there has not been carried out major measures to reduce overflows along the river after 2011. However, it is conducted rehabilitation of pipes in bad condition which may have given an impact on the sewer flow in the sewage network. In addition, some places have been converted from combined sewer to separate system. Oslo

VAV provided updated CSO events for the last five years. It shows, somehow, a change in frequency for the CSO which were active in this thesis. See Table 21.

Table 21: CSO activity the last 5 years given by Per Ole Israelsen from Oslo VAV

	Sum of the time active in minutes and number of events in ( )				
CSO\Year	2011	2012	2013	2014	2015
HO11Ma	5077 (6)	41743 (4)	20930 (7)	13025 (59)	5400 (58)
HO9Ma	15854 (45)	6395 (40)	32066 (34)	3 (0)	0 (0)
HO6Ma	0 (0)	24 (1)	2732 (46)	6067 (184)	3676 (92)

Based on the updated history of CSO event, it might be easier to understand why the model did not catch the active CSO from the period in 2014. The change in activity from year to year, without any major measures done, seems to be hard to predict without calibration.

When we look at the timing of the CSO events compared with the observed discharge in the river (Figure 43), we see that the CSOs become active in the rising limb of the hydrograph. One would maybe expect them to become active closer to the peak. This might have to do with the delay in runoff, because the Oslo VAV is located almost at the outlet of the river it will peak later at the station than further upstream in the river. The delay effect is also shown in Figure 80 where the peak of concentration is delayed by 40 minutes. It can also have something to do with time zone challenges. In Norway we have the daylight saving time in the summer months where the clocks are turned forward one hour. The daylight saving lasts from 27. Mars to 30. October. The meteorological institute uses the normal +1 GMT time zone for all their recordings of precipitation, no matter if it is summer or not. This means the precipitation data should have been adjusted with one hour. The MIKE URBAN results should then have been adjusted with one hour, so the CSO would have been active one hour later than what is shown in the Figure 43.

The work that was put into simulating the surface runoff contribution to river discharge, were replaced by the simplified hydrological model for river discharge created by Ashenafi Seifu Gragne.

4.2 HEC-RAS

A model is just a simplified representation of a real world system. In this thesis the HEC-RAS model is a simplified model. This is due to the problems with numerical instability in the unsteady simulation and lack of discharge measurements.

The digital elevation model

The first simplification lies in the digital elevation model, which consist of laser points which was obtained from airborne laser scan data of the surface. The DEM does not contain water depths in the river channel and it is not corrected for vegetation that may give wrong elevation of the water surface. But as a simplification the surface of the water is assumed to be the river bed because of the low depths in general, along the river. Other simplifications regarding the river geometry, are the neglecting of culverts and the cross-section interval of 20 meters. With a smaller interval, the model would get a higher accuracy in representing the river geometry, but with respect to the length of the whole river system, it was evaluated to be an ok assumption.

The steady flow simulation

For the steady model, the accuracy of the model geometry can be pretty detailed and cover the whole river system. The steady simulation is a lot more stable when it comes to the calculations of water flow and water stage in the cross sections. The problem with steady flow is that it uses fixed constant water flow as boundary conditions, and thereby do not have the ability to replicate an actual rain event where the water flow varies over time. In this case the author ended up with using the steady flow simulation results to simulate the water quality in the river.

The unsteady flow simulation

The results from the unsteady model show a great difference between simulated and observed water flow at cross section 718, where the "Oslo VAV" station is located (Figure 61). The original idea was to assign each sub-catchment hydrograph to the river with the use of later inflow boundary conditions. In that way HEC-RAS would do the routing of water and the time-lag would be incorporated and the simulated values would probably show a better fit. As the problems with the unsteady model occurred, it became clear that simplifications had to be done to reduce the model area. As a backup plan, the aggregated hydrographs were used as inflow boundary conditions in lack of discharge measurements. This led to higher simulated values than what was observed, so it was chosen to adjust the inflow hydrographs to match the observed values.

The high values of simulated flow may be an indication of a water balance problem. As the conservation equation (Eq. 1) states: amount in – amount out = change in storage. The three storage areas: Holmendammen, øvre Smestaddammen, and nedre Smestaddammen, are not included in the simplified unsteady model. In reality, the storage areas will have a dampening effect on the hydrographs coming from upstream the storage areas. This effect is not taken into account when the hydrographs are summarized over the same time step and set as inflow boundary condition in the unsteady model. If we were to calculate the area below the aggregated hydrograph, and compare it to the area below the observed hydrograph, then it is no doubt that the area corresponding to the aggregated hydrograph would be higher. This could be due to several things. It can be due to invalid assumption of hydrological similarity between the catchments. All of the sub-catchments are assumed to have the same hydrological response as the sub-catchment nr. 10 with the measurements at “Log A”. However, this sub-catchment mainly consists of forested areas (See Figure 81). From the figure we can see an example of differences in land use between sub-catchment 10 and sub-catchment 7. Clearly catchment nr. 7 will not have the same hydrological response as catchment nr. 10, but this this is an assumption that had to be made based on the available information.

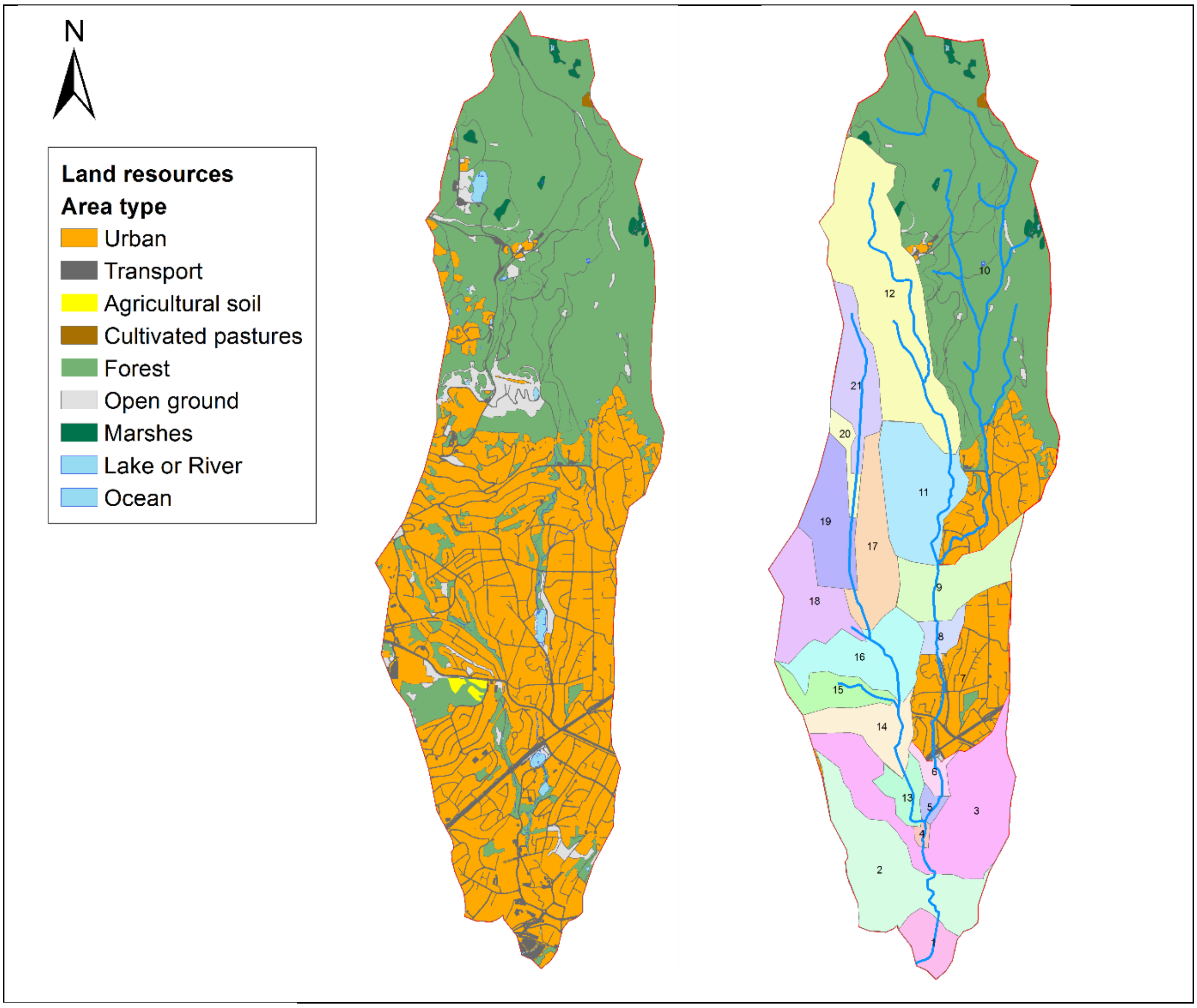


Figure 81: Land use map

The changes can also be due to limitations in the way the hydrographs were aggregated. Adding together the flows of corresponding time steps removes the moderating effect of the catchment. It can also be an issue of precipitation heterogeneity, that the amount of precipitation the sub-catchments might not be equal. There are also some uncertainties related to the measurement stations. The gauge-discharge relationship at the temporary station “Log A” was based on five measurements covering discharges between 0.02 and 1.4 m3/s at Skådalsbekken. The values were extrapolated for higher river discharges, which may lead to uncertainties.

The cross sections were also simplified in an attempt to make the model more stable, and the Manning’s n values were also adjusted to make the model more stable. Based on all the simplifications and uncertainties, it seemed more reasonable to adjust the model to the observed values rather than claiming the simulated values are more accurate for the simulation period.

Water quality simulation

The plan was to run the water quality simulation with the hydraulic plan from the unsteady flow simulation. In that way the change of flow in each cross section over time, would have been implemented in the water quality simulation. Unfortunately, the error occurred so it was decided to use the hydraulic plan from the steady flow data instead. As an alternative to the automatically variation in flow from the unsteady, two different flow scenarios were created based on the average flow during the CSO event. In reality the water flow would have been lower in the beginning of the CSO event, and the flow would increase during the CSO event. (See also Figure 43). Then it would be a higher dilution effect later in the CSO event than at the beginning.

The concentrations of SS and distribution of the concentration were chosen based on samples taken from previous measurements in Hoffselva. It is possible to use values based on literature, but they were found to vary too much from case to case. Then it felt more right to use actual measurements from the river. The measurements of Tot P, Tot N, Pb, and Ni had a great correlation with SS on 23. October 2014, but that is not always the case. For the same period, in a river west of Hoffselva named Mærradalsbekken, measurements showed that SS-Tot N had a correlation of $R^2 = 0.27$ (Tryland et al., 2016). The weekly observations at the Oslo VAV station for 2014, showed less good correlations between SS-Tot P and SS-Tot N. This might indicate that for Hoffselva, the correlations can be used to calculate Tot N and Tot

P for the specific CSO event in this thesis, but in other rivers and other time periods it should be done measurements to verify a correlation between SS- Tot P and SS-Tot N within the time period of interest. An important thing to highlight here is that the concentrations of Tot P, Tot N, Pb and Ni are based on the correlation with SS. This means that the amount of suspended solids, with and without treatment, are converted with the correlation formulas. In principle this means that the filter is assumed to have the same treatment rate as SS for the rest of the parameters. Results from previous measurements in the filter showed a low removal of Tot P (6.3 %) and Tot N (15 %), while the removal of Ni and Pb are unknown.

Ecological state

As mentioned earlier in this thesis, the classification for each parameter should be done based on annual values or season values based on mean, median or a specified percentile value of several observations in time. In this thesis the results from each scenario are compared with the threshold values given by the WFD. Since the threshold values are based on mean values with a predetermined frequency interval of the samples, it is not right to conclude with a water quality condition for the river based on a few data points from a single CSO event. They are meant to be a threshold values for long term effects. In this thesis the threshold values are used as a comparing measurement to say something about the effect if the CSO pollutions will continue over longer periods of time.

Scenario 1 and 3 use a background concentration of 5 mg SS/L, which is expected to be in the river under normal conditions based on the river type. Even under this normal conditions, the river has a “moderate” condition of 0.0348 mg/L Tot P and a “bad” condition of 1.1224 mg/L Tot N for the simulated results already before the CSO event kicks inn. Scenario 2 and 4 use a background concentration of 58 mg SS/L, which is expected to be in the river during wet periods. With the 58 mg SS/L the river has a “Very bad” condition of 0.1368 mg/L Tot P and a “Very bad” condition of 1.4754 mg/L Tot N for the simulated results already before the CSO event kicks inn. The results show that the initial background concentration in the river has a great impact on the condition of the river. High background concentrations in the river might be there even if the CSO spills are reduced or eliminated. The treatment will reduce the concentration peak, but very often the background concentration yields a high value where the reduction of the peak will not have a great impact on the classification. The only scenario where the treatment changes the condition is in scenario 1 where the peak for the untreated reaches a “Very bad” state, but with treatment the peak is reduced to a “Bad” condition (see Table 18).

Chemical state

In this thesis the chemical state is based upon two of the 45 prioritized pollutants given by the WFD. Pb and Ni were chosen as chemical parameters because they showed a good correlation with the concentration of suspended solids. The results showed a "Good" chemical condition where none exceeded the maximum allowed values. The results for the initial conditions showed that during wet periods (S2 and S4), the initial concentrations in the river exceeds the average annual threshold values for Ni. Only during normal background concentration conditions (S1 and S3) the threshold values for Ni were acceptable. For Pb the threshold value was exceeded in all of the scenarios. It is import to understand that the heavy metals do not only come from CSO spills. They also come from stormwater pipes and surface runoff, which can be the reason to the high background concentrations in the first place.

Results compared to observed values

The water quality results are based on the computed correlations with SS from measurements conducted in Hoffselva during 23-24 October 2014. The Oslo VAV station has records of weekly data of SS, Tot N, and Tot P from 2014, and weekly data of Pb and Ni from 2012.

Table 22: Range of mean simulated values in the untreated scenarios, compared with the range of weekly mean observed values at Oslo VAV from October 2014.

Mean range	Tot P, mg/L	Tot N, mg/L	Pb, µg/L	Ni, µg/L	SS, mg/L
Simulated	0.037-0.138	1.126-1.482	2.744-5.142	1.776-5.029	5.961-58.961
Oslo VAV	0.033-0.129	0.562-1.610	1.0-7.4 *	0.1-6.8*	2.500-55.000
* weekly mean values from 2012					

In Table 22, the simulated values for the untreated scenarios are shown because the observed values are also without treatment of CSOs. As we can see, the simulated values are within the range of what can be expected in Hoffselva. This was not unexpected, because the correlations were computed from measured values in Hoffselva. However, this was a simulation of a single CSO event due to a low intensity rain with a low return period. The future climate change will probably lead to higher intensity rain and the future urbanization of the catchment will contribute to faster runoff, thus higher CSO activity and more pollutants due to denser urban surfaces.

Other assumptions and remarks

In the “treated” scenarios it is assumed that all of the volume coming in to the CSO is treated. This means that the treatment solution is assumed to be dimensioned to handle the variation in volume inflow to the filter. The outflow from the CSO after treatment is assumed to have the same flow pattern as the incoming water. This means there are no storage of treated water before it is released to the river. The only difference from a CSO without a treatment solution is that the concentration of the treated water is lower due to the treatment process.

The water quality model only simulates one of the active CSOs. During a rain event, several CSOs might be active. From the MIKE URBAN simulation, we know that two more CSOs were active in the same period (HO9Ma and H11Ma). In addition, the CSOs outside of the MIKE URBAN model area are not accounted for. The initial background concentrations of 58 mg SS/L were based on measurements from the river during the rain event. The active CSO are likely to have an effect on the measurements which were taken that day. Maybe if the treatment would have been applied to all of the active CSOs, then the initial background concentration would be lower and then the treatment effect would have a meaningful effect on the threshold values in the simulated scenarios. With hindsight, the scenarios with the high background concentrations do not make much sense, because the river was already in a bad condition from the beginning of the simulation period.

Bathing water quality

Unfortunately, it was not possible to say something about the bathing water quality in the river. The chosen parameter, SS, did not have a good correlation with E. Coli or IE. In literature there are a wide variety in results from attempts to find the correlation between SS and E. Coli. But as other relationships between water quality parameters, the relations seem to be depending on the local conditions.

5 Conclusion

In this thesis a description of the area, and theoretical background related to the role of CSO spills have been given. Hydrodynamic computations and water quality modelling have been done. MIKE URBAN has been used to simulate CSO activity within the catchment of Hoffselva during a selected 9-days period in Autumn 2014. A hydrodynamic model, has been established in HEC- RAS to simulate the flow conditions during the selected period. Further, the hydraulic plan from the river flow computations, together with the results from MIKE URBAN, have been used to simulate water quality in the lower part of the river Hoffselva based on a few selected water quality parameters.

The MIKE URBAN results showed three active CSOs during the 9-days period from 18. October - 27. October 2014. This was a low intensity rain which is quite common for Hoffselva. The results fit with the statistical activity of CSO events for the years before 2011, but the model was not able to predict all of the activity which occurred in the actual event in 2014. The model was calibrated with observations done before 2011, so changes which have been done to the sewage system after 2011 have not been incorporated to the model. Updated data on the CSO activity history showed a change in the CSO activity pattern from 2011 to 2015. It is suggested to update the model with new calibrations to be able to predict future CSO activity in the catchment.

The establishment of the HEC-RAS model proved to be a complicated task. The discharges for the model had to be estimated using a simple hydrological modelling relationship, since no rainfall-runoff-model of the river basin was available. The model had to be reduced to the lower part of the river, due to numerical instability problems during computations of unsteady flow. The final result was a calibrated unsteady model for the lower part of the river where the river flow matched the observed flow at the Oslo VAV station. Due to all the simplification, which had to be made, it is recommended to use the model with great precaution.

The water quality simulation was supposed to use the hydraulic plan from the unsteady model. With an unsteady model one would be able to have the variation in river flow for the rain event in combination with the CSO spill going into the river. Due to an unsolvable error in the water quality module, an alternative water quality simulation by using the hydraulic plan from the steady flow simulation, had to be made. Four scenarios were created to replicate different conditions in the river, and the simulations were conducted with and without treatment of the CSO spill. The results showed that the background concentration had a great impact on the water quality in the river. The CSO spill caused a peak in concentration, which only lasted for a short period as the CSO becomes active, but the peak only comes in addition to the background concentration of the river. From the results it is clear that the treatment reduced the concentration peaks, but due to the "high" background concentration, this will not have a great impact on the water quality classification of the river for the selected CSO event.

The correlations and concentrations in the water quality module are based on previous measurements by NIVA and Inrigo Water. The simulation results are consistent with the results given in previous reports and online databases regarding the water quality of the river. Both the simulated results and previous reports indicate a bad chemical condition and a very bad ecological condition for the lower part of the river Hoffselva. As discussed in the discussion chapter, the water quality model is a simplified model and the results are computed based on measured correlations based on suspended solids. SS was found to have a good correlation with Tot P, Tot N, Pb, and Al. This might not be the case for other time periods and other rivers, so it is advised to verify the correlations before using the model for other purposes.

For future investigations it is recommended to rather establish a rainfall-runoff model of the river catchment, and to implement the CSO-spills and the chemical modelling there. Future work on the models should focus on using more detailed measurements as input to the models, as appropriate information about the river discharges is essential. It is suggested to make an unsteady calibrated model for the whole river network in order to have the opportunity to simulate multiple active CSOs at the same time. In this thesis many simplifications and assumptions had to be taken, but the results still gave reasonable results when compared to the observed values from the Oslo VAV station.

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Attachments

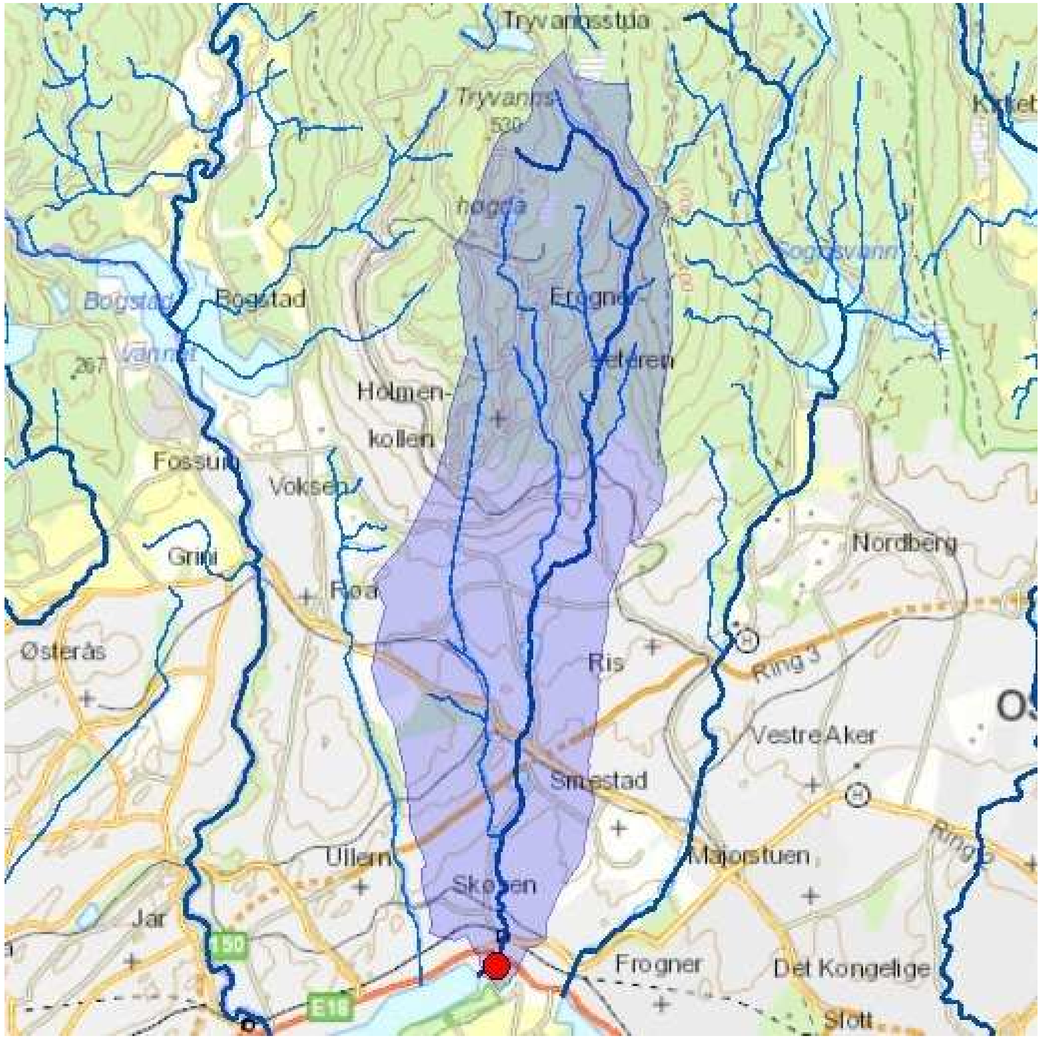
Attachment 1: Catchment description from The Norwegian Water Resources and Energy Directorate (NVE) interactive mapping tool.

Attachment 2: Calibration parameters for river discharge calculations

Attachment 3: CSO discharge hydrographs from MIKE URBAN

Attachment 4: typical values and ranges of pollutants in stormwater and wastewater.

Attachment 1: Catchment description from The Norwegian Water Resources and Energy Directorate (NVE)



Norges vassdrags- og energidirektorat

NVE

Kartbakgrunn: Statens Kartverk

Kartdatum: EUREF89 WGS84

Projeksjon: UTM 33N

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

Lavvannskart

Vassdragsnr.:	007.1Z
Kommune:	Oslo
Fylke:	Oslo
Vassdrag:	HOFFSELVA

Vannføringsindeks, se merknader		
Middelvannføring (61-90)	18.4	l/s/km²
Alminnelig lavvannføring	0.6	l/s/km²
5-persentil (hele året)	0.7	l/s/km²
5-persentil (1/5-30/9)	0.4	l/s/km²
5-persentil (1/10-30/4)	1.5	l/s/km²
Base flow	6.6	l/s/km²
BFI	0.4	

Klima		
Klimaregion		Ost
Årsnedbør	881	mm
Sommernedbør	424	mm
Vinternedbør	457	mm
Årstemperatur	4.9	°C
Sommertemperatur	12.7	°C
Vintertemperatur	-0.6	°C
Temperatur Juli	15.4	°C
Temperatur August	14.2	°C

Feltparametere	
Areal (A)	14.6 km²
Effektiv sjø (S_{eff})	0.2 %
Elvelengde (E_L)	9.9 km
Elvegradient (E_G)	50.4 m/km
Elvegradient$_{1085}$ (G_{1085})	51.9 m/km
Feltlengde(F_L)	8.5 km
H_{min}	1 moh.
H_{10}	43 moh.
H_{20}	90 moh.
H_{30}	122 moh.
H_{40}	139 moh.
H_{50}	196 moh.
H_{60}	264 moh.
H_{70}	342 moh.
H_{80}	404 moh.
H_{90}	453 moh.
H_{max}	528 moh.
Bre	0.0 %
Dyrket mark	0.2 %
Myr	0.6 %
Sjø	0.5 %
Skog	48.2 %
Snaufjell	0.0 %
Urban	37.7 %

De estimerte lavvannsindeksene i denne regionen er usikre. Spesielt gjelder dette 5-persentil (vinter) når sjøprosenten er høy.Indekser som ikke er beregnet skyldes manglende parameter(e).

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.

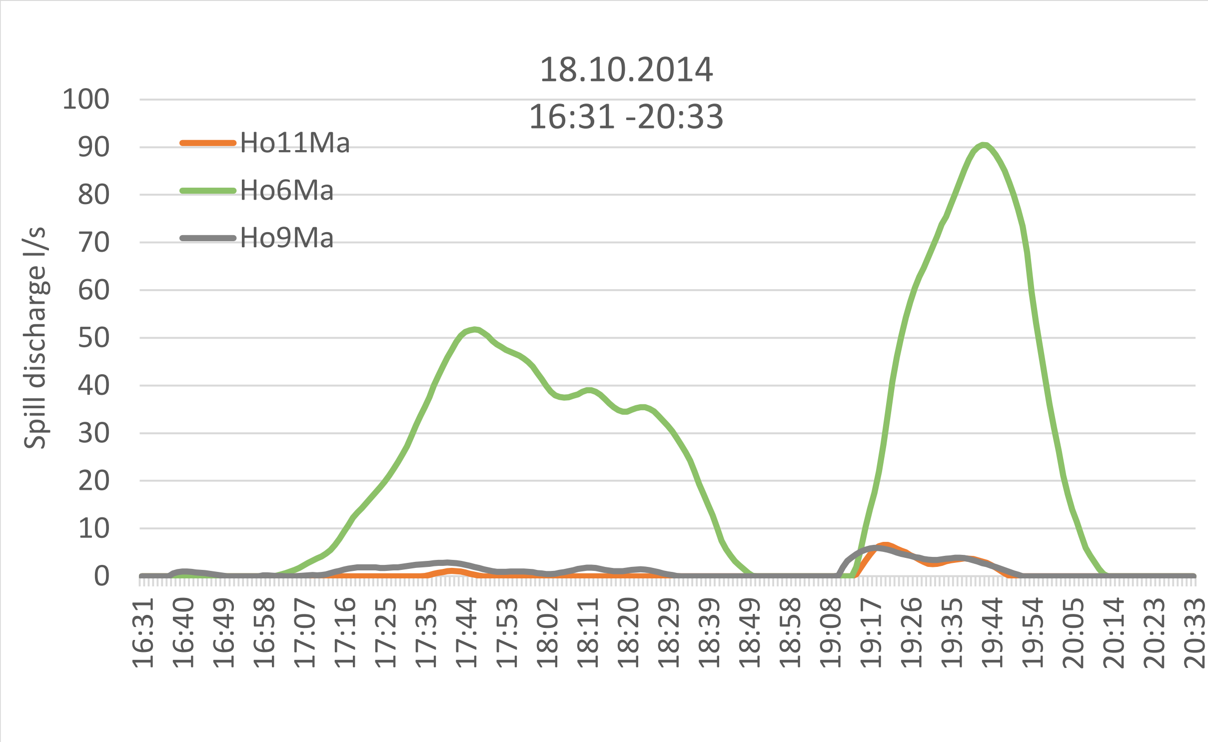
Attachment 2: Calibration parameters for river discharge calculations

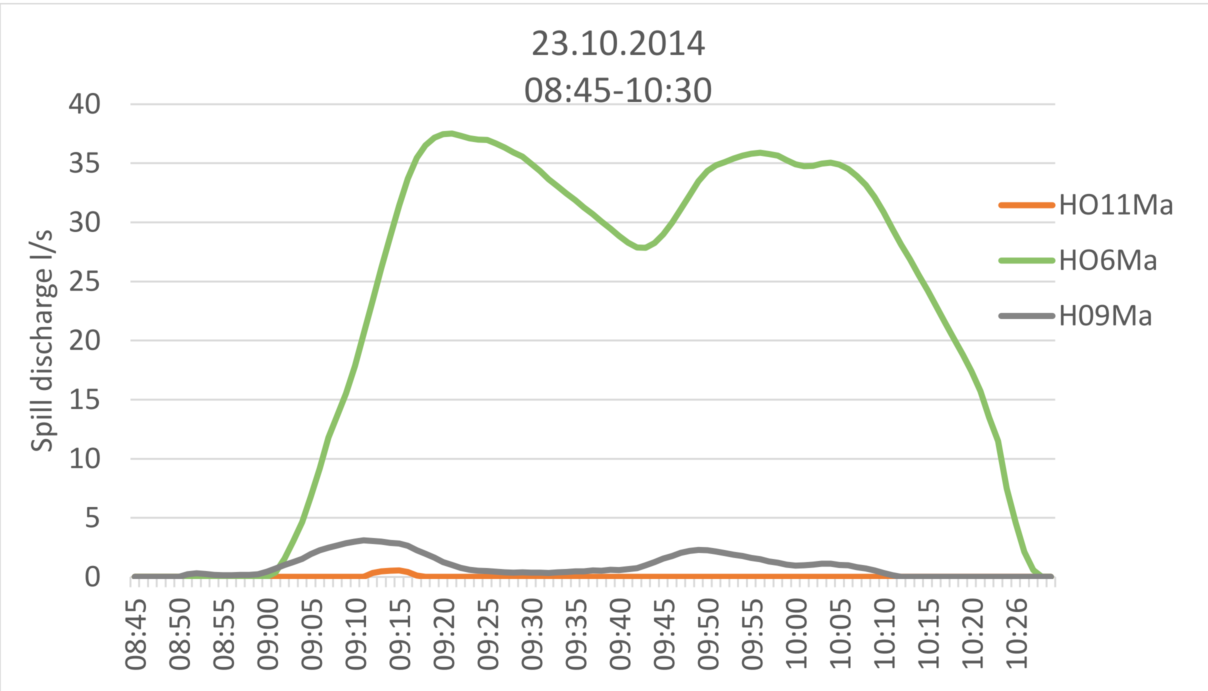
1. Data
   - Missing – 12 data points (Oslo VAV)
     `"2014-09-26 09:30:00", "2014-09-26 09:35:00", "2014-09-26 09:40:00", "2014-10-15 13:30:00", "2014-10-15 13:35:00", "2014-10-23 09:25:00", "2014-11-06 12:30:00", "2014-11-06 12:35:00", "2014-11-18 13:50:00", "2014-11-18 13:55:00", "2014-11-18 14:00:00", "2014-11-18 14:05:00"`
     - Filled in using Kalman filtering – assimilating flow from an ARIMA model and observation

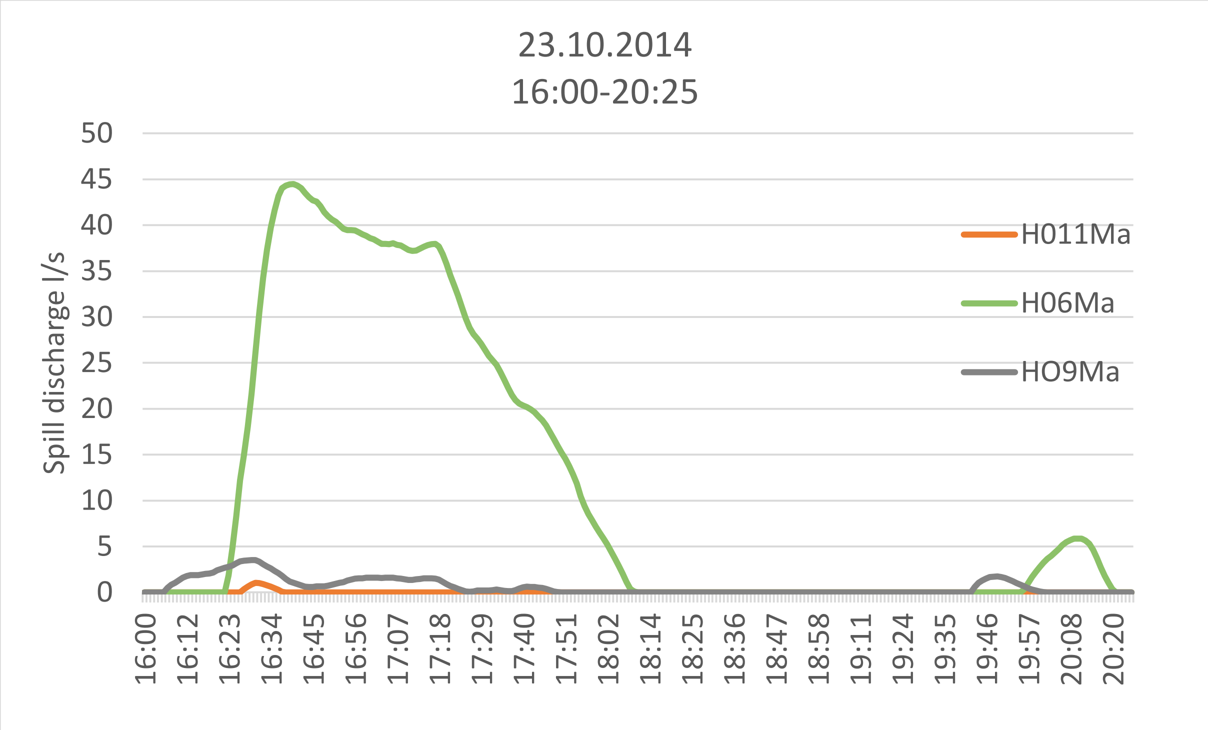
2. Model parameters

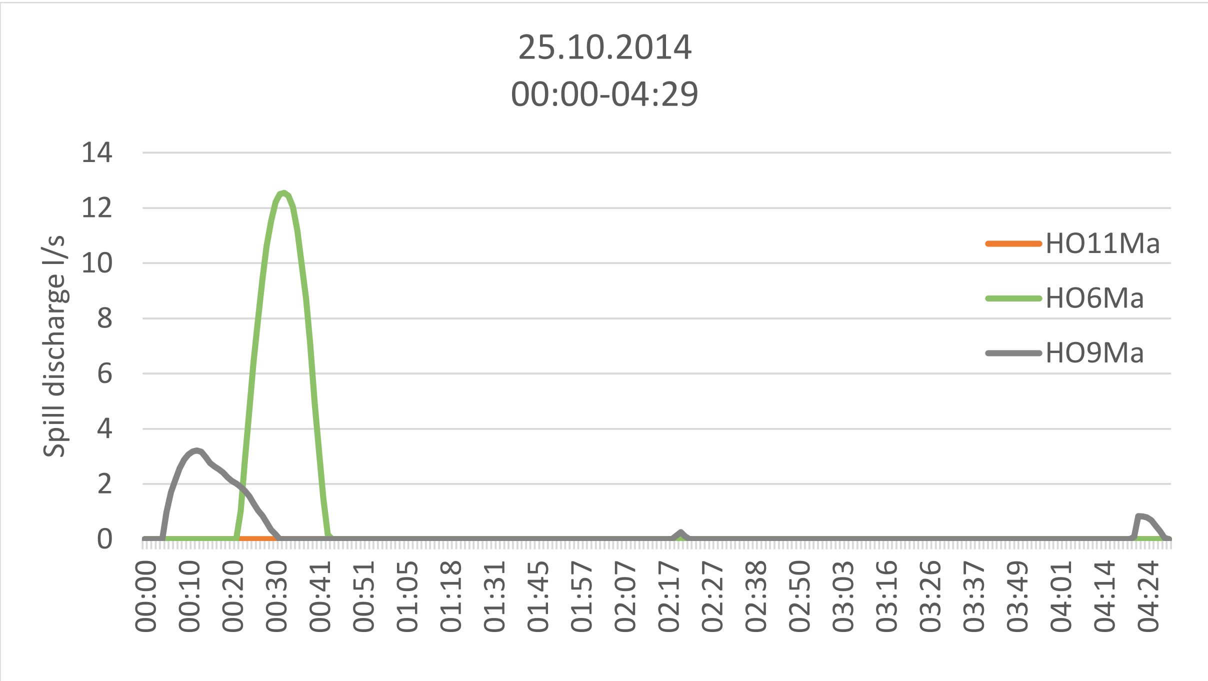
Sub-catch. ID	α	μ	β	θ	C1	C2	γ	τ	C3	ε
2	0.485	2.227	5.000	0.624	-0.869	0.197	2.703	-1.842	5.000	-0.013
3	0.933	0.562	2.266	-0.636	-2.170	-0.644	1.578	0.324	-1.004	-0.078
4	0.950	0.530	2.135	-0.440	-2.018	-0.135	2.207	0.349	-2.923	-0.110
5	0.931	0.691	2.227	1.816	-3.239	-1.191	2.108	0.692	-0.592	-0.021
6	0.967	0.691	4.421	0.908	-1.979	-3.476	1.288	2.582	-2.977	-0.021
7	0.972	0.694	2.122	2.415	-1.488	-0.099	0.000	5.000	-0.006	-0.020
8	0.950	0.692	3.394	0.689	-0.092	-1.844	3.596	-0.112	-2.004	-0.020
9	0.854	0.691	2.612	1.540	-4.820	-2.839	2.944	0.691	-0.408	-0.021
10	0.937	0.558	2.531	0.714	-1.121	-3.694	4.981	-0.608	-1.014	-0.080
11	0.967	0.691	1.254	2.818	0.837	-4.766	1.385	1.629	-3.315	-0.021
12	0.967	0.691	2.285	2.300	-1.855	-2.069	3.331	1.938	-2.772	-0.021
13	0.967	0.691	2.457	3.011	-2.476	-1.293	3.234	0.946	-2.365	-0.021
14	0.919	0.585	1.524	-1.091	-2.822	-1.051	4.776	4.909	-2.253	-0.056
15	1.271	2.278	5.000	0.424	-1.478	0.575	1.071	-0.149	-0.398	-0.181
16	0.966	0.690	1.082	0.813	-1.390	-2.457	2.304	2.828	-1.167	-0.021
17	0.968	0.691	1.744	2.852	0.923	-4.882	1.197	1.668	-1.577	-0.021
18	0.968	0.691	4.262	4.258	-1.624	-2.741	2.563	1.302	-1.331	-0.020
19	0.923	0.578	1.237	1.178	-3.399	1.962	4.140	-0.861	-1.225	-0.062
20	0.967	0.691	2.232	2.218	-3.073	-1.340	0.558	1.605	-1.806	-0.020
21	0.965	0.505	2.187	3.602	1.264	-3.148	2.134	-0.323	-0.591	-0.147

Attachment 3: CSO discharge hydrographs from MIKE URBAN






23.10.2014
16:00-20:25
Spill discharge l/s
50
45
40
35
30
25
20
15
10
5
0
16:00
16:12
16:23
16:34
16:45
16:56
17:07
17:18
17:29
17:40
17:51
18:02
18:14
18:25
18:36
18:47
18:58
19:11
19:24
19:35
19:46
19:57
20:08
20:20
H011Ma
H06Ma
HO9Ma


25.10.2014
00:00-04:29
Spill discharge l/s
14
12
10
8
6
4
2
0
00:00
00:10
00:20
00:30
00:41
00:51
01:05
01:18
01:31
01:45
01:57
02:07
02:17
02:27
02:38
02:50
03:03
03:16
03:26
03:37
03:49
04:01
04:14
04:24
HO11Ma
HO6Ma
HO9Ma

Attachment 4: typical values and ranges of pollutants in stormwater and wastewater.

Pollutant concentrations and unit loads for wastewater adapted from the book Urban Drainage (David Butnd John, 2010)

Parameter type	*Parameter*	*Unit load (g/hd.d)*	*Concentration (mg/l) mean (range)*
Physical	Suspended solids		
	volatile	48	240
	fixed	12	60
	Total	60	300 (180–450)
	Gross (sanitary) solids		
	sanitary refuse	0.15*	
	toilet paper	7	
	Temperature		18 (15–20) °C: summer 10 °C: winter
Chemical	BOD_5		
	soluble	20	100
	particulate	40	200
	Total	60	300 (200–400)
	COD		
	soluble	35	175
	particulate	75	375
	Total	110	550 (350–750)
	TOC	40	200 (100–300)
	Nitrogen		
	organic N	4	20
	ammonia	8	40
	nitrites		0
	nitrates		<1
	Total	12	60 (30–85)
	Phosphorus		
	organic	1	5
	inorganic	2	10
	Total	3	15
	pH		7.2 (6.7–7.5): hard water 7.8 (7.6–8.2): soft water
	Sulphates	20	100: dependent on water supply
	FOG		100
Microbiological	Total coliforms		10^7–10^8 MPN/100 ml
	Faecal coliforms		10^6–10^7 MPN/100 ml
	Viruses		10^2–10^3 infectious units/100 ml

Pollutant event mean concentrations (EMC), (range and mean), and unit loads for urban stormwater from the book Urban Drainage (David Butnd John, 2010)

Quality parameter	*EMC (mg/l)*	*Unit load (kg/imp ha.yr)**
Suspended solids (SS)	21–2582 (90)	347–2340 (487)
BOD_5	7–22 (9)	35–172 (59)
COD	20–365 (85)	22–703 (358)
Ammoniacal nitrogen	0.2–4.6 (0.56)	1.2–25.1 (1.76)
Total nitrogen	0.4–20.0 (3.2)	0.9–24.2 (9.9)
Total phosphorus	0.02–4.30 (0.34)	0.5–4.9 (1.8)
Total lead	0.01–3.1 (0.14)	0.09–1.91 (0.83)
Total zinc	0.01–3.68 (0.30)	0.21–2.68 (1.15)
Total hydrocarbons	0.04–25.9 (1.9)	0.01–43.3 (1.8)
Polyaromatic hydrocarbons (PAH)	0.01	0.02
Faecal coliforms (*E. Coli*)	400–50 000 (MPN/100 ml)	0.9–3.8 (2.1) (1 10^9 counts/ha)

*imp ha = impervious area measured in hectares

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