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Author: Hadyeh Salamatravandi	Signature of Author
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Abstract

As urbanized areas grow in scale, the negative impact on urban surface runoff increases. This fact creates the urge to take proper measures to control and prevent the downside effects of urbanization on natural water resources. This study analyzed the water quality of Madlabekken stream and Madlabekken constructed wetland. The main focus of this work is to evaluate whether the inlet to the wetland is urban area runoff, or if it contains periodic household wastewater contributions. In addition, estimating the wetland's efficiency is the secondary objective. Weekly samplings were collected from January to May 2018 continuously, and some grab samplings were done before this period between October to December 2017. Evaluation of water quality parameters including TSS, COD_t, COD_s, TP, PO_4^{-3}, TN and NH_4^+ at both inlet and outlet of the wetland was achieved by performing weekly analyses of water samples. The overall results showed that the quality of water is in range of urban storm runoff and in some cases much lower. The analyzed samples did not show a trace of wastewater and sewage. The highest concentrations were observed in February due to temperatures below zero which caused low levels of water in channels. Also, due to low concentrations, this constructed wetland did not show high efficiency in removing pollutants. Nevertheless, generally removal efficiency found to increase in the higher concentration of TSS and nutrients, and it was close to similar CWs removal efficiency in higher concentrations. TSS was reduced by 46%, and the reduction percentage for COD_t and COD_s was 22% and 6% respectively. For TP and PO_4^{-3}, in average the reduction is approx. 25% and 5% respectively. For TN and NH_4^+, considering the removal efficiency variation in different months, on average no reduction was found from influent to effluent. Ultimately, comparing to similarly CWs, this wetland has a lower removal efficiency.

Keywords: *Water quality, constructed wetland, Madlabekken stream, Madlabekken wetland, Open ponds, Nutrients removal, Wastewater treatment.*

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Hedyeh Salamat Ravandi

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Abbreviation

BOD Biochemical oxygen demand

COD_t Total Chemical oxygen demand

COD_s Soluble Chemical oxygen demand

CSO Combined sewer outflow

CW Constructed wetland

DON Dissolved organic nitrogen

DOP Dissolved organic phosphorous

FWS Free water surface

HRT Hydraulic retention time

HSF Horizontal subsurface flow

MDL Method detection limit

$NH4^+$ Ammonium

NO_2^- Nitrite

NO_3^- Nitrate nitrogen

PO_4^{-3} Phosphate

SS Suspended solids

TKN Total kjeldahl nitrogen

TN Total Nitrogen

TP Total phosphorous

TS Total solids

TSS Total suspended solids

TVS Total volatile solids

USEPA United States Environmental Protection Agency

VSF Vertical subsurface flow

Chapter 1

Introduction

1-1 Background

Water as a critical element of life is one of the most valuable natural resources on the planet. Since the start of the industrial revolution, we have witnessed a dramatic increase in damaging our natural resources which among water has been the biggest victim. Humankind has already polluted natural resources to some critical point where we face the danger of not being able to go back. This bitter fact is backed up by thousands of scientific researchers and the majority of intellectual society. The problem is deeply rooted in our economic and political structures which are huge complexes. Nonetheless accepting this challenge requires continuously improved developments around integrated water resources management policies as well as a substantial global collaboration (*Martin, et al., 2016).*

Water resource management as a subset of water cycle management implements various techniques and practices to optimize the use of water resources. Observing how nature purifies itself has been a leading source of inspiration for developing effective treatment practices. Among various natural purification means wetlands play an essential role. Wetlands point out to a land where there is water near the surface throughout or significant parts of the year. In common, wetlands are known as swamps, marshes, sloughs, fens, or bogs (*Australian guidelines, 2000*). Inspired by natural wetlands, constructed wetlands are designed and used to remove water pollutants. They implement natural treatment mechanisms provided by aquatic plants, soil, and associated microorganisms.

Generally, the three types of wetland are distinguished based on the presence/absence of free water surface, use of rooted/floating aquatic plants, and direction of the stream. The three types of constructed wetlands are known as:

1. **Horizontal free-water surface (FWS) flow constructed wetlands**

FWS wetlands replicate a natural wetland such as marsh or swamp. As the water slowly flows through the wetland, particles settle, pathogens are removed, and nutrients are utilized by microorganisms and vegetation. These wetlands are commonly used after secondary or tertiary treatment processes as a supplementary treatment (*Oginni, & Isiorho, 2014*).

2. Horizontal subsurface (HSSF) flow constructed wetlands

HSSF wetland is constructed of large sand and gravel-filled basins covered by plant vegetation. As wastewater flows horizontally beneath the surface, particles get filtrated, and organics degrade by microorganisms (*Sarafraz, 2009).*

3. Vertical flow constructed wetlands

This type of constructed wetland is a planted filter bed, which drains at the bottom. A mechanical dosing system pours wastewater onto the surface from above. Water flows vertically down through the filter matrix and gets collected at the bottom of the basin in a drainage pipe. Vertical and horizontal wetlands differ not only by the direction of the flow path but rather by the aerobic conditions (*Brix, et al., 2005*).

Urban stormwater also called runoff is the water that originates flows during rain as well as dry weather flows, from impervious surfaces of urban areas. Typically, dry weather flows include wash-downs, groundwater, garden watering, water pipes leakages. In some cases, overflow from sewage systems and septic tanks get mixed into urban stormwater (*Headley, & Tanner, 2008).*

Urbanization has significantly affected the characteristics of stormwater as natural areas are transformed to impermeable surfaces such as asphalt roadways, house roofs, and car parks. As urban areas grow, a more extensive range of pollutants such as nutrients, solids, and organic matter change the quality of stormwater runoff. These pollutants end up into waterways and receiving waters resulting in a negative impact on water quality, water quantity, habitat and biological resources, public health, and the aesthetic appearance of the urban waterway. The stormwater pollution is already recognized as an essential environmental problem which requires better stormwater quality treatment strategy for effective urban stormwater management (*EPA, 1999; Stephen, 2007*).

Inadequate information, data and inappropriate sampling methods concerning stormwater, limits addressing all issues related to urban stormwater. Consequently, developing new alternatives for traditional systems becomes challenging. Achieving reliable and indicative data requires setting standardized sampling and analysis procedures which are optimal and cost-effective (*stormwater guidebook, 2012*).

Generally, pollutants from the urban environment are divided into two fundamental processes, namely, pollutant build-up and wash-off. Build-up refers to pollutant generated and accumulated on urban surfaces mainly affected by Traffic, land use on porous surfaces affect. Build-up pollutants are particularly affected by the antecedent dry period and catchment characteristics associated with traffic, land use and impermeable surfaces. Wash-off relates to the mobilization and transportation of pollutants by stormwater runoff. Commonly intensity and duration of rainfall characteristics, as well as slope and roughness of urban area surface characteristics are recognized as the key factors affecting pollutant wash-off (*Stephen, 2007).*

An internationally wide range of programs has been developed to manage the water quality impacts of the urban area and highway stormwater runoff- related constituents. Of these constituents, certain heavy metals, such as zinc, copper, lead and sometimes cadmium; oil and grease; specific organics, such as the PAHs; nutrients (nitrogen and phosphorus compounds); and pathogen-indicator organisms, such as fecal coliforms are in primary concern. (*Fisher, & Acreman, 2004*).

As reported by the National Water Quality Inventory 1996, Report to Congress (*US EPA, 1998d*), the urban runoff pollution was recognized as a significant cause of water quality deterioration linked to human activities in ocean coastline waters and the next leading cause in estuaries, rivers, and lakes. The total percentage of impairment related to urban runoff is considerable. Around 5,000 square miles of estuaries, 1.4 million acres of lakes, and 30,000 miles of rivers were affected by runoff pollution as well as wetlands degradation in seven states (*Wong, 1999*).

EPA (*1995b*) have classified destructive impacts on receiving waters related to stormwater discharges into three general classes (*Wong, 1999*):

1. Short-term water quality impacts during and after storm events are causing the temporary rise of one or more pollutants, toxins or bacteria levels.
2. Long-term changes in water quality created by the cumulative effects associated with frequent stormwater discharges from several sources.
3. Physical impacts caused by erosion, scour, and deposition related to increased frequency and volume of stormwater which changes the natural aquatic environment.

As explained in the Terrene Institute's Fundamentals of Urban Runoff Management (*Headley, & Tanner, 2008*), potential harmful pollutants linked to urban run-off are categorized as solids, oxygen-demanding substances, nitrogen, and phosphorus, pathogens, petroleum, hydrocarbons, metals, synthetic organics (*Wong, 1999*).

Urban stormwater runoff generally originates from several sources such as residential areas, commercial and industrial areas, roads, highways, and bridges. In fact, runoff during storm events is generated by any porous surface without the capability to pond and infiltrate water. Naturally, this water would pond on the forest floor, get infiltrated into the soil and converted to groundwater, get utilized by plants and evaporates or transpire into the atmosphere, while urbanization alters the hydrology of the system significantly. The level of impervious surfaces can be used as an essential measure to determine the degree of urbanization in a watershed. As the level of imperviousness rises in a watershed, turns more rainfall into the runoff (*Wong, 1999*).

Commonly sewer systems are used to transfer urban runoff to receiving waters as a quick and efficient mechanism. Two types of sewer systems are known as separate storm sewers, and combined sewers describe as:

1. Separate storm sewer systems transport only stormwater runoff which is often discharged straight to receiving streams without any prior treatment.
2. Combined sewer systems, combine stormwater runoff with sanitary sewer flows for conveyance. Flows from combined sewers get treated by urban wastewater treatment plants before discharge to receiving waters.

Occasionally, in combined sewers, the water volume after significant rainfall events surpasses the capacity of the wastewater treatment system. Consequently, a mixture of untreated stormwater and sanitary wastewater discharges directly into receiving streams. These types of discharges also known as combined sewer overflows (CSOs) frequently occur in Combined sewer systems.

To achieve appropriate stormwater management of all urban stormwater systems requires adopting multiple objective approaches considering objectives such as (*Headley, & Tanner, 2008*):

- Ecosystem health, both aquatic and terrestrial;
- Flooding and drainage control;
- Public health and safety;

- Economic considerations;
- Recreational opportunities;
- Social considerations; and
- Aesthetic values.

Systematic monitoring of urban runoff is essential to manage urban stormwater quantitatively and qualitatively. The data collected from monitoring can help early detection of changes and shifts in water quality. Information obtained from monitoring also improves water quality strategies toward effective recycling of urban runoff (*Kadlec, & Wallace, 2009*).

It is now clear that stormwater management requires new approaches to address the challenging issues related to stormwater quality, quantity, and aquatic ecosystem health. New approaches should focus mainly on identifying the negative impacts of urbanization, the connection between natural environments and water management, and the significance of public values and the engagement (*Headley, & Tanner, 2008*). Besides, the importance of retention ponds and wetlands are recognized as most effective management practices for treating urban stormwater runoff.

This study has investigated Madlabekken constructed wetland in the city of Stavanger in Rogaland county, Norway. This wetland is built on the Madlabekken stream, the largest inlet to Mosvatnet lake. Mosvatnet was Stavanger's water source between 1863 and 1931, initially built to supply sufficient residential water. After construction, the water level of the pond increased remarkably where several small islets and rocks disappeared. Shortly after construction, it was found that Mosvatnet capacity could not support the growing city with drinking water in the long term. As a result, lake Store Stokkavatn became an alternative for city's new water reservoir. Mosvatnet is at 497 acres and 3.2 meters at the deepest point. The lake is 37 meters above sea level, surrounded by the walking path is 3.2 kilometers long. The lake is the third largest lake in Stavanger after Hålandsvatnet and Store Stokkavatn (*Molversmyr, 2001*).

The research documented in this study was aimed to evaluate the water quality of Madlabekken wetland built on Madlabekken stream which was highly polluted at time of construction. This study has monitored the current water quality of the wetland to investigate the possibility of wastewater overflow getting mixed into the urban stormwater runoff.

The Madlabekken wetland is an open surface wetland, which is constructed in 1991 to treat stormwater of urban area before entering lake Mosvatnet, to improve the quality of the lake.

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Chapter 2

Theoretical background and literature review

2.1 Stormwater overflow

Urban stormwater overflows are recognized as some of the main pollutant's sources which have a negative impact on quality of water resources (*Sansalone, & Buchberger, 1997; Deletic, 2001; Lee, et al., 2004; Nordeidet, et al., 2004*). Developing urban areas, and changes in land usage have caused adverse and negative transitions in urban overflow qualities (*Bannerman, et al. 1993; Brattebo & Booth 2003*). The water quality and nutrients in stormwater depend on area properties as land use, traffic, and imperviousness factor (*Karouna-Renier & Sparling, 2001; Nelson, E. J. & Booth, D. B. 2002; Van Metre & Mahler 2003; Chang, et al., 2004*). According to *McPherson et al., (2002)* and *Muthukrishnan et al. (2006*), there have been found high concentrations of nutrients in stormwater runoff. The nutrients include heavy metals, organic pollutants, pathogens, biological compounds and sediments in urban discharges (*McPherson, et al., 2002; Muthukrishnan, et al., 2005*). Building and construction materials, rooftops, asphalts, atmospheric degradations, are the main sources of pollution in urban overflows (*Davis, et al., 2001; Farm, 2002; Muthukrishnan, & Selvakumar, 2006*).

Table 2-1 and 2-2 present range of different water qualities in stormwater and domestic wastewater (*Hammer, & Bastian, 1989; Henze, et al., 2008*) and municipal wastewater with minor contributions of industrial wastewater.

Table 2-1 Typical composition of raw municipal wastewater with minor contributions of industrial wastewater (*Henze, et al., 2008*)

parameter (mg/l)	High	Medium	Low
COD total	1200	750	500
COD soluble	480	300	200
COD Suspended	720	450	300
BOD	560	350	230
VFA (as acetate)	80	30	10
N total	100	60	30
Ammonia-N	75	45	20
P total	25	15	6
Ortho-P	15	10	4
TSS	600	400	250
VSS	480	320	200

Table 2-2 Comparison of Water Quality Parameters in Urban Runoff with Domestic Wastewater (mg/l) (*Hammer & Bastian, 1989*)

	Urban Runoff		Domestic wastewater		
	separate sewers		Before treatment		After secondary
Constituent (mg/l)	Range	Typical	Range	Typical	Typical
COD	200-270	75	250- 1000	500	80
TSS	20- 2,890	150	100-350	200	20
Total P	0,02- 4,30	0,36	4- 15	8	2
Total N	0,4- 20,0	2	20-85	40	30
Lead	0,01- 1,20	0,18	0,02-0,94	0,1	0,05
copper	0,01- 0,40	0,05	0,03-1,19	0,22	0,03
Zinc	0,01- 2,90	0,02	0,02-7,68	0,28	0,08
Fecal coliform per 100 ml	400- 50000		10^6-10^8		200

Most of the studies being done on improving stormwater runoff have focused on an approach called “Best management practices “(BMPs). This approach aims to reduce the pollutant input discharging into water resources. In this approach pollutants primarily are removed by sedimentation in constructed wetlands or retention ponds as BMPs. (*Muthukrishnan, & Selvakumar, 2006*). This approach has been used for management of stormwater flow in urban areas and is becoming common in the world especially the U.S. and Europe. e.g., the UK and France (*Dechesne, et al., 2004*).

More studies are required for evaluating and treating stormwater runoff quality in urban areas using BMPs such as constructed wetlands in the current state. The objective is to minimize pollution concentration in receiving waters as much as possible (*Persson, & Wittgren, 2003; Muthukrishnan, & Selvakumar, 2006*).

Many studies point out the importance of wetland treatment efficiency for treating urban runoff (*Muthukrishnan, & Selvakumar, 2006*).

2.2 Wetlands

Among different treatment systems, natural methods such as wetland systems are known as best policies. These systems can mitigate different pollution parameters, including heavy and trace metals, organics (COD, BOD), suspended solids, pathogens, phosphorous, nitrogen (*Vymazal, et al., 2013*). Natural and constructed wetlands can be of great help to treat industrial outlet runoff, such as pulp and paper mills (*Kadlec, & Wallace, 2009*).

2.2.1 Natural wetlands

Natural wetlands for the first time were studied during 1967 to 1972 by Howard T. Odum and A.C. Chestnut in the University of North Carolina. They tried to recycle and reuse municipal wastewaters by treating the water through coastal lagoons including planted and marsh wetlands. Years later more studies were done on almost all aspects of biological, chemical and physical processes during treatment in natural wetlands.

At the same time in 1971, Robert Kadlec and his coworkers at the University of Michigan began to work on wastewater recycling using engineered wetlands. The research was continued for some more years. During 1978 the research continued on a full scale and still is under development until today.

At the end of 20th century, natural wetlands were declared as protected natural resources in federal law stated by *Hammer and Bastian* (*1989*). Natural wetlands are known for great value in wildlife habitat and biological productivity, flood control, river stabilization and groundwater discharges and water quality improvements. These natural resources need to be protected. Unfortunately, many of natural wetlands have already been destroyed, and the remaining ones need urgent protection. On the other hand, using constructed wetland for treatment of many water contamination issues is an inexpensive way besides having many benefits such as improving biological and wildlife activities, and not affecting natural wetlands resources (*Hammer, & Bastian, 1989; Kadlec, & Wallace, 2009).*

2.2.2 Constructed wetlands

A constructed wetland is, in fact, a model of natural wetlands for treating contaminated water, alongside protecting natural resources. In these systems, plants, soil, and microbial activities are involved to treat polluted water in natural ways (*Hammer, & Bastian, 1989; Vymazal, et al., 2013*). These wetlands are classified according to water flow regime and type of macrophytic growth (*Vymazal, et al., 2013*). Constructed wetlands were first studied in universities of U.S. later developed further in Europe as well. In Europe Käthe Seidel was one of the early researchers who started the study on constructed wetland development for improving water quality (Kadlec, & Wallace, 2009). The studies on wetland technology had two aspects. The first aspect was studying values of natural wetland resources besides their effect on improving water qualities during their usage phase for wastewater treatments. The other aspects were the performance of engineered wetlands in both types of FWS and HSSF which began years after (*Kadlec, & Wallace, 2009*).

Today wetland treatment has advanced in many ways, and new systems have been engineered. And more knowledge is gathered on the subject of wetland treatment functionality and efficiency. Many of these new methods have been applied and adopted worldwide (*Kadlec, & Wallace, 2009*).

Furthermore, in comparison to many ecosystems, biological activities in wetlands are of higher rates, and due to these activities, common contaminants in typical wastewaters are turned to essential nutrients or harmless byproducts (*Kadlec, & Wallace, 2009*). At present time to perform some or all function of secondary treatment, the constructed wetland can be useful, and pretreated effluents can go via wetland for further treatment (*Kadlec, & Wallace, 2009*).

Figure 2-1 displays classification of constructed wetlands used for wastewater treatments at current times.

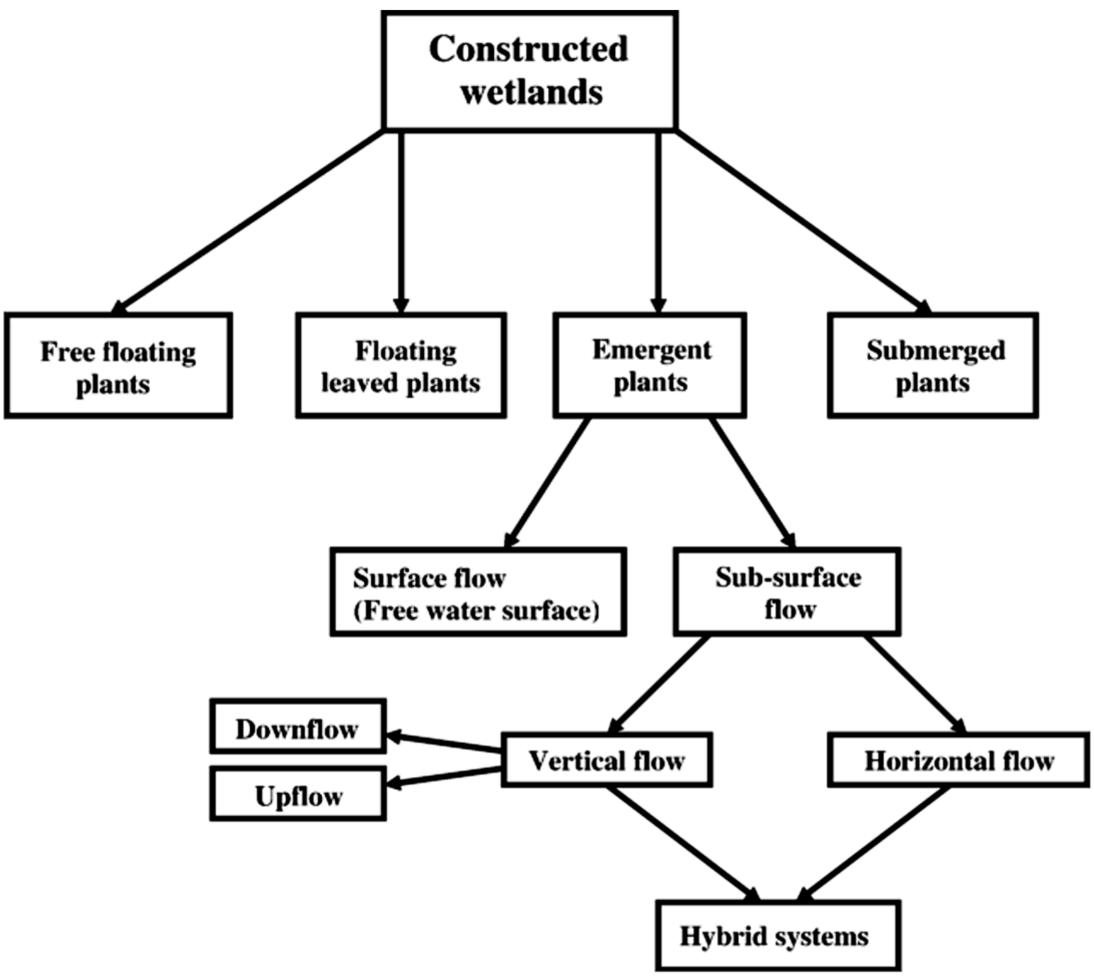


Fig 2-1 Classification of constructed wetlands for wastewater treatment (*Vymazal, et al., 2013*)

2.2.3 Wetland efficiency

Although constructed wetlands have been used as a sustainable form of wastewater treatment which removes adequate levels of organic matter in wastewaters, they may not be so compelling to remove nutrients. An eleven-month study undertaken on a constructed wetland (HSSF) located in Centre Region of Portugal showed relatively poor removal efficiencies (RE) of nitrogen and phosphorus. However, according to this study, it, the significant effect of the season on removal efficiency of nutrients, was found. (*Mesquita, et al., 2018*).

Preliminary results from the mesocosm studies showed that retention ponds and cattail wetlands are effective in removing heavy metal particles loads, particularly, Al, Cu, Pb, and Zn in the urban stormwater runoff, which consequently can improve the water quality of receiving water bodies. Probably settling of soluble particles to hydraulically inactive parts of pond or wetland causes a low rate of removal of dissolved metals. The role of vegetation in metals absorption has not been evident as metals removal rate did not change significantly between the retention pond and the wetland (*Muthukrishnan1, & Selvakumar, 2006*).

A three years long study on constructed wetland in Santo Tomé, Santa Fe, Argentina, showed high efficiencies in pollutants removal. The regulating capacity demonstrated by the CWs implies an important advantage if the primary treatment failed and there would be an accidental loading of high concentrations of metals, in which case the CW would retain them. Despite unlike retention mechanisms among the three vegetation stages removal efficiencies did not show significant differences (*Maine, 2009*).

Studies have shown depending on CWs type, and inflow loading, removal of total nitrogen can vary between 40 and 50%. However, the removal process may differ among various wetland systems. For example, single-stage constructed wetlands cannot remove high levels of total nitrogen as the wetland cannot provide both aerobic and anaerobic conditions simultaneously. Vertical-flow constructed wetlands successfully remove ammonia-N, but very limited denitrification occurs in these systems. Horizontal-flow constructed wetlands provide favorable conditions for denitrification but very limited to nitrify ammonia. Therefore, combining various types of constructed wetlands (hybrid systems) may achieve more efficient removal by utilizing specific advantages of the individual systems. Removal of phosphorus in all types of constructed wetlands is low unless particular substrates with high sorption capacity are used. Removal of both nitrogen and phosphorus by harvesting of above ground biomass of emergent vegetation is low, but it could be considerable for lightly loaded systems (*Vymazal, 2006*). Table 2-3 and 2-4 show efficiency of some studied wetlands.

Table 2-3 Summary of the removal efficiency observed in natural and constructed wetlands (*Ceballos et al., 2001*).

Effluent characteristic	**Natural wetland (W_n) average efficiency (%)**	**Constructed wetland (W_c) average efficiency (%)**	**Remark**
BOD_5	78	76	Constructed wetland showed relatively modest efficiency over the natural one
TP	24	12	
NH_4-N	27	70	
FC	90	90	
SS	50	66	

Table 2-4 Efficiencies of Up-flow constructed wetland system with various types of media under HRT of 3.0, 1.5 and 0.75 days (*Sirianuntapiboon et al., 2006*)

Parameters	Soil: sand ratio					
	75:25		50:50		25:75	
	Effluent	% Removal	Effluent	% Removal	Effluent	% Removal
HRT of 3.0 days						
COD	21±8	90 ± 4	21±8	90 ± 4	18±7	91 ± 5
BOD	15±10	91± 5	16±1	91 ± 5	15±10	92± 5
SS	14±5	76± 10	13± 6	78 ± 12	14±6	76 ± 9
TP	0.8±0.3	93 ± 3	0.6±0.3	9.3± 3	0.5±0.3	95 ± 3
TKN	5.7±1.9	84± 5	6.1±1.3	83 ± 4	3.6±1.4	90± 3
Ammonia	14.0±3.0	62± 3	16.0±2.8	57 ± 3	15±2..9	59± 3
Nitrate*	1.7±0.7	-	1.7±0.7	-	1.3±0.9	-
Nitrite	1.2±0.8	25 ± 1	1.2±0.9	25 ± 1	1.4±.0.1	13 ± 0.9
HRT of 1.5 days						
COD	33±12	82 ± 7	37±11	80 ± 6	51±13	73.± 7
BOD	13±7	91 ± 5	11±8	91 ± 7	18±6	90± 6
SS	8±6	84± 11	13±7	74 ± 11	15±6	71 ± 9
TP	1.0±0.3	89 ± 3	2.1±0.5	78 ± 7	3.2±1.1	66 ± 14
TKN	11.0±2.1	67 ± 6	16.4±2.4	51 ± 8	23.1±7.2	32.7 ± 19.2
Ammonia	3.0±0.8	64 ± 3	3.4±0.4	56 ± 3	2.7±0.5	33.3 ± 8.2
Nitrate*	1.8±0.4	-	2.1±0.7	-	1.3±0.7	-
Nitrite	1.3±1.0	19 ± 1	1.31.0	19 ± 1	1.5±1.0	6.3± 1.2
HRT of 0.75 days						
COD	27±6	84 ± 5	40±10	76 ± 7	48±10	71± 9
BOD	15±6	88 ± 6	17±7	86 ± 6	23±6	83± 5
SS	38±9	30±12	41±9	24 ± 11	39±10	28 ± 13
TP	1.9±0.8	84 ± 6	3.1±1.1	73 ± 9	4.7±0.9	60 ± 11
TKN	14.3±3.8	63 ± 8	18.0±3.4	53± 7	27.1±3.2	29 ± 7
Ammonia	2.6±0.9	28 ± 3	2.4±0.9	23 ± 3	2.6±0.9	-
Nitrate*	1.0±0.6	-	1.8±0.7	-	1.5±0.7	-
Nitrite	1.7±0.7	9 ± 1	1.1±0.7	9 ± 1	1.1±0.7	9 ± 1

*Effluent nitrate was higher than influent nitrate.

Table 2-5 Effluent quality after treatment of domestic wastewater with CW (*Von Sperling, 2007b*)

Parameters	Effluent %	Removal efficiency mg/l
COD	75-85	100-150
SS	87-93	20-40
Ammonia	<50	>15
Nitrogen	<60	>20
Phosphorus	<35	>4

2.2.4 Madlabekken wetland

Madlabekken is the largest inlet channel for Mosvatnet and leads overwater of areas around with large amounts of sand and organic particles to Mosvatnet. During 1990 the study has shown that water is extremely polluted and it needed to be treated before discharging into the lake Mosvatnet. For treating water of this stream, the best way was constructing Madlabekken wetland (*Molversmyr, et al., 2008*). A plant-based treatment system for Madlabekken (wetland) was established as a measure to reduce external nutrient supplies to the Mosvatnet.

The main process in Madlabekken wetland is sedimentation as the largest source of pollution for the Mosvatnet contains significant amounts of particles (*Molversmyr, et al., 2008*). A study carried out between 1999-2000 showed the construction of this wetland had helped a significant reduction in the content of phosphorous and to lesser extent nitrogen in the water. However, a survey of the sediment in Mosvatnet in 1999 showed that there still existed significant amounts of phosphorus potentially released into the water mass. Consequently, it was expected that it might have taken a long time before the lake could response to the reduced phosphorus supplies from the Madlabekken. Phosphorous was especially high during spring/early summer seasons.

The study concluded that, in this condition, further studies were required (*Molversmyr, et al., 2008*). However, the phosphorus content had varied considerably from year to year, which indicated that the sediment in the Mosvatnet could be an important internal phosphorus source. Accordingly, significant amounts of phosphorus can be fed to the lake water under certain conditions through the sediment. Considering the role of the sediment as a potential source of phosphorus, it was expected that the improvement could still take a long time (*Molversmyr, 2003*)

2.3 Water quality parameters

To define a condition for water to be usable by human and biotic species, taking proper measurements on water quality is required. The water quality consists of physical, chemical and biological properties of water. Besides, bad quality of water threatens biological life aquatic ecosystem (*Chapman, 1996*).

To characterize and evaluate quality water resources characterization, three main components are required. These components include hydrology, physical-chemistry, and biology (*Vymazal, 2005*).

2.3.1 Hydrodynamic features

Naturally, water resources are inter-connected through hydrological cycles. The water resources studied in this thesis include inland water resources such as lakes and rivers. The inter-connectivity between water resources can cause the water bodies to have impacts on each other (*Vymazal, 2005*).

By knowing this fact, improving water quality in each stage is essential for treating the quality of other water resources. Studies on the hydrodynamics of water resources have shown that size and climate condition of water bodies significantly influence hydrodynamic characteristics. On the other hand, hydrological regimes temporal and spatial variability are required to use water quality data measurements and interpret these data in a meaningful way (*Vymazal, 2006*).

Hydrodynamic features consist of physical and chemical properties and biological properties. To classify water resources of the same nature, physical characteristics such as conductivity and redox potential, total dissolved solids are needed to be measured (*Vymazal, 2005*).

To classify water bodies according to their location, distance from ocean, geology and amount of soil cover, and chemical quality of the environment will be helpful. Surface water has up to 90-99 percent chemical concentrations essential for habitat, aquatic life, and human needs, unless anthropogenic activities, which cause changes in water chemical quality (*Vymazal, 2013*). Biological characteristics of surface water including biota (flora and fauna) development also depends on different conditions (*Vymazal, 2005*).

2.3.2. Pollutant sources and pathways

Generally, aquatic environment is polluted by gases released into the atmosphere, soluble/ solid substances, and particulate forms. According to studies pollution sources can be point or diffuse sources which cannot be differentiated clearly. Mainly the difference between these two sources is that point sources are usually controlled and treated while the diffuse sources are not unless the source is identified and controlled. Collection and discharge of domestic, industrial and specific agricultural activities wastewater, are the primary point sources of pollution for freshwaters. Pesticide spraying and fertilizer application in agriculture activities are considered diffuse sources (*Vymazal, 2013*).

The pollution source type in this study is considered as a point pollution source originating from urban areas which is collected in urban storm overflow runoff and discharges to a stream and ends up in the lake.

According to different studies done on urban runoff such as NURP projects conducted by EPA between 1978 and 1983, urban runoff is a significant origin for water quality problems. Moreover, according to this study, different management practices and their effectiveness should be examined (*EPA., 1999*).

According to NURP projects, the following ten constituents are considered as main pollution sources in stormwater runoff (*Wong, 1999*):

- Total Suspended Solids (TSS)
- Biochemical Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Total Phosphorus (TP)
- Soluble Phosphorus (SP)
- Total Kjeldahl Nitrogen (TKN)
- Nitrate + Nitrite (N)
- Total Copper (Cu)
- Total Lead (Pb)
- Total Zinc (Zn)

NURP studies indicate that runoff produced in urban and non-urban areas vary significantly. However, different urban land use categories have almost same pollutant concentrations. The primary resources of stormwater runoff are contaminants from residential and commercial areas, construction, streets, industrial activities, and parking lots, and atmospheric deposition (*Wong, 1999*).

In this research, we have studied, the water quality of Madlabekken constructed wetland. During past studies, it was found that the inlet of Madlabekken stream is overwater or rainwater. Moreover, it has been shown that it had not been any wastewater or sewage, but some overflow from sewage system might be suspected (*Molversmyr, 2003*). Further studies are required to investigate whether any wastewater overflowing get mixed with the urban stormwater runoff which discharges to Madlabekken stream.

2.4 Objectives of this research

The overall objective of this study aims to monitor the water quality in this wetland and the treatment system at both inlet and outlet points.

Specific objectives of this study are as follows:

- Whether the water entering this stream and wetland is constant drainage overflow or periodic overflow and sewage in high overflow rates.
- To study the effectiveness of this wetland system, and to compare the water inflow and outflow quality.

The hypothesis is that during high flow rates, there is the possibility of some wastewater overflow getting mixed into the stormwater runoff and entering into the wetland. In addition to investigating the entrance of wastewater in the inlet, the wetland effect was also studied on the outlet to see if the wetland is of enough efficiency.

Chapter 3

Methods and materials

This chapter presents all the methods and materials used for conducting this thesis, including the site description of the case study, the methods used for sampling and analysis of various parameters. This research studies Madlabekken wetland constructed on Madlabekken river inlet merging into Mosvatnet lake. The parameters analyzed and measured include:

- Total phosphorus
- Phosphate
- Total nitrogen
- Ammonium
- COD
- Suspended solids in water samples.

3.1 Site description

Figure 3-1 shows the location of Madlabekken constructed wetland and Madlabekken stream. Madlabekken stream is the largest inlet channel for Lake Mosvatnet located in Stavanger city, Rogaland county, Norway. The lake is located in the Eiganes and Våland area, west of the city center of Stavanger. The lake area is 0.45 square kilometers (110 acres), and after Hålandsvatnet and Store Stokkavatnet is the third largest lake in Stavanger. The lake lies at an elevation of 37 meters (121 ft) above sea level, and its maximum depth is 3.2 meters (10ft). The outlet of the lake is through underground culverts to the lake Breiavatnet before emptying into the nearby Byfjorden (*Vassdrag, 2015*).

Figure 3-1 Location of Mosvatnet lake (red pin) and the constructed wetland (Photo: Google Map)

Madlabekken stream was highly polluted in the past according to Stavanger municipality. Currently, it is only street or rainwater runoff being carried in the stream, not wastewater or sewage.

The Madlabekken wetland was first established in 1991 and expanded just over ten years later. It was constructed to clean the overflow water, before entering into the Mosvatnet lake. Madlabekken is an open pond system with free water surface flow. This wetland includes two water ponds and one planted pond which are connected through two pumps (figure 3-2). The constructed wetland uses the principle of sedimentation as the cleaning method where unwanted particles sink to the bottom and create precipitated sludge. Both organic and inorganic particles follow the stream water into the constructed wetland. In this wetland, the water is first entered into a channel (inlet) where large particles sink to the bottom. The water is pumped from the channel to a sedimentation pool (first pond, fig 3-2). The pool is designed in such a way that the water flows slowly from one end to the other, allowing the heaviest particles to settle in the bottom. The sediments caught in the pool contain mainly road dust and other mineral particles.

This sedimentation is removed by vacuum trucks. Then the water is transferred to a channel system, where the smaller particles fall to the bottom (*Molversmyr, 2003*). In the channel, the water is staying for a longer time due to low flow velocity. The finely divided particles, consisting mainly of organic matter and nutrients such as nitrogen and phosphorus, are captured by vegetation or sediment. This sludge is consumed in the pond by bacteria and microorganisms (*Molversmyr, 2003*). The water that is not pumped into the cleaning loop from the bioreactor first gets a stay in a channel before it is returned to Madlabekkens old outlet to the Mosvatnet (*Molversmyr, 2000*). Finally, flow is entering the last pond (2nd. pond) and then to the mainstream of Madlabekken flowing toward Mosvatnet lake (figure 3-2).

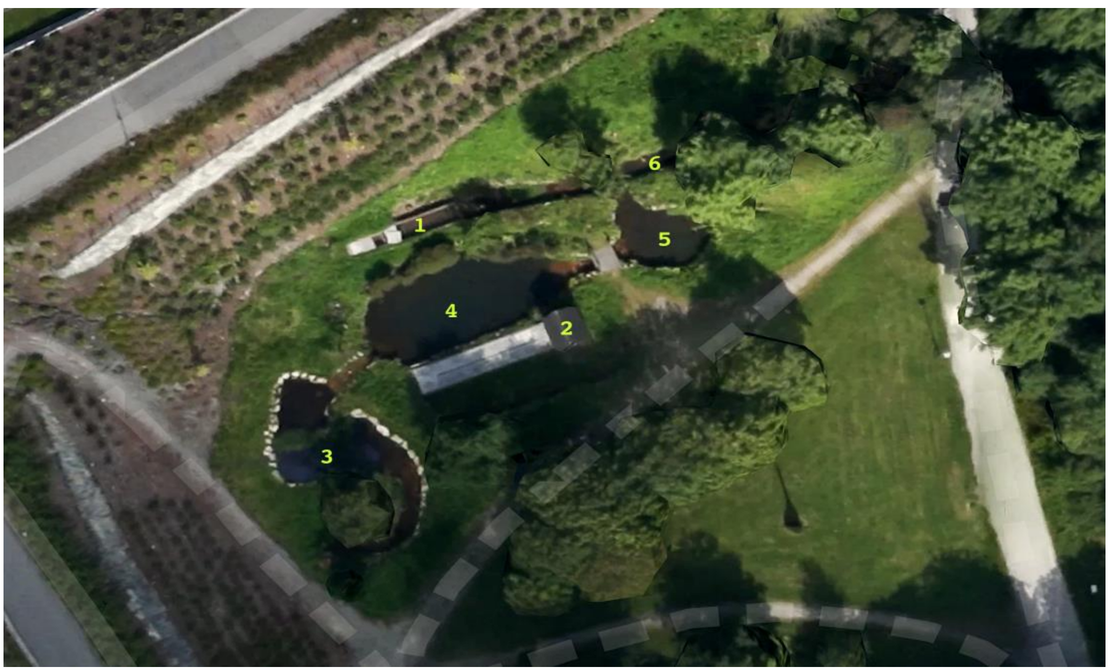


Fig 3-2 Madlabekken constructed wetland (1: Inlet channel, 2: Pump station, 3: planted pond, 4: first sedimentation pond, 5: second sedimentation pond, 6: Outlet channel) (*Photo: Google map*)

Plants and trees in the constructed wetland will also absorb some of the nutrients from the stream water. However, the plants are also there to have a beautiful view, as a part of the recreation area around the Mosvatnet. The wetland will also help maintain the birdlife in the area (*Molversmyr, 2003*). The plants for the wetland were taken from Mosvatnet and were placed at a reasonable distance from each other. In this way, one could easily map the growth of the different species during the establishment, with varied nutrition and at different times of the year (*Molversmyr, 2003*).

3.2 Sampling procedure

Inlet samples were taken from the flow in inlet channel (first channel) before pumping to sedimentation pool. Outlet samples were taken from the outlet of the second sedimentation pond (figure 3-2) before entering into the main Madlabekken stream. The sampling procedure before installing samplers from October to January (2018), was every day manually samples for both Inlet and outlet. From late January to May (2018) two portable samplers (automatic samplers) were installed in the pump station. The inlet sampler was a Sigma Max 900 sampler (portable sampler) which was connected to inlet channel with around 15 meters tube and was sampling 250 ml water every 6 hours (time-based sampling) for a week, and after a week the samples were collected for analyses. The outlet sampler was ISCO 6712 which was connected to the outlet with around 20 meters tube and same as the inlet sampler was sampling every 6 hours around 250 ml sample for one week, and after one week the samples were collected to be analyzed. Samples were pumped into 10-liter bottles, which were kept dark in the pump station, for storage. Figure 3-4 shows the - samplers installed in the pump station.

A B

Figure 3-3 Automatic samplers, A. ISCO 6712, B. Sigma max 900

3.3 Analytical methods

After a week sampling, samples were taken to the lab for analyzing. Samples were analyzed for estimating parameters as TSS, total and dissolved COD, total nitrogen (TN), ammonium (NH_4^+), total phosphorus (TP) and phosphate (PO_4^{-3}) based on the methods presented in table 3-1.

3.3.1 TSS analyses

In this study, Total suspended solids analysis was done according to “Standard method 2540-D” (*Clesceri, et al., 1998*). In this method, a standard glass microfiber filter with pore size 1.5 µm of type Whatman (GF/F) was used. The residue remained on the filter surface after filtration was TSS and the filtered sample was used for analyzing soluble COD. The filter was dried for 1 hour in oven 105ºC and cooled 10 min in a desiccator. After cooling the filter was weighed. Total suspended solids were calculated according to equation 3-1 (*Clesceri, et al., 1998*).

$$TSS\ [mg] = (weight\ of\ filter\ and\ dried\ residue\ [mg] - weight\ of\ filter[mg]) \quad \text{Equation (3-1)}$$

3.3.2 Analyzing total and soluble COD

Total COD and soluble COD were analyzed using direct colorimetric analysis procedure.

For measuring total COD, 3 mL of a sample was taken to COD vial (already prepared range 4- 40 mg/l), the sample was digested in a thermoreactor at 148°C for 2 hours. After removing COD vial from the reactor, it was cooled in metal test tube rack until room temperature. Upon reaching room temperature (very important), the test cell was placed in spectrophotometer then concentration and absorbance value were registered. Before analyzing soluble COD, the sample was filtered through a standard glass microfiber filter with pore size 1.5 µm of type Whatman (GF/F).

This method is a standard spectrophotometric method, equivalent to ASTM 5220 D, closed reflux with colorimetric detection and corresponds to DIN ISO 15705 and is equivalent to EPA 410.4.

The procedure for COD test is so that potassium dichromate, a strong chemical oxidant in sulfuric solution an acid solution, is used and after digestion using heat at temperature 148 °C for 2 hours, the organic carbon is oxidized to CO_2 and H_2O. By measuring the oxygen equivalent of the organic matter content of the oxidized sample, using titrimetric or photometric methods, the oxygen demand is determined (*Boyles, 1997*).

3.3.3 Analysing total nitrogen (TN) and ammonium (NH_4^+)

Total Nitrogen (TN) and ammonium (NH_4^+) were also analyzed using direct colorimetric analysis procedure.

For measuring total Nitrogen 10 mL of a sample was taken to an empty cell, and one dose reagent N-1K and six drops N-2K was added to the sample and sample was digested in a thermoreactor at 120°C for an hour. After removing the cell from the reactor, it was cooled in metal test tube rack until room temperature. Upon reaching room temperature (very important), one dose reagent N-3K was added to a nitrogen vial (already prepared range 0.01 - 2.58 mg/l). After dissolving 1.5 ml of digested and cooled sample, it was added to N vial, and after 10 min reaction time, the test tube was placed in the spectrophotometer.

This method is equivalent to DIN EN ISO 11905-1, and the procedure in this method is organic, and inorganic nitrogen compounds are transformed into nitrate according to the Koroleff¨s method by treatment with an oxidizing agent in a thermoreactor. The nitrate reacts with benzoic acid derivative in concentrated sulfuric acid and is determined photometrically.

For measuring NH_4^+, 5 mL of a sample was taken to ammonium vial (already prepared range 0.01-2.0 mg/l) and one dose reagent NH_4^+-1K was added, after 15 min reaction time, the test tube was placed in the spectrophotometer, concentration and absorption were registered.

The method in this test is equivalent to EPA 350.1, APHA 4500-NH3 F, ISO 7150-1, and DIN 38406-5, and the procedure is so that ammonium nitrogen (NH_4^+-N) occurs partly in the form of ammonium ions and partly as ammonia. Between two forms there is a PH-dependent equilibrium. If the solution is strongly alkaline, nitrogen will be present as ammonia, which forms monochloramine in reaction with hypochlorite ions. Moreover, this will form a blue indophenol derivative after reaction with a substituted phenol. The measurement solution is yellow-green to green in color, due to intrinsic yellow coloration.

3.3.4 Analyzing total phosphorus and PO_4^{-3}

Total phosphorus (TP) and phosphate (PO_4^{-3}) were analyzed using direct colorimetric analysis procedure.

For measuring total phosphorus 5 mL of a sample was taken to the phosphorous vial (already prepared range 0.05-5 mg/l) and one dose of reagent P-1K was added. So, the sample was digested in a thermo reactor at 120°C for 30 minutes. After removing P vial from the reactor, it was cooled in metal test tube rack until room temperature. Upon reaching room temperature (very important), five drops reagent P-2k, and one dose reagent P-3K was added, after 5 min reaction time, the test tube was placed in a spectrophotometer, concentration and absorbance were registered.

For measuring phosphate 5 mL of a sample was taken to the phosphorous vial (already prepared range 0.05-5 mg/l), five drops reagent P-2k, and one dose reagent P-3K was added. After five min reaction time, the test tube was placed in a spectrophotometer, concentration and absorbance were registered.

The procedure is so that in sulfuric solution orthophosphate, ions react with molybdate ions to form molybdophosphoric acid. Ascorbic acid reduces this to phosphomolybdenum blue (PMB) that is determined photometrically. For determining total phosphorus samples must be decomposed by digestion. This method is equivalent to EPA 365.2+3, APHA 4500-P E, and DIN EN ISO 6878. Table 3-1 shows the test kits description and methods corresponded to used test kits for each analyzed parameter.

Table 3-1 Test kits description and methods used during Laboratory analysis

Parameters	Test kit number and description	Methods
TSS	---	Standard method 2540-D
COD	1.14560.0001, 1.14560.007, EMD Millipore Corporation	EPA 410.4 APHA 5220 D ASTM D1252-06 B
Total phosphorus (TP)	1.14543.0001, EMD Millipore Corporation	EPA 365.2+3 APHA 4500-P E
Phosphate (PO_4^{-3})	1.14543.0007, EMD Millipore Corporation	EPA 365.2+3 APHA 4500-P E
Total nitrogen	1.14537.0001, EMD Millipore Corporation	DIN EN ISO 11905-1
Ammonium (NH_4^+)	1.14739.0001, EMD Millipore Corporation	EPA 350.1, APHA 4500-NH

3.3.5 Weather condition

Daily weather data during this study (October 2017-May 2018) is presented in figure 3-3 (Yr, 2018). Table 3- 2, shows average, highest and lowest temperature, as well as average and highest precipitation for each month. According to average temperatures, May 2018 was the warmest month, while February 2018 was the coldest. Most precipitation and highest precipitation was received in October 2017, while March 2018 with the lowest average and peak precipitation, was the driest month. Snow was observed in December, January, February, and March. The weather observation station is located in Stavanger municipality, 72 m above sea level.

Table 3-2 Monthly average, max. and min. temperature with peak and average precipitation during study period

Month	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18	Apr-18	May-18
Average precipitation (mm)	9	8,1	6,7	4,5	3,8	1,2	1,2	4,2
Peak precipitation (mm)	38,6	34,8	23,7	23,7	33,5	9,7	11,7	33,7
Average temperature (◦ C)	10	5,2	3,5	2,7	0,2	0,9	7,9	13
Max. temperature (◦ C)	13	10,5	8,6	6,5	3,5	5	15,5	25
Min. temperature (◦ C)	4,8	-0,8	-2,2	-1	-9	-7	1	7

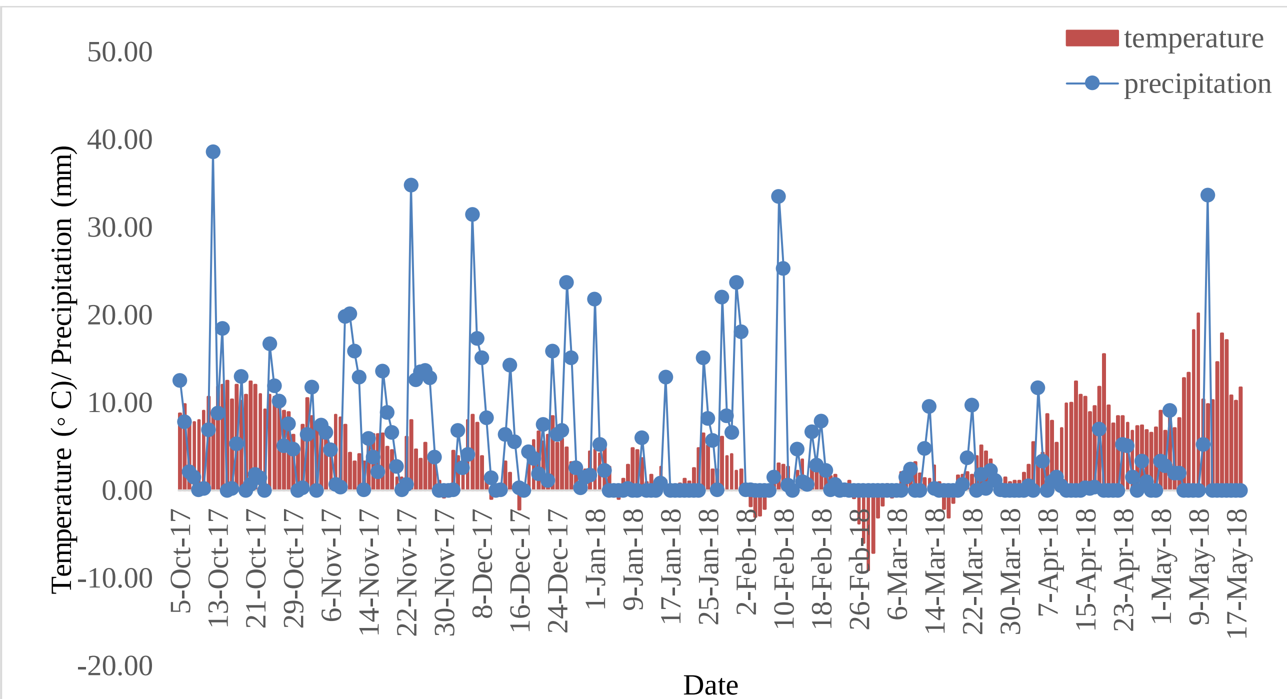


Figure 3-4 weather data during the study period

3.3.6 Error analyses

While doing experimental works errors cannot be avoided, and there could be different sources to cause the error.

For error analyses of parameters of test analysis, TSS, total and soluble COD, total phosphorus and phosphate, total nitrogen and ammonium, three parallel samples were analyzed. The standard deviation was calculated for each parameter. The calculated standard deviation includes possible errors while sampling, sample preparation, and analysis, and apparatus errors. In addition to standard deviation method detection limit (MDL) which is the minimum concentration of the parameter, greater than zero, was evaluated.

Although the linear correlation between different parameters using scatter diagram method was analyzed and the correlation coefficients are presented in table 4-1.

Chapter 4

Results

In this Chapter results obtained from water samples, analysis and raw data and correlations of experiments are presented. The results are summarized in graphs and tables. Samples were taken from October 2017 until May 2018. Additional data not presented in this chapter are in the appendices. Results are presented in four main sections.

The first section presents data of inlet channel which shows the overall water quality of this stream before treatment. The second section is the results obtained from the outlet of the wetland. Graphs and tables of correlation of inlet and outlet concentrations are in third section. And in the last section errors are analyzed.

Data on precipitation was collected from Yr. (2018) meteorological website of Norway for the experiments period. Precipitation during the study period is presented in figure 3-3 in the previous chapter.

4.1 Inlet

4.1.1 Total suspended solids

Total suspended solid was measured in the lab from weekly samples. The data are presented in figure 4-1 for the study period. The range is varied from MDL (method detection limit) which was 0.7 mg/l to 70 mg/l. The peak value of TSS occurred during February.

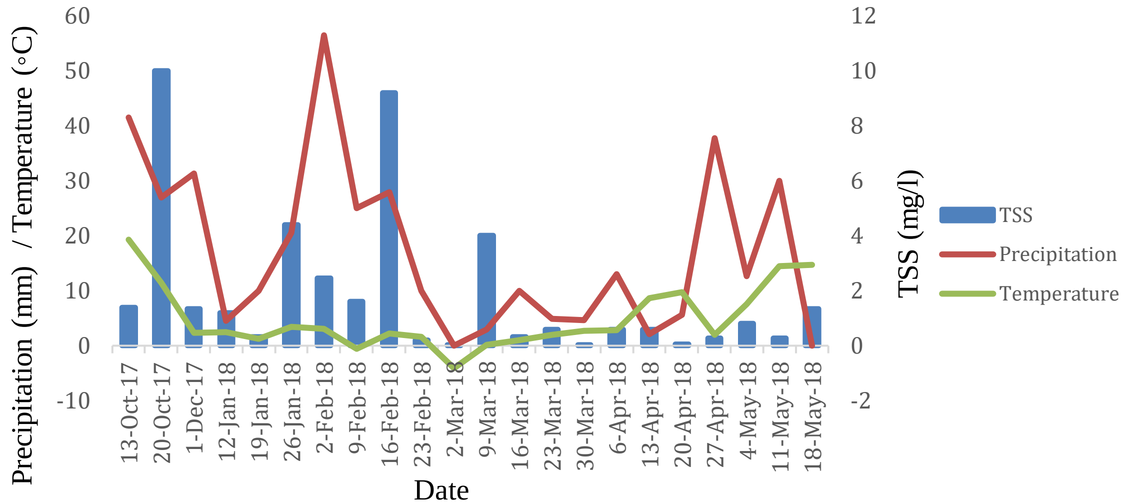


Figure 4-1 Total suspended solids of Madlabekken stream

4.1.2 Total and soluble COD

Total and soluble COD was measured using EPA 410.4 APHA 5220 D and done weekly. The data are presented in figure 4-2 for the experiments period. The range for total COD is from minimum 6 mg/l to 50 mg/l. The range for soluble COD is varied from minimum 4.7 mg/l to maximum 26,7 mg/l. Maximum total COD considering peak TSS, was during February. Soluble COD shows a less variation.

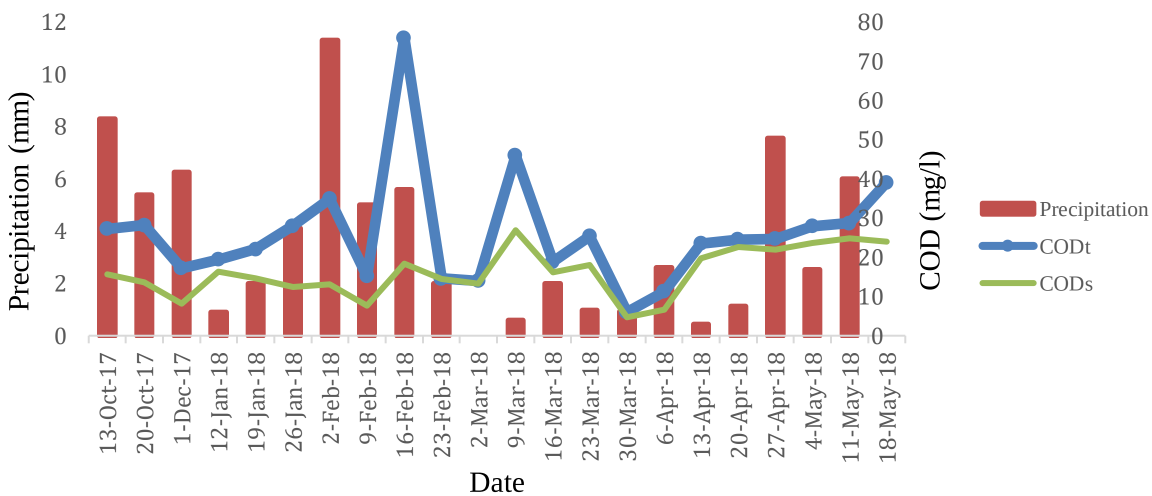


Figure 4-2 Total COD and soluble COD in Madlabekken stream at the inlet of wetland with precipitation

4.1.3 Total phosphorus and phosphate (PO_4^{-3})

Total phosphorus (TP) and phosphate (PO_4^{-3}) were measured using EPA 365.2+3, APHA 4500-P E, and done weekly. The lab analysis results are presented in figure 4-3 and 4-4 for the experiments period with weekly average precipitation and temperature respectively. The range for total phosphorus is from minimum 0.05 mg/l to maximum 0.42 mg/l. The range for phosphate varied from minimum 0.03 to maximum 0.28 mg/l. The maximum TP and PO_4^{-3} are found in January.

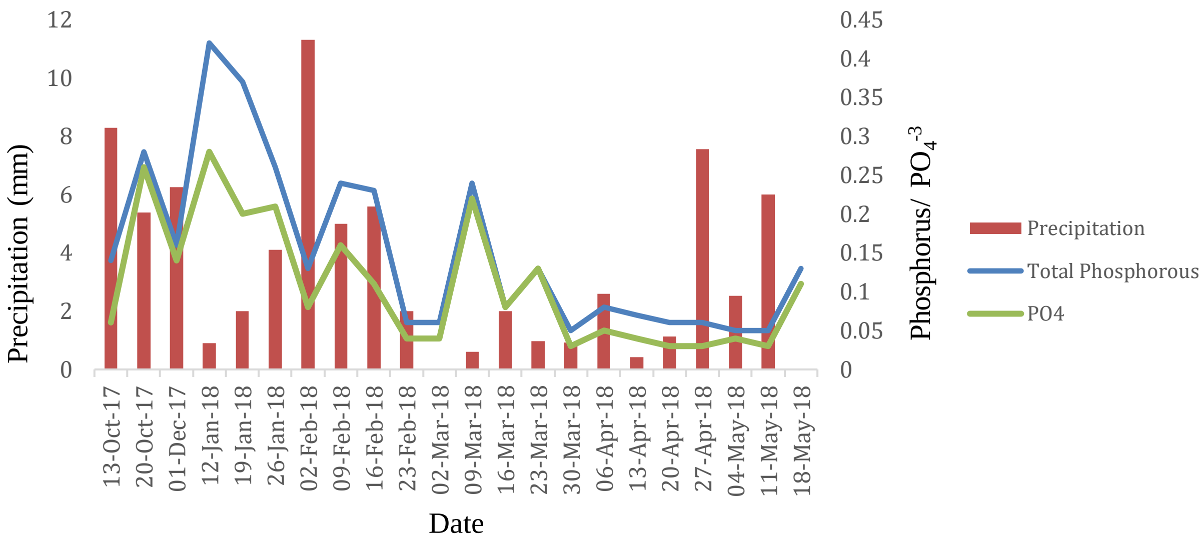


Figure 4-3 Total phosphorus and phosphate (PO_4^{-3}) in Madlabekken stream together with precipitation

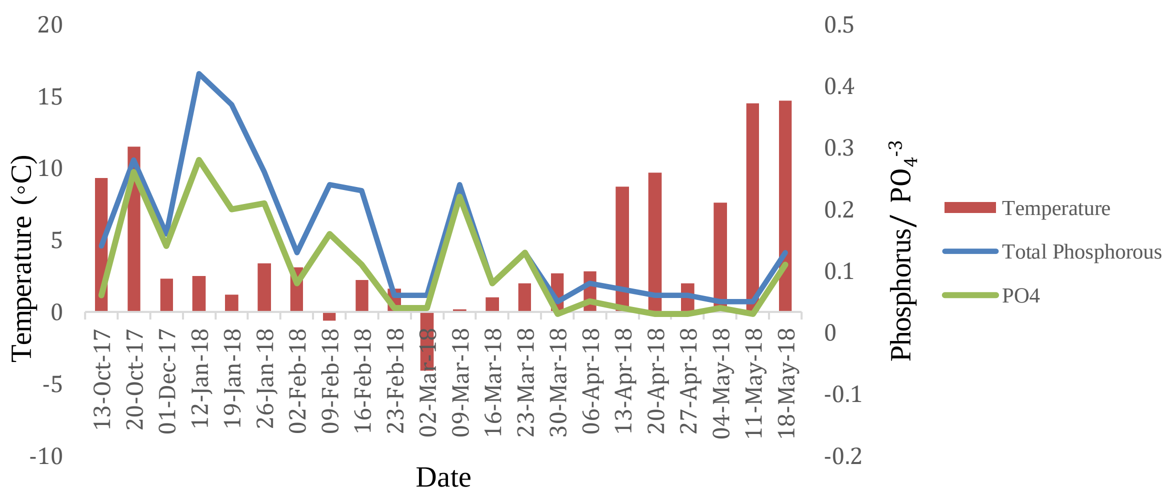


Figure 4-4 Total phosphorus and phosphate (PO_4^{-3}) in Madlabekken stream together with temperature

4.1.4 Total nitrogen (TN) and Ammonium (NH_4^+)

Total nitrogen and ammonium were measured using DIN EN ISO 11905-1 and the measurements were done weekly. The lab analysis results are presented in figure 4-5 and 4-6 for the whole monitoring period with weekly average precipitation and temperature. The range for total nitrogen varies from minimum 0.5 mg/l to maximum 3.4 mg/l. The range for ammonium is from 0.03 mg/l to 1.077 mg/l. The maximum TN occurred in October, due to manually sampling. During May TN and NH_4^+ are decreased considerably.

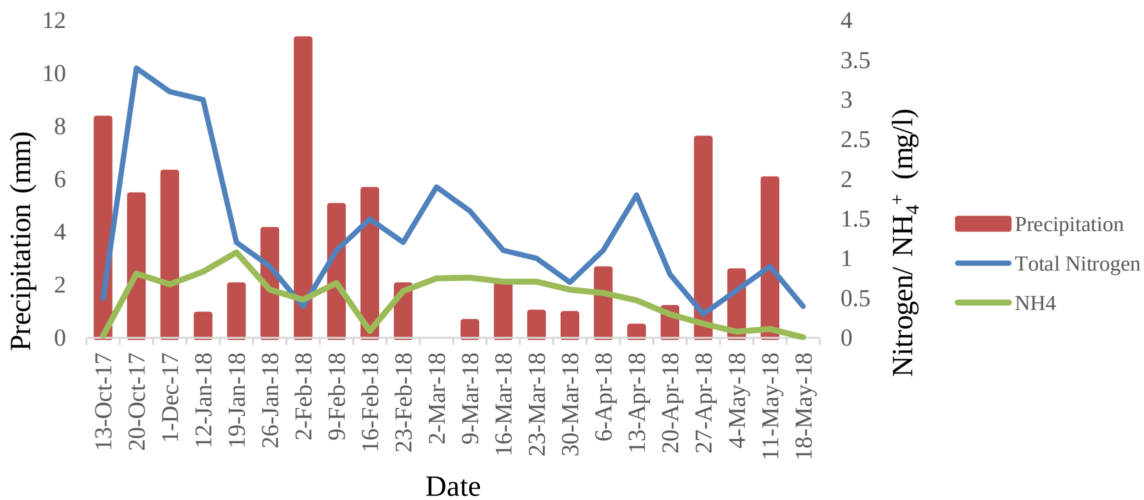


Figure 4-5 Total nitrogen and ammonium (NH_4^+) in Madlabekken stream with precipitation

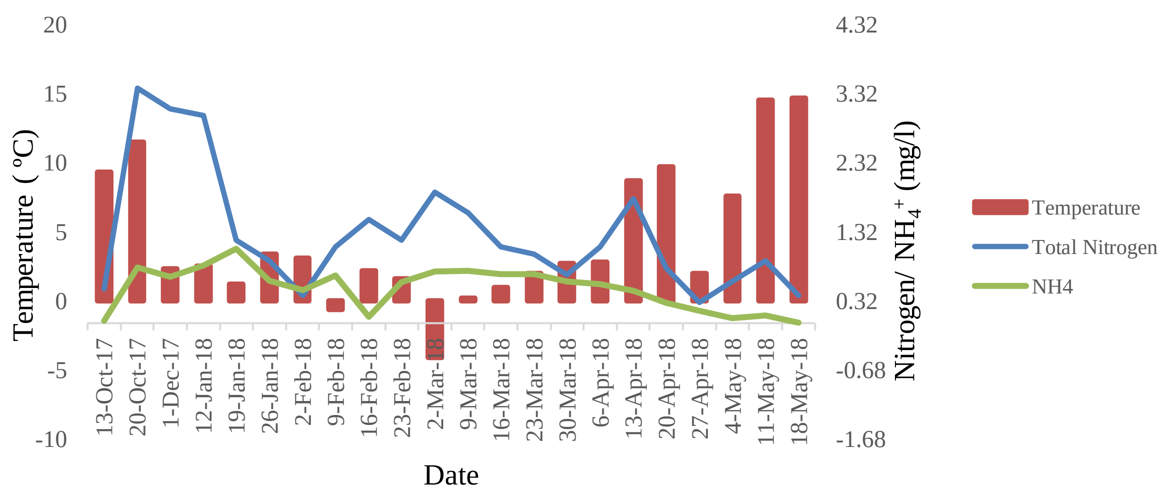


Figure 4-6 Total nitrogen and ammonium (NH_4^+) in Madlabekken stream with the temperature

4.1.5 Correlations

Table 4-1 shows the linear correlation between different parameter in the whole monitoring period of this study at the inlet. The table also shows the positive and negative relationship of parameters with each other. The table does not suggest significant relationships except for COD_t with TSS, TP with PO_4^{-3}, which are most related parameters.

Table 4-1 linear correlation of different analyzed parameters during the study period at the inlet

	analyzed parameters linear correlation R^2 at the inlet							
Parameter	TSS	COD_t	COD_s	TP	PO_4^{-3}	TN	NH_4^+	Precipitation
TSS	1							
COD_t	+0,51	1,00						
COD_s	+0,03	+0,28	1,00					
TP	+0,20	+0,08	0,00	1,00				
PO_4^{-3}	+0,26	+0,05	0,00	+0,85	1,00			
TN	+0,16	0,00	-0,01	+0,22	+0,35	1,00		
NH_4^+	-0,01	-0,17	-0,06	+0,20	+0,33	+0,212	1,00	
Precipitation	+0,15	+0,09	-0,02	+0,01	0,00	0,00	-0,23	1,00

Table 4-2 presents the overall average of analyzed parameters during the study period. The overall concentration in table 4-2 in compare to pollution range for urban and storm runoff in literature, is within or lower than the range.

Table 4-2 average concentration of analyzed parameters during monitoring period at inlet

Parameters	Average concentrations (mg/l)
TSS	8,93
COD_t	35,77
COD_s	14,89
TP	0,17
PO_4^{-3}	0,12
TN	1,46
NH_4^+	0,60

The ratio of soluble COD to total COD, PO_4^{-3} to total phosphorus, NH_4^+ to total nitrogen is shown in table 4-3.

Table 4-3 ratio of parameters at inlet

Inlet concentrations ratio			
weeks	COD_s/COD_t inlet %	PO_4^{-3}/TP %	NH_4^+/TN %
13-Oct-17	57,14	42,86	6,20
20-Oct-17	48,23	92,86	23,68
1-Dec-17	47,67	87,50	21,71
12-Jan-18	84,02	66,67	27,73
19-Jan-18	66,52	54,05	89,75
26-Jan-18	44,64	80,77	67,89
2-Feb-18	37,54	61,54	119,75
9-Feb-18	50,00	66,67	63,09
16-Feb-18	24,21	47,83	5,90
23-Feb-18	98,63	66,67	49,42
2-Mar-18	95,00	66,67	39,26
9-Mar-18	58,48	91,67	47,44
16-Mar-18	86,17	100,00	64,73
23-Mar-18	70,87	100,00	70,50
30-Mar-18	78,33	60,00	86,71
6-Apr-18	58,41	62,50	51,73
13-Apr-18	83,83	57,14	26,22
20-Apr-18	92,65	50,00	36,75
27-Apr-18	88,66	50,00	59,00
4-May-18	84,95	80,00	12,83
11-May-18	86,41	60,00	12,78
18-May-18	67,80	84,62	1,75
Average	68,64 ±20	69,55±16	44,76 ±30

4.2 Outlet

4.2.1 Total suspended solids

The results of lab analysis for total suspended solids from the outlet of Madlabekken constructed wetland are presented in figure 4-7 for the experiments period. The range is varied from 0.7 (MDL) mg/l to 32 mg/l. The maximum TSS in October is due to manually sampling and resuspension by birds.

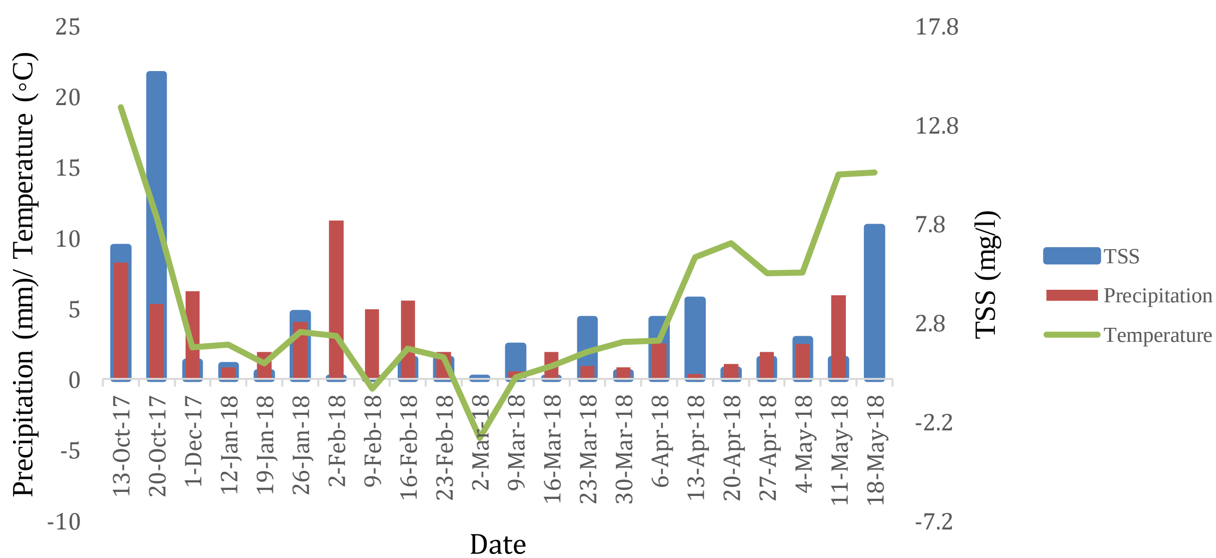


Figure 4-7 Total suspended solids of Madlabekken wetland outlet with precipitation and temperature during the study period

4.2.2 Total and soluble COD

The lab analysis results of total COD and soluble COD, with precipitation regarding the date, are presented in table 4-8. The range for total COD varies from minimum 5,9 mg/l to 23.9 mg/l, and for soluble COD it varies from 3.1 mg/l to 22.9 mg/l. The concentrations are not varied so much after water is treated by wetland except for lowest concentration in March due to the minimum concentration of COD at the inlet.

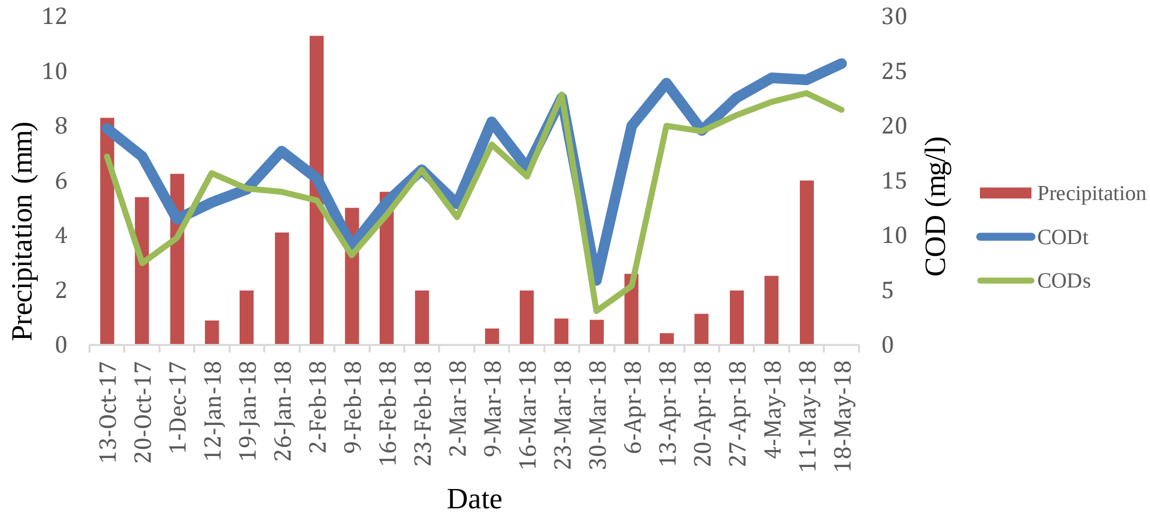


Figure 4-8 Total COD and soluble COD, in Madlabekken wetland at the outlet, with precipitation

4.2.3 Total phosphorus and phosphate (PO_4^{-3})

The lab analysis results of total phosphorus and phosphate with weekly average precipitation and temperature regarding the date are presented in figure 4-9 and 4-10. The minimum range of phosphorous is 0.03 mg/l, and the maximum is 0.23 mg/l. The range for phosphate varies from 0.03 mg/l to 0.22 mg/l.

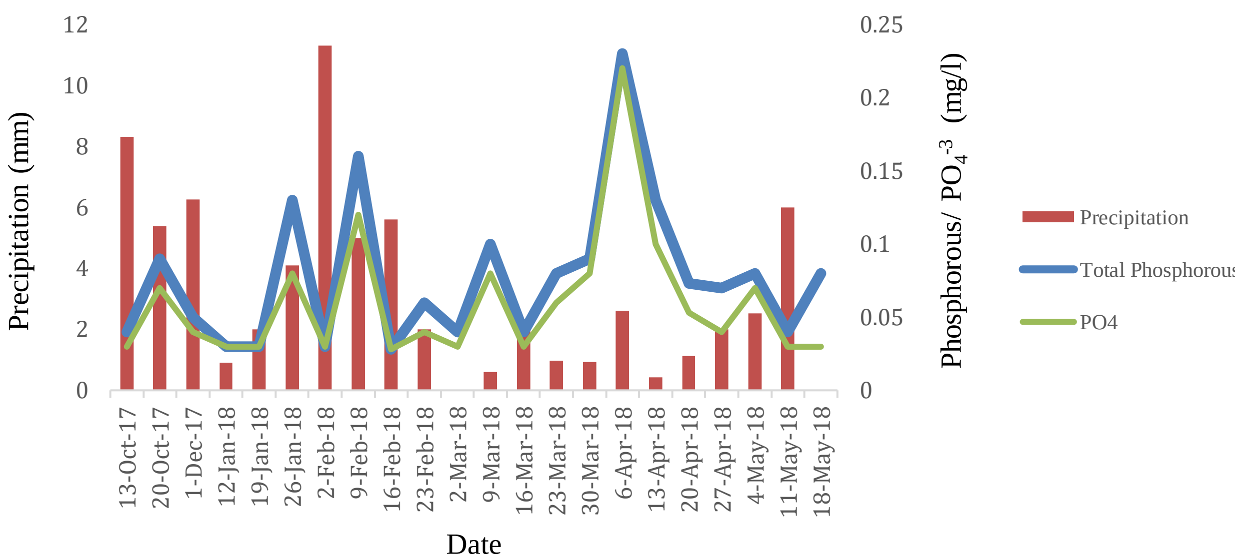


Figure 4-9 Total phosphorus and PO_4^{-3} concentrations of Madlabekken wetland at the outlet, with precipitation during the study period

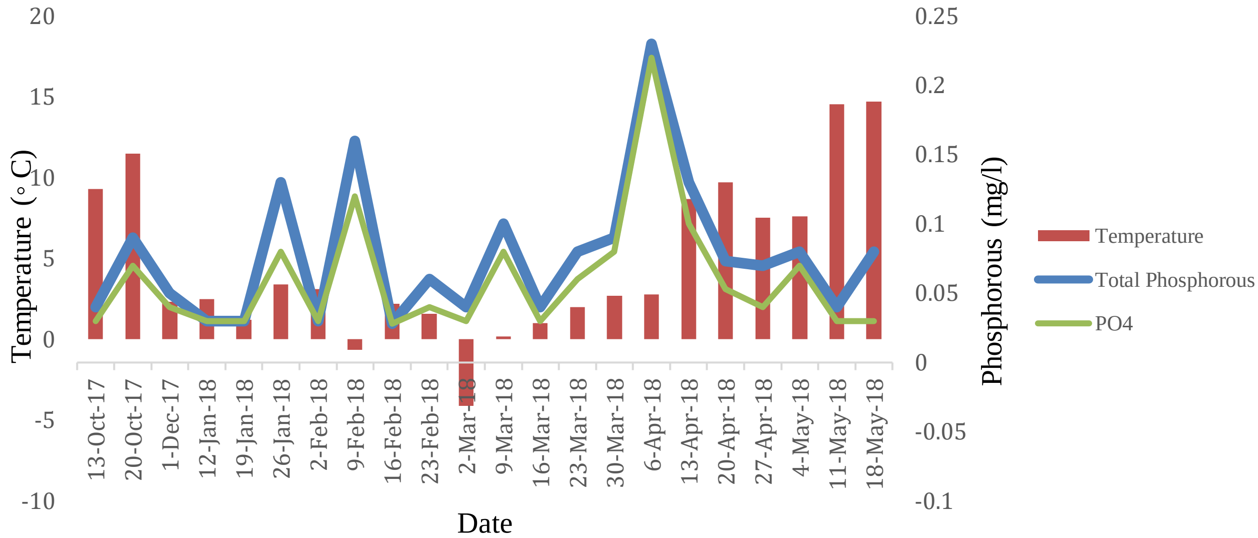


Figure 4-10 Total phosphorus and PO_4^{-3} concentrations of Madlabekken wetland at the outlet, with temperature during the study period

4.2.4 Total nitrogen and NH_4^+

Figure 4-11 and 4-12, presents total nitrogen and ammonium range with weekly average precipitation and temperature in front of sampling date. The range for nitrogen is from 0,7 to 1.8 and range for ammonium is from 0.088 mg/l to 0.928 mg/l.

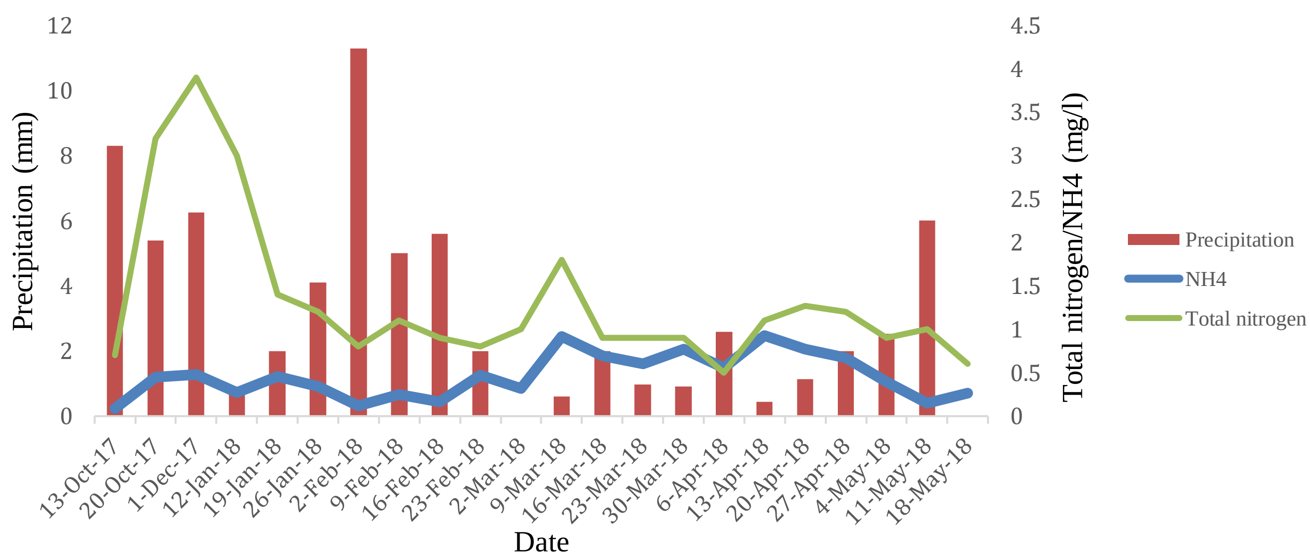


Figure 4-11 Total nitrogen and NH_4^+ concentrations of Madlabekken wetland at the outlet, with precipitation during the study period

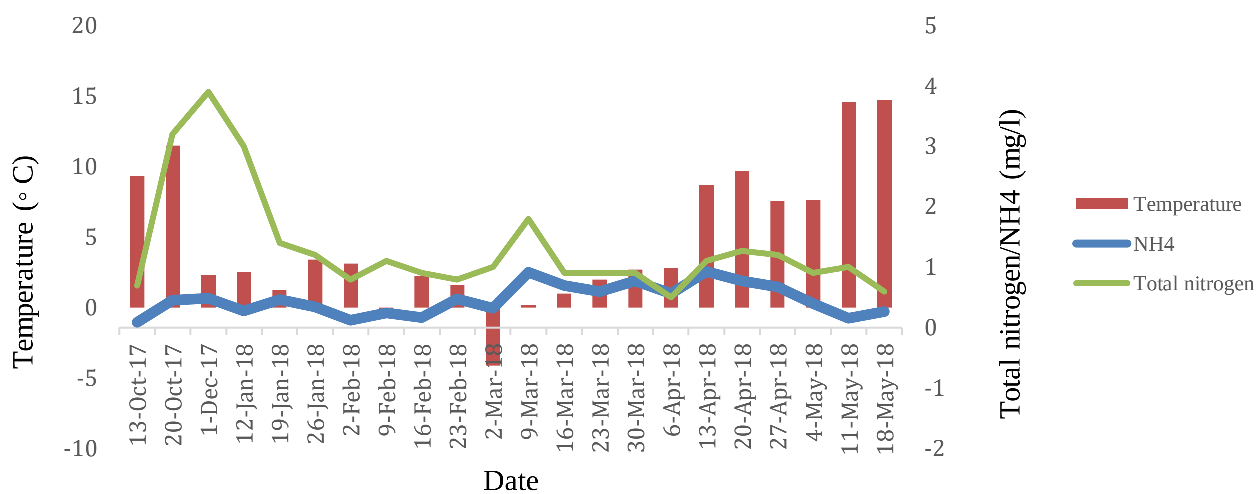


Figure 4-12 Total nitrogen and NH_4^+ concentrations of Madlabekken wetland at the outlet, with temperature during the study period

Table 4-4 shows the linear correlation between different parameter in the whole monitoring period of this study at the outlet. The table also shows the linear correlation of parameters with each different parameter.

The ratio of soluble COD to total COD, PO_4^{-3} to total phosphorus, NH_4^+ to total nitrogen at the outlet is presented in table 4-5.

Table 4-4 linear correlation of different analyzed parameters during the study period at the outlet

	analyzed parameters linear correlation R^2 at the Outlet							
Parameters	TSS	COD_t	COD_s	TP	PO_4^{-3}	TN	NH_4^+	Precipitation
TSS	1							
COD_t	+0,09	1,00						
COD_s	-0,01	+0,57	1,00					
TP	-0,03	+0,04	-0,09	1,00				
PO_4^{-3}	-0,02	+0,03	-0,14	+0,94	1,00			
TN	+0,10	-0,05	-0,03	-0,04	-0,04	1,00		
NH_4^+	0,00	+0,10	+0,04	+0,09	-0,07	+0,10	1,00	
Precipitation	+0,05	-0,03	-0,06	-0,03	-0,02	+0,01	0,47	1,00

Table 4-5 ratio of parameters at the outlet

Outlet			
weeks	COD_s/ COD_t Outlet	PO_4^{-3}/TP	NH_4^+/TN
13-Oct-17	86,87	75,00	12,57
20-Oct-17	43,60	77,78	14,13
1-Dec-17	85,51	80,00	12,38
12-Jan-18	120,77	100,00	9,20
19-Jan-18	100,70	100,00	32,79
26-Jan-18	79,10	61,54	28,17
2-Feb-18	86,84	100,00	14,75
9-Feb-18	91,11	75,00	22,36
16-Feb-18	90,84	100,00	18,22
23-Feb-18	100,00	66,67	58,75
2-Mar-18	90,70	75,00	32,10
9-Mar-18	89,71	80,00	51,17
16-Mar-18	95,06	75,00	77,11
23-Mar-18	101,33	75,00	66,78
30-Mar-18	52,54	88,89	85,44
6-Apr-18	27,00	95,65	112,00
13-Apr-18	83,68	76,92	84,36
20-Apr-18	99,64	72,60	60,63
27-Apr-18	92,92	57,14	55,92
4-May-18	90,98	87,50	43,89
11-May-18	95,04	75,00	15,00
18-May-18	83,66	37,50	44,67
Average	85,80 ± 20	78,74 ±15	43,29 ±28

4.3 Correlation between inlet and outlet

4.3.1 Total suspended solids

Figure 4-13 shows the graph of total suspended solids at inlet and outlet together with precipitation.

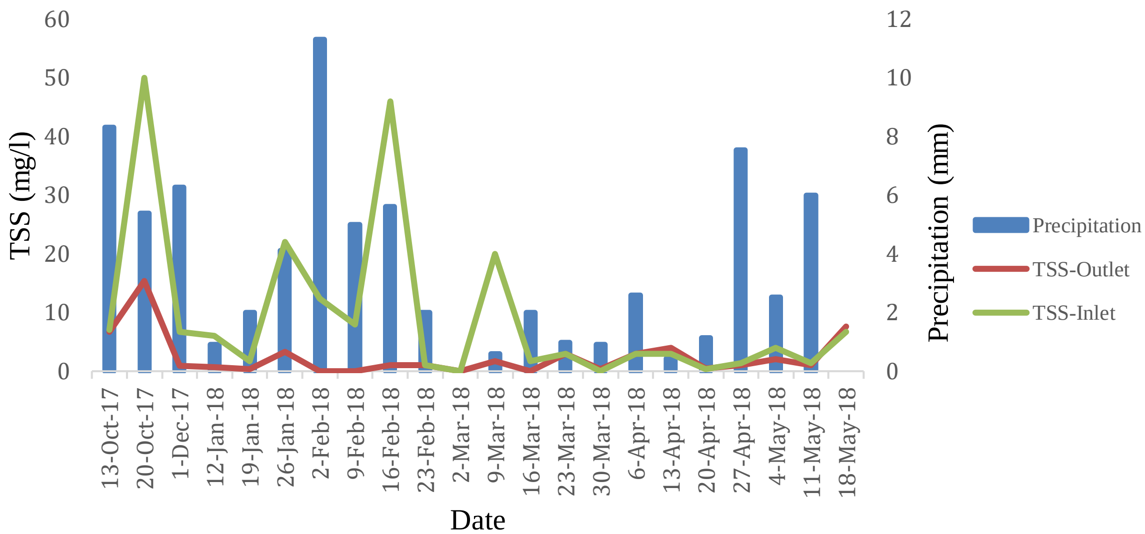
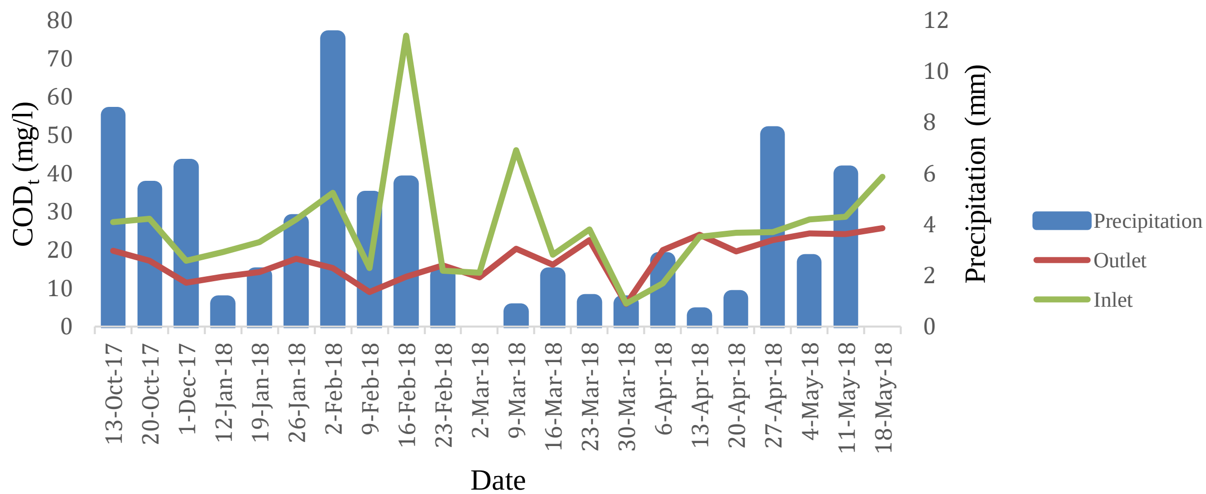


Figure 4-13 Total suspended solids from Madlabekken wetland inlet vs. outlet, October to May

The monthly average concentration of TSS, from inlet and outlet and retained percentage, are presented in table A-9, appendix i.

4.3.2 Total and soluble COD

Figure 4-14 shows the correlation between total and soluble COD from inlet and outlet with precipitation.



a.

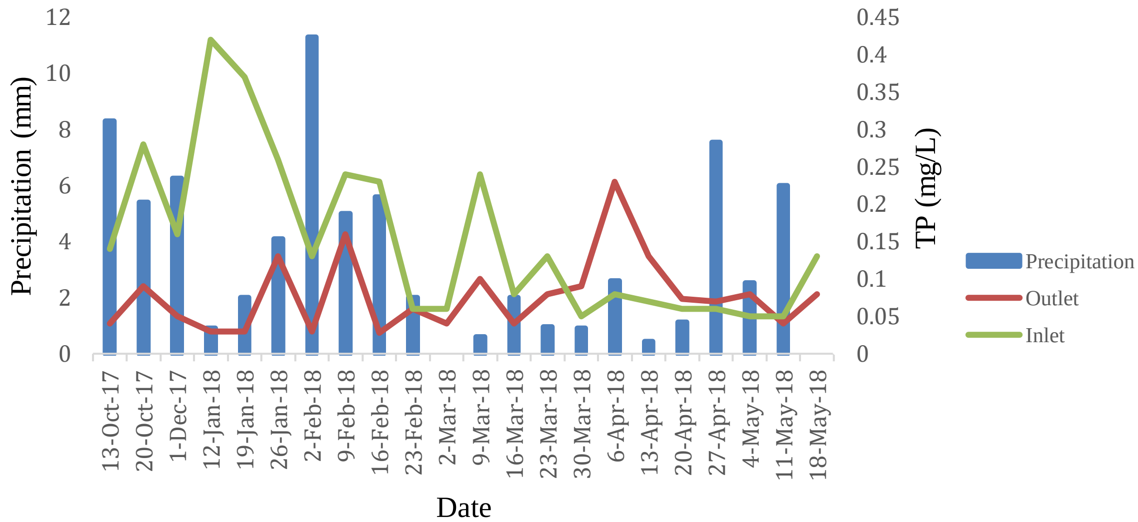
b.

Figure 4-14 a. Total COD b. Soluble COD, from Madlabekken wetland inlet vs. outlet, October to May

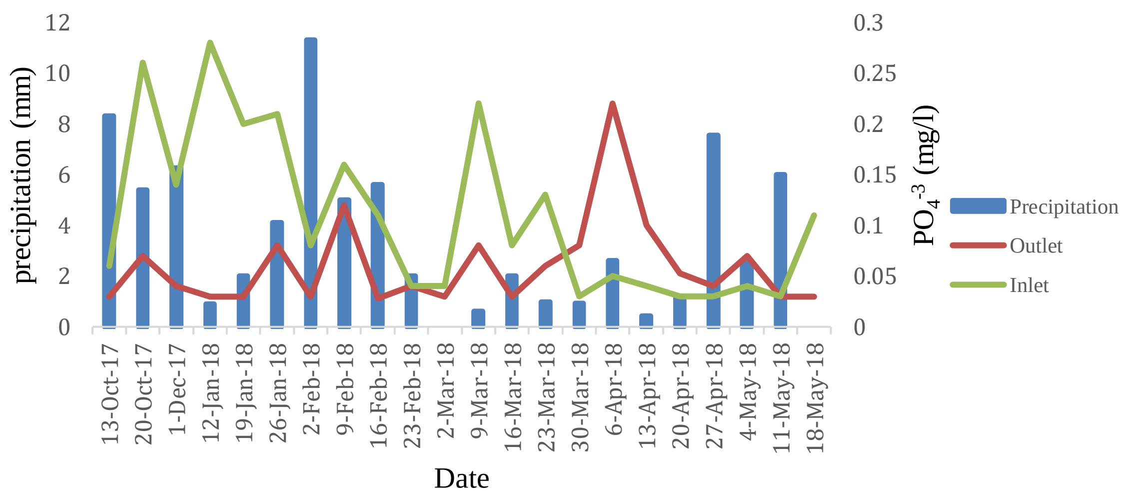
Table A-9 in appendix i presents the monthly average concentrations of total and soluble COD and the retained percentage.

4.3.3 Total phosphorus and phosphate (PO_4^{-3})

Figure 4-15 shows total phosphorus and phosphate (PO_4^{-3}) graph at inlet and outlet together with precipitation. Both TP and PO_4^{-3} at inlet and outlet, are following the same trend, and as it is seen during April for both TP and PO_4^{-3}, the Outlet concentrations are higher than the inlet.



a.



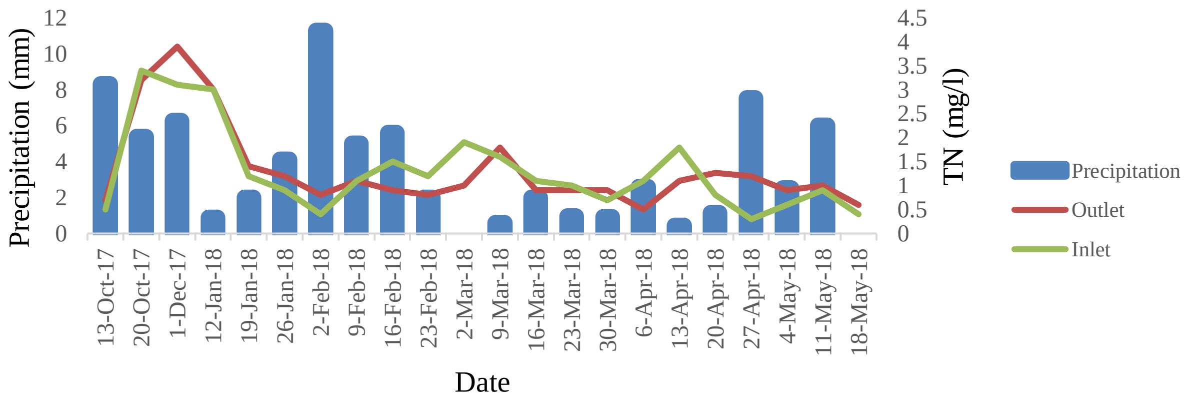
b.

Figure 4-15 a. Total phosphorus b. Phosphate, from Madlabekken wetland inlet vs. Outlet, October to May

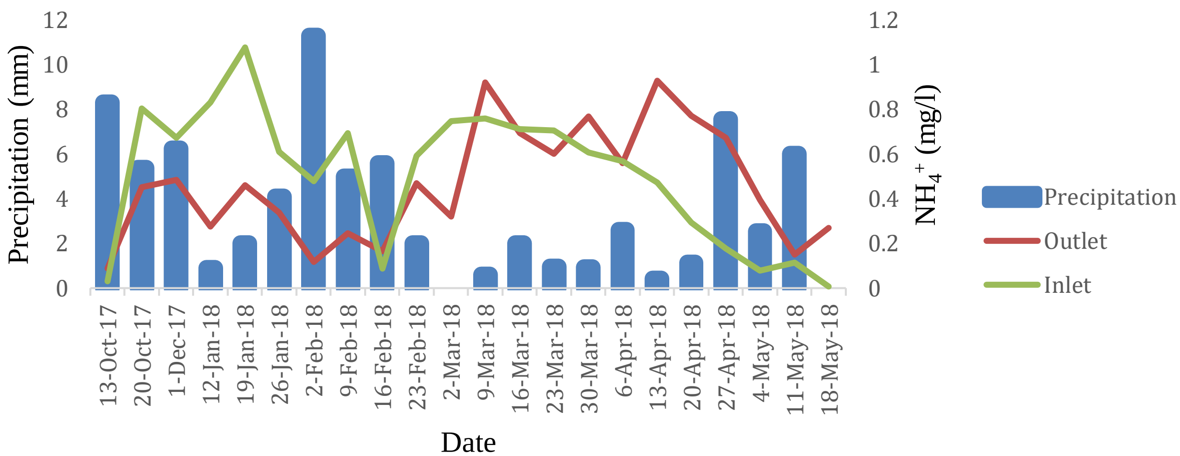
Monthly average concentration and retained percentage of total phosphorus and phosphate per week are shown in table A-9, appendix i.

4.3.4 Total nitrogen and ammonium (NH_4^+)

Total nitrogen and ammonium (NH_4^+) at inlet and outlet are graphed at figure 4-16 together with precipitation. Both graphs show a higher concentration at outlet compare to inlet during late April and May. However, the variation is not significant.



a.



b.

Figure 4-16 a. Total nitrogen b. ammonium, from Madlabekken wetland inlet vs. outlet, October to May

Average concentration and retained percentage of total nitrogen and phosphate per month are shown in table A-9, appendix i

4.3.5 Removal efficiency of Madlabekken constructed wetland

Table 4-6 presents average concentrations of analyzed parameters at inlet and outlet with reduction percentage of each parameter at Madlabekken constructed wetland.

Monthly average TSS and nutrients in Madlabekken constructed wetland during the study period, and their reduction percent is shown in table A-9, appendix I.

Table 4-6 Average pollutant concentration at inlet and outlet during the study period and reduced percent in Madlabekken wetland

Parameters	Mean IN	Mean Out	reduction %
TSS	8,93±0,416	2,43±0,416	46,45
COD_t	35,77±0,249	16,18±0,249	22,13
COD_s	14,89±0,216	13,83±0,216	6,20
TP	0,17±0,005	0,08±0,005	24,78
PO_4^{-3}	0,13±0,005	0,06±0,005	4,84
TN	1,46±0,386	1,41±0,386	-3,75
NH_4^+	0,60±0,012	0,481±0,012	-5,46

4.4 Error analyses

For measuring the error occurred during performing tests, both while sampling and while preparing in the lab for analysis, the standard deviation was calculated.

For calculating the standard deviation for each parameter, three parallel samples were analyzed, and the standard deviation was calculated using equation (4-1).

Table 4-7 shows the results of error analysis. In this table, the average deviation and relative average deviation (Equation (4-2)) in percent and method detection limit (MDL) (Equation 4-3) are presented.

As it is seen from the table, CV of TSS is significantly high. Results in the mentioned table are discussed in next chapter.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X-\bar{X})^2}$$ Equation 4-1

$$Coefficient\ of\ variation = \frac{\sigma}{\bar{X}} * 100$$ Equation 4-2

$$MDL = N * (\sigma/(\sqrt{N}))$$ Equation 4-3

Table 4-7 Error analysis of test parameters

Parameters	TP	PO_4^{-3}	TN	NH_4^+	COD_t	COD_s	TSS
Standard deviation	0.005	0.005	0.386	0.012	0.249	0.216	0.416
Coeffiecient of variation %	6	9	30	2	1	1	94
MDL	0.01	0.01	0.67	0.02	0.43	0.37	0.72

Chapter 5

Discussion

In this chapter results obtained during study period which was from October to May are discussed. This chapter is divided into four main sections. The first section is the discussion on the water quality of Madlabekken stream which is done according to results of inlet sample analysis. In the second section efficiency of Madlabekken constructed wetland in removing pollutants is discussed. This section is according to reduction percentage of pollutants at the outlet of wetland. The third section is based on observations that during sampling, were done including smell and color of water. In the last section, errors occurred during experimental work, are discussed.

5.1 Madlabekken Water quality

According to the results obtained in chapter 4, Madlabekken water quality was assessed. The assessment was done based on analyzed parameters including, TSS, TP, and PO_4^{-3}, TN and NH_4^+, COD_t and COD_s.

5.1.1 Total suspended solids (TSS)

Referring to figure 4-1, total suspended solids at inlet varied from 0.7 (MDL) to 50 mg/l. According to analyzed data of TSS from the Madlabekken stream compared with the different water quality range table in literature. According to table 2-1 and 2-2 in literature chapter, generally the TSS range was pretty low and not considered as wastewater. Hence there seems the TSS concentration is mostly in the range of stormwater runoff except in some observed conditions of water surface pollution discussed in section 5.3.

During May which was the warmest month in the study period, and no precipitation was occurred for a long period, the water surface at inlet channel looked polluted. However, as water was carried underneath of inlet channel and flow velocity was slow in inlet channel, all the light pollution including detergents foam, cigarette butts from streets, and oil accumulated on the top of the water and not carried to the sampler (Figure 5-1 (t)).

Mostly TSS analyzed during the experiment period can be from sediment transported by stormwater runoff. Also, during high flow rate, TSS can be in the cause of erosion due to fast running water and wash off of soil, or particles and debris from streets and residential or industrial areas. The carried suspended solids, from the area around, is depended on the land use and constructions around. As Madlabekken stream receives water from the urban area, most of the TSS is coming from streets, precipitation runoff, parking lots, and car pollution washed off by rain or snow, household gardens watering, and their drainage systems. TSS in water can be both from surface runoff or drainage water from urban areas.

The highest TSS concentration mainly was observed during February. As February was the coldest month, and water was frozen in some parts of the stream, and this has caused concentrated TSS. Also, after a high rainfall and some days of drought due to dilution, and after some days of drought and a high rainfall due to wash off, TSS concentration is on its peak value.

According to figure 4-1 TSS vs. precipitation during the study period, TSS concentration, in low or no precipitation weeks, and after a high rain and some days drought is high. Nonetheless, according to table 4-1, correlation of TSS and precipitation is 0,14 and not so high. Moreover, this is due to indirect relation of TSS and precipitation. As during high storm, due to high flow, concentrations can be varied, depending on resuspension of sedimentation and erosion of soil or dilution. However, as mentioned already, a long period of drought and lower depth of water in inlet channel can show a high concentration, as well as a short period of drought after a high storm, can follow the same trend.

Moreover, exhaust from car and homes during winter has caused TSS concentrations to increase during winter.

5.1.2 Total and soluble COD (COD_t and COD_s)

During the study period, from October to May, total COD at the inlet of wetland was ranged between 6-76 mg/l. Figure 4-2, is presenting total and soluble COD with precipitation during the study period. The highest total COD concentration was observed during February while a high

TSS concentration was noticed. The minimum concentration was registered during March in a low precipitation period and TSS concentration under MDL.

According to analyzed samples at the inlet, observed total COD concentration during the study period, even at the highest concentration, compared to urban storm runoff is low. Soluble COD analysis also showed a low range of concentration between 4.7 to 26 mg/l. According to table 4-2, total COD has an $R^2=0,51$ with TSS and is in direct relation with TSS. Also observing figure 4-2, the soluble COD is not so varied, which can be concluded that variation of total COD is mostly due to the variation of TSS and in fact particulate COD. Also, low and approximately constant COD_s shows that water is received from urban and storm runoff but not drainage of the area around.

Table 4-3 shows the percentage of soluble COD in total COD. During study time approximately 65 % of total COD is soluble, which this ratio is mostly varied due to the variation of COD_t concentration rather than COD_s.

5.1.3 Total phosphorus (TP) and phosphate (PO_4^{-3})

Figure 4-4 shows the concentration of total phosphorus and phosphate at the inlet with precipitation. The concentration of total phosphorus is in range of 0.05 to 0.42 mg/l. The range of total phosphorus is in range of urban runoff. The figure shows that in peak storm, TP and PO_4^{-3} are in the minimum concentration. This is due to dilution and low concentrations of phosphorus and phosphate. In addition to weekly samples from water in the inlet, three samples were taken from an accumulated dark and oily foam in inlet channel shown in figure 5-1 (d, m, t) and analyzed in the lab. The results are discussed in section 5.3.

Figure 4-4 presents the concentration of total phosphorus and phosphate at the inlet, together with weekly average temperature. The graph shows no significant relationship between phosphorus and temperature.

The correspondingly PO_4^{-3} range was 0.03 to 0.28 mg/l, and it was in urban runoff range (table 2-2). Except for those mentioned water surface samples which PO_4^{-3} concentration was much higher (section 5.3) than typical urban runoff (table 2-2). According to table 4-1, there is no correlation between phosphorus and precipitation. Three reasons can be suggested for this. First due to low concentrations of TP the relation cannot be so obvious. Second, the precipitation does not affect the concentration directly and a peak storm before effecting TP, dilute the receiving water which can present even a lower concentration. And, the third might be due to weekly analyses which does not show the exact day precipitation effect, on TP. Overall, the concentration of total phosphorus and phosphate even in the highest concentration, are low and in urban runoff water quality range. As it is seen in figure 4-4 and 4-5, TP and PO_4^{-3} are following the same trend.

5.1.4 Total nitrogen (TN) and ammonium (NH_4^+)

Total nitrogen and ammonium for inlet are shown in figure 4-5. Referring to this figure, TN is found to be in the range of 0.66 mg/l (MDL) to a maximum of 3.4 mg/l. For ammonium, the range is varied from 0.03 mg/l to 1.077 mg/l.

As it is observed in figure 4-5, nitrogen concentration at inlet during January to April has been in the range of 1-2 mg/l. Referring to table 4-9, the coefficient of variation is 30%. On the other hand, considering error analysis, concentrations are almost constant and low. As the area around has no agricultural lands, and the receiving waters are from the storm and urban runoff, the nitrogen mostly comes from urban and storm runoff.

At the end of April and start of May, with increasing temperature, nitrogen concentration and to considerable level ammonium at the inlet has decreased due to an unfavorable condition in the inlet channel. The inlet channel which sampling is done in it is a covered channel, with poor ventilation, and anoxic conditions. Denitrification (reaction 5-1), as well as anaerobic ammonium oxidation (reaction 5-2), could have happened through this condition.

$2\ NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O$ Reaction (5-1)

$NH_4^+ + NO_2^- \rightarrow N_2 + 2\ H_2O$ Reaction (5-2)

5.1.5 Parameters linear correlations of Madlabekken stream

Table 4-1 shows the linear correlation between analyzed parameters during this study using scatter diagram method. As this table presents, there is a rather high correlation between TSS and COD_t, which show that most of total COD variation at the inlet is due to suspended solids concentration. TSS is correlated with TN, TP, and PO_4^{-3}, with a correlation factor of 0,2. Due to low concentrations of the mentioned parameters, TSS does not show a high correlation with the mentioned parameters.

NH_4^+ has a correlation of around 0.2 with total COD but does not correlate with TSS. Correlation of TN, PO_4^{-3}, and total phosphorus with COD is almost zero. Total COD has a correlation of 0.28 with soluble COD. It is not a high correlation comparing to a rather high ratio of COD_s to COD_t.

According to table 4-3, the average percentage of soluble COD to total COD is %69, and this ratio is higher during April and May, which can be in case of high temperatures and more biological degradable pollutants.

According to table 4-1 and 4-3, total phosphorus and phosphate are correlated with a high correlation of 0.85, which shows that high fraction of total phosphorus is in soluble reactive form of phosphate PO_4^{-3}. According to this table, 70% of total phosphorus is phosphate. Phosphate mostly can be added to runoff and stream from detergents used for car washes or from households which are released in streets and discharged into receiving water through urban runoff.

According to table 4-3 average ratio of NH_4^+ to TN is 45% which is varied during weeks and doesn't follow a constant variation. The variation is due to dilution occurred after precipitation and high temperatures during drought causing denitrification and anaerobic ammonium oxidation.

By considering the low concentrations measured at inlet during the study period, it is found that Madlabekken stream receives water from urban and storm runoff. The results do not show any trace of sewage, and as compare to literature tables, concentrations are in the range of urban storm runoff.

5.2 Madlbekken constructed wetland efficiency

For investigation of Madlabekken constructed wetland, the analysis done on inlet and outlet are compared, and the reduction in concentrations are calculated.

5.2.1 Total suspended solids reduction

As shown in figure 4-13 total suspended solids from the inlet to outlet, for relatively high TSS concentrations at inlet shows a significant reduction. However, for low concentration TSS, as the coefficient of variation is high. The difference between concentrations at inlet and outlet is not considerable. Average monthly reduction of TSS is presented in table 4-8. The highest reduction has occurred in February, where the TSS is relatively high. In April the effluent is more than influent or approximately same, which is due to low and close to MDL concentrations of TSS in this month. As it is seen in table 4-8, the TSS concentration standard deviation is ±0.41, which compared to the concentration measured, is a significant error. The overall average reduction for TSS in Madlabekken constructed wetland is % 47 of influent, which compared to similar constructed wetlands reduction in the literature (table 2-3, 2-4, 2-5) and considering low concentrations; the reduction efficiency is close to similar CWs.

5.2.2 Total COD and soluble COD reduction

Figure 4-14, a and b shows total and soluble COD respectively, at the inlet and outlet together with precipitation. As it is seen in figure 4-14 (a), there is a significant reduction in total COD at the outlet at high concentrations. Highest reduction efficiency has occurred during February which is 62 %. Nevertheless, the average reduction efficiency for COD_t in whole study period is 22% due to variable reduction efficiency of concentrations. Comparing this efficiency with previous studies, it is a rather low reduction efficiency, which explains that the wetland does not work properly. This can be due to wetland design system, as only a fraction of water is transferred to planted wetland and the rest is directly discharged to sedimentation ponds.

Figure 4-14 (b) shows soluble COD at the outlet. Considering the influent, it does not show a considerable reduction. The average reduction in whole study period is 6%. Which shows that

Madlabekken wetland is more efficient in removing total COD rather than soluble COD. The wetland has two sedimentation ponds and one small planted pond, and as expected it has mostly affected the particulate COD. The study period mostly was during cold months while less vegetation was in the planted pond. To show higher efficiencies in soluble COD reduction a longer study period is required.

5.2.3 Total phosphorus and phosphate reduction

Total phosphorus at inlet and outlet is shown in figure 4-15 (a). As the figure shows, there is a significant reduction from the inlet to the outlet from October to March, and on average 54% of total phosphorus is retained after passing through wetland during study period except for April. During April the effluent has been more. This can be due to using grab samples during April, as during this month outlet sampler had a defect. In May, due to the low concentration of TP at both influent and effluent, the reduction percentage registered in table 4-8 is less than other months.

Figure 4-15 (b) shows the same graph as phosphorus, for phosphate at inlet and outlet. As it is seen from the figure, there is an apparent reduction in phosphate concentration at the outlet as well. The average reduction for phosphate during experiment period, except April is 52%, but for April the effluent is more than influent.

5.2.4 Total nitrogen and ammonium reduction

According to results in table 4-7 and 4-8, total nitrogen and ammonium at outlet compare to the inlet has not changed significantly, as the concentrations are already low and the wetland is not able to treat it to a lower concentration.

According to table 4-8, and considering high variation coefficient of TN, on average there has been no reduction in TN by constructed wetland and the reason is the low level of TN concentration and the unfavorable condition on wetland for reducing TN.

The correspondingly NH_4^+ reduction is not considerable as well. And in May the effluent is much more than influent. Higher effluent than influent is due to decrease of NH_4^+ at the inlet, that as discussed already might be in the cause of anaerobic ammonium oxidation in the covered channel by increasing temperature. Despite that, considering the low concentrations of TN and NH_4^+, during May while almost every day was sunny, it seems TN, and in a relatively high concentration, NH_4^+ has been produced at the outlet. This result shows the occurrence of photochemical degradation of organic matters (left during cold weather) and as a result photochemical production of ammonium (photo ammonification) from nitrogenous compound (*Kitidis, 2002*).

5.2.5 Parameters correlations of Madlabekken wetland at the outlet

Table 4-4, shows the correlation between analyzed parameters at the outlet of Madlabekken wetland.

According to this table, COD_t does not correlate with TSS, while has a rather high correlation with COD_s. According to this result, the concentration of COD_t at the outlet is mostly biological degradable COD and not particulate COD. Besides, as the expected particulate fraction of total COD is mostly retained by wetland, and what is left is mostly the soluble part.

As it is seen in the mentioned table, TP is highly correlated (0.94) with PO_4^{-3} at outlet same as the inlet. In addition, referring to table 4-5, the average ratio of PO_4^{-3} to TP is 80%. On the other hand, 80% of total phosphorus is in its reactive form of PO_4^{-3}, which is available for biological breakdown without a further breakdown.

The correlation between NH_4^+ and TN is 0.1, which is not high compared to the average ratio of NH_4^+ to TN which is 45% in table 4-3. As it is seen in the mentioned table, from March to May, the ratio is higher which can be due to higher temperatures, and more microorganism's activity. As the process of nitrogen decomposition to NH_4^+, by heterotrophic microbes through mineralization, is more likely in warm and moist environments (*Lindenbaum, 2012*).

5.3 Direct observations

Figure 5-1 (a- t) shows the inlet channel in different sampling days, with the precipitation and temperature of that special day.

As it was discussed in previous sections, the overall results of sample analysis from Madlabekken constructed wetland shows relatively low concentration at inlet and outlet. The analyzed parameters are all in range of storm and urban runoff, and some cases even lower, compared to past studies. Despite this, some days, while sampling, the site observations, including water surface look, the smell of area seemed to have higher pollution concentration than experimental results. Some of these observations are reported in figure 5-1 (a-t)

Figure 5-1 (d, m, t) during January and March, plus May, shows a dark bubbled and oily substance accumulated on the water surface in inlet channels. As it is seen the water depth in inlet channel during mentioned figures is at the lowest level. In the inlet channel, water is transferred from the small beneath conduit to the pump station. Moreover, the flow velocity is low during low levels of water, and most of the impurities including oils form cars, detergents in urban runoff and pollution from streets and parking lots are accumulated on inlet channel water surface exactly before the mesh gate and on top of the beneath conduit. As the inlet sampler collected water under the water surface, this accumulated pollution has not been collected during sampling.

Some samples were grabbed while observing the mentioned pollution on the water surface and was analyzed in the lab. The results are summarized in table 5-1.

Table 5-1 average concentration of observed substance on water surface of inlet channel

Parameters	TSS	COD_t	COD_s	TP	PO_4^{-3}	TN	NH_4^+	VSS	Fixed
Average concentrations (mg/l)	1300	> 5000	41	4,9	4,6	6	2,6	605	738

The high concentration in the first place is due to the concentrated substance at the water surface, and the sample was taken from this concentrated substance without mixing with the under-surface water. In fact, the results from concentrated pollution on a small part of water surface cannot be interpreted correctly.

However, the observed high-water surface pollution can be caused by high flow rate while raining and wash off from street and parking lots. Some days of drought after rain wash off, the water depth has decreased, and all the washed off light pollution has concentrated and accumulated on the surface.

a) Date	Precipitation (mm)	Temperature ℃
09.01.18	0	4.80

b) Date	Precipitation (mm)	Temperature ℃
12.01.18	0	0.90

c) Date	Precipitation (mm)	Temperature ℃
13.01.18	0	1.80

d) Date	Precipitation (mm)	Temperature ℃
16.01.18	12.90	1.20

e) Date	Precipitation (mm)	Temperature ℃
17.01.18	0	0.30

f) Date	Precipitation (mm)	Temperature ℃
18.01.18	0	0.50

g) Date	Precipitation (mm)	Temperature °C
19.01.18	0	0.80

h) Date	Precipitation (mm)	Temperature °C
24.01.18	15.1	6.50

i) Date	Precipitation (mm)	Temperature °C
25.01.18	8,2	5.10

j) Date	Precipitation (mm)	Temperature °C
31.01.18	23,7	2.20

k) Date	Precipitation (mm)	Temperature °C
09.02.18	33,5	3.10

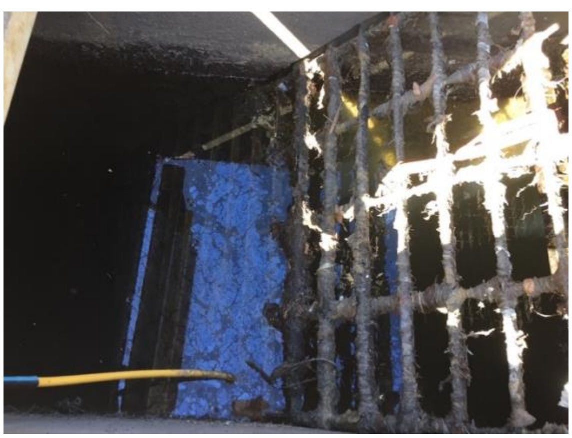
l) Date	Precipitation (mm)	Temperature °C
13.02.18	4.7	2.20

m) Date	Precipitation (mm)	Temperature °C
01.03.18	0	-7.10

n) Date	Precipitation (mm)	Temperature °C
13.03.18	9.6	1.30

o) Date	Precipitation (mm)	Temperature °C
29.03.18	0	1.50

p) Date	Precipitation (mm)	Temperature °C
5.04.18	11,7	2.90



q) Date	Precipitation (mm)	Temperature °C
12.04.18	0	10

r) Date	Precipitation (mm)	Temperature °C
26.04.18	0	7.30

s) Date	Precipitation (mm)	Temperature ℃
28.04.18	1	6.90

t) Date	Precipitation (mm)	Temperature ℃
19.05.18	0	12

Figure 5-1 a- t inlet channel of Madlabekken constructed wetland during the study period

5.4 Error analyses

During experimental and laboratory works, a wide range of errors in data collection could have occurred. While sample collection, or during laboratory analysis and result recordings, or while interpretation and reporting, different errors are possible.

During this study, the main errors during sampling include automatic samplers, which were not running all the time due to errors occurred during runs or while water was frozen. Also not recording time of collection and the effect of time. Sampling was done every six hours, and sample might have been taken in the driest or wettest time of day, or day of the week, which can affect the week sample. Resuspension of solids by birds and ducks on the water was another source of sampling error. Sampling point and placing of the tube in water, or resuspension while pumping water to the sampler, also could have affected the sample. Also, not appropriate sample preservation techniques and storage of samples in plastic bottles that could cause sticking of contamination to walls during storage were among sampling errors.

During laboratory works, while sample preparation and analysis, recording results and electronic processing errors could have occurred. There were several contamination sources in the lab, as different wastewater samples were analyzed in the same lab. While preparing samples, adding less or more reagents to test cells could be another source of error. Contamination of distilled water used for washing equipment, including sample bottles, pipettes may have contributed to occurring errors.

However, to show the error value and mitigating the effect, the standard deviation, coefficient of variation and MDL (Method Detection Limit), were calculated and are presented in table 4-9.

In Addition to standard deviation calculated from lab data, the standard deviation for test kits used methods, according to test kit leaflet are also reported in table 5-2.

Comparing table 4-9 with table 5-1, a significant difference is seen. Considering this fact that, table 5-1 is estimated from around 40 samples under ideal condition, while the parallel samples used for table 4-9 were only three samples, and the concentrations were relatively low for TSS, PO_4^{-3}, TN, NH_4^+, and TP. On the other hand, for each parameter, the concentration of the mentioned parameters was close to estimated MDL which can be the reason for high CV of these parameters. The values shown in discussed tables for COD_t and COD_s are close to each other, which shows a good accuracy of COD concentrations.

Table 5-2 Accuracy parameters according to methods used in test cell kit for each parameter

parameters	standard deviation (mg/l)	coefficient of variation (%)	confidence interval (mg/l)	absorbance 0.010 A correspond (mg/l)	accuracy of measurement value (mg/l)
COD	±0.28	±1.3	±0.7	0.4	± 1.5
P-PO_4^{-3}	±0.023	±1.0	±0.05	0.02	± 0.06
N	±0.14	±1.7	±0.3	0.1	± 0.6
NH_4^+-N	±0.0138	±1.4	±0.033	0.009	± 0.050

5.5 Suggestions and recommendations

Madlabkken constructed wetland is a small wetland and in comparison to other CWs has lower performance in treatment. The wetland consists of two sedimentation ponds in addition to a planted pond. Only a small portion of water passes through the planted pond before flowing into sedimentation ponds. The rest of water is directly flowed to sedimentation pond, without passing through the planted pond. To enhance the wetland efficiency, a proper way is to pass all the water through the planted pond. Plants play an essential role in managing the storm and high flow rates. Passing all the water through the planted pond can help avoid resuspension and washing sedimentation out.

Another way to develop the wetland is to manage the plants vegetated in the wetland. During April and May, ammonium and nitrogen effluent was more than influent which seems the wetland is producing nitrogenous compounds instead of retaining, due to weak management of water distribution, across the wetland.

During this study flow and types of it was not investigated due to lack of information on the wetland design. The study results could have been more reliable by studying flow conditions along with water quality parameters. This needs to be considered before starting new studies on the wetland.

All the aspects of selecting the best point for fixing sampler tube and sampling need to be considered. As during this study, the Outlet tube was located close to bedrocks and sedimentation due to low depth of water. While sampler was running and sending the water back, resuspension of sedimentation caused the more TSS and particles to be collected in the sampler.

Locating a weir or barrier in the outlet of the last pond would be an efficient way for both managing the flow velocity and a proper location for locating sampler tube.

The inlet channel and the mesh gate located there should be cleaned before starting a new study, as the past sedimentation and pollution accumulation can affect the data.

For further studies on this wetland, the sampling point can be an important variable. During this study, sampling was done only under the water surface, while the water surface and sedimentation can be included in investigations to give more reliable conclusions on the water quality and efficiency of the wetland.

Management and estimation of plant species distribution and plant uptake of nutrients can be next study topic and a proper way to develop the efficiency of this wetland.

The effect of each plant species in the uptake of different nutrients and affecting wetland efficiency need to be studied more.

In general, to have a more reliable overview of this constructed wetland, the study must be done in a longer period including both warm and cold months.

Chapter 6

6.1 Conclusion

Due to low concentrations observed during monitoring of Madlabekken stream water quality, urban wastewater contamination was very low compared to past studies on urban storm runoff concentrations. The only noteworthy contamination observed was a dark oily foam on the surface of the inlet channel, which had accumulated some days after high rate flow and peak storm. The mentioned contamination was considerable during May due to a long drought period, low level of water in the covered inlet channel, the high temperature of weather and more microorganism activity. By Careful observation, it was found that the mentioned contamination in a small part of water surface at the inlet was due to the low flow velocity and mesh gate as an obstacle.

As one can see, low and high flow rate could have a significant effect on the concentration. In low or no flow rate weeks, TSS and as a result COD concentration was relatively high. Besides, some days after a peak flow rate, relatively high contamination concentration was observed.

The maximum concertation of TSS and correspondingly, total COD, while performing autosampler (not grabbing samples) was observed in February due to under zero temperature and low level of water. Maximum soluble COD was observed in May, due to higher temperatures, and more biological activities.

Total nitrogen regarding high coefficient of variation and low concentrations was constant during the study period at Madlbekken stream. By increasing weather temperature, NH_4^+ has decreased due to anaerobic ammonium oxidation.

A significant fraction of TP was PO_4^{-3}, and due to the high ratio of COD_s to COD_t, it can be concluded that PO_4^{-3}, even at low concentration is not from soap and detergents, but biological processes.

Overall, it was found that Madlabekken stream pollution concentration, was in or below urban runoff concentration range, especially after high storm runoff. Besides, it was found that the water quality is improved in comparison to past reports. On the other hand, the findings are in contrast to our primary hypothesis that there might be some sewage overflow into the receiving waters.

Instead, the contamination is a wash off from streets and parking lots and cars at different flow rates.

While few correlations were found in this study, the apparent correlations were between COD_t and TSS, and TP with PO_4^{-3} at influent. The effluent concentrations of TSS with COD_t was not correlated due to the high ratio of COD_s to COD_t.

By observing the water quality at the outlet of the Madlabekken constructed wetland, the efficiency of wetland was evaluated. For TSS the average reduction was 46.5 %. For total and soluble COD, the average reduction was 22%, 6%, respectively. The average reduction for total phosphorus and phosphate was 24,8%, 5%, respectively. Also, for TN and NH_4^+, no reduction was observed during the study period. By comparing the overall efficiency of this constructed wetland with the similarly constructed wetlands, the efficiency is lower. The efficiency for months with higher concertations is higher compared to efficiency for lower and close to MDL concentrations.

Ultimately, Madlabekken CW does not seem to have a good reduction efficiency and to improve the efficiency, more studies in longer periods are needed to be done.

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Appendices

Appendix A, shows the measured total suspended solids with average temperature and precipitation of sampling week at inlet of Madlabekken constructed wetland.

Table A-1 Total suspended solids of Madlabekken stream/ inlet of wetland

Inlet			
weeks	weekly mean T (°C)	Precipitation (mm)	TSS (mg/L)
13-Oct-17	19,3	8,3	7
20-Oct-17	11,49	5,39	50
1-Dec-17	2,31	6,26	6,67
12-Jan-18	2,5	0,9	6
19-Jan-18	1,2	2	1,67
26-Jan-18	3,4	4,1	22
2-Feb-18	3,1	11,3	12,33
9-Feb-18	-0,63	5	8
16-Feb-18	2,2	5,6	46
23-Feb-18	1,6	2	1
2-Mar-18	-4,1	0	< MDL
9-Mar-18	0,2	0,6	20
16-Mar-18	1	2	1,67
23-Mar-18	2	0,97	3
30-Mar-18	2,7	0,92	< MDL
6-Apr-18	2,8	2,6	3
13-Apr-18	8,7	0,43	3
20-Apr-18	9,7	1,13	0,333
27-Apr-18	2	7,55	1,33
4-May-18	7,6	2,53	4
11-May-18	14,53	6	1,33
18-May-18	14,7	0	6,67

Appendix B, shows the measured total and soluble COD with average temperature and precipitation of sampling week at inlet of Madlabekken constructed wetland.

Table A-2 Total and soluble COD of Madlabekken stream / inlet of wetland

Inlet				
Weeks	Weekly mean T	Precipitation (mm)	COD_t (mg/L)	COD_s (mg/L)
13-Oct-17	19,3	8,3	27,3	15,6
20-Oct-17	11,49	5,39	28,2	13,6
1-Dec-17	2,31	6,26	17,2	8,2
12-Jan-18	2,5	0,9	19,4	16,3
19-Jan-18	1,2	2	22,1	14,7
26-Jan-18	3,4	4,1	28	12,5
2-Feb-18	3,1	11,3	34,9	13,1
9-Feb-18	-0,63	5	15,2	7,6
16-Feb-18	2,2	5,6	76	18,4
23-Feb-18	1,6	2	14,6	14,4
2-Mar-18	-4,1	0	14	13,3
9-Mar-18	0,2	0,6	46	26,9
16-Mar-18	1	2	18,8	16,2
23-Mar-18	2	0,97	25,4	18
30-Mar-18	2,7	0,92	6	4,7
6-Apr-18	2,8	2,6	11,3	6,6
13-Apr-18	8,7	0,43	23,5	19,7
20-Apr-18	9,7	1,13	24,5	22,7
27-Apr-18	2	7,55	24,7	21,9
4-May-18	7,6	2,53	27,9	23,7
11-May-18	14,53	6	28,7	24,8
18-May-18	14,7	0	39,1	24

Appendix C, shows the measured total phosphorus and phosphate (Po_4^{-3}) with average temperature and precipitation of sampling week at inlet of Madlabekken constructed wetland.

Table A-3 Total phosphorus and PO_4^{-3} of Madlabekken stream / inlet of wetland

Inlet				
weeks	weekly mean T	Precipitation (mm)	Total phosphorous (mg/L)	PO_4^{-3} (mg/L)
13-Oct-17	19,3	8,3	0,14	0,06
20-Oct-17	11,49	5,39	0,28	0,26
1-Dec-17	2,31	6,26	0,16	0,14
12-Jan-17	2,5	0,9	0,42	0,28
19-Jan-18	1,2	2	0,37	0,2
26-Jan-18	3,4	4,1	0,26	0,21
2-Feb-18	3,1	11,3	0,13	0,08
9-Feb-18	-0,63	5	0,24	0,16
16-Feb-18	2,2	5,6	0,23	0,11
23-Feb-18	1,6	2	0,06	0,04
2-Mar-18	-4,1	0	0,06	0,04
9-Mar-18	0,2	0,6	0,24	0,22
16-Mar-18	1	2	0,08	0,08
23-Mar-18	2	0,97	0,13	0,13
30-Mar-18	2,7	0,92	0,05	0,03
6-Apr-18	2,8	2,6	0,08	0,05
13-Apr-18	8,7	0,43	0,07	0,04
20-Apr-18	9,7	1,13	0,06	0,03
27-Apr-18	2	7,55	0,06	0,03
4-May-18	7,6	2,53	0,05	0,04
11-May-18	14,53	6	0,05	0,03
18-May-18	14,7	0	0,13	0,11

Appendix D, shows the measured total nitrogen and ammonium NH_4^+ with average temperature and precipitation of sampling week at inlet of Madlabekken constructed wetland.

Table A-4 Total nitrogen and NH_4^+ of Madlabekken stream/ inlet of wetland

Inlet				
weeks	weekly mean T	Precipitation (mm)	Totalt nitrogen (mg/L)	NH_4^+ (mg/L)
13-Oct-17	19,3	8,3	0,5	0,031
20-Oct-17	11,49	5,39	3,4	0,805
1-Dec-17	2,31	6,26	3,1	0,673
12-Jan-18	2,5	0,9	3	0,832
19-Jan-18	1,2	2	1,2	1,077
26-Jan-18	3,4	4,1	0,9	0,611
2-Feb-18	3,1	11,3	0,4	0,479
9-Feb-18	-0,63	5	1,1	0,694
16-Feb-18	2,2	5,6	1,5	0,0885
23-Feb-18	1,6	2	1,2	0,593
2-Mar-18	-4,1	0	1,9	0,746
9-Mar-18	0,2	0,6	1,6	0,759
16-Mar-18	1	2	1,1	0,712
23-Mar-18	2	0,97	1	0,705
30-Mar-18	2,7	0,92	0,7	0,607
6-Apr-18	2,8	2,6	1,1	0,569
13-Apr-18	8,7	0,43	1,8	0,472
20-Apr-18	9,7	1,13	0,8	0,294
27-Apr-18	2	7,55	<MDL	0,177
4-May-18	7,6	2,53	0,6	0,077
11-May-18	14,53	6	0,9	0,115
18-May-18	14,7	0	<MDL	<MDL

Appendix E, shows the measured total suspended solids with average temperature and precipitation of sampling week at outlet of Madlabekken constructed wetland.

Table A-5 Total suspended solids concentrations of Madlabekken constructed wetland at outlet

Outlet			
weeks	weekly mean T	Precipitation (mm)	TSS (mg/L)
13-Oct-17	19,3	8,3	6,67
20-Oct-17	11,49	5,39	15,38
1-Dec-17	2,31	6,26	0,87
12-Jan-18	2,5	0,9	0,67
19-Jan-18	1,2	2	0,3
26-Jan-18	3,4	4,1	3,33
2-Feb-18	3,1	11,3	< MDL
9-Feb-18	-0,63	5	< MDL
16-Feb-18	2,2	5,6	1
23-Feb-18	1,6	2	1
2-Mar-18	-4,1	0	< MDL
9-Mar-18	0,2	0,6	1,67
16-Mar-18	1	2	< MDL
23-Mar-18	2	0,97	3
30-Mar-18	2,7	0,92	0,33
6-Apr-18	2,8	2,6	3
13-Apr-18	8,7	0,43	4
20-Apr-18	9,7	1,13	< MDL
27-Apr-18	7,55	2	1
4-May-18	7,6	2,53	2
11-May-18	14,53	6	1
18-May-18	14,7	0	7,67

Appendix F, shows the measured total COD and soluble COD with average temperature and precipitation of sampling week at outlet of Madlabekken constructed wetland.

Table A-6 Total and soluble COD of Madlabekken constructed wetland at outlet

Outlet				
weeks	weekly mean T	Precipitation (mm)	COD_t(mg/L)	COD_s (mg/L)
13-Oct-17	19,3	8,3	19,8	17,2
20-Oct-17	11,49	5,39	17,2	7,5
1-Dec-17	2,31	6,26	11,46	9,8
12-Jan-18	2,5	0,9	13	15,7
19-Jan-18	1,2	2	14,2	14,3
26-Jan-18	3,4	4,1	17,7	14
2-Feb-18	3,1	11,3	15,2	13,2
9-Feb-18	-0,63	5	9	8,2
16-Feb-18	2,2	5,6	13,1	11,9
23-Feb-18	1,6	2	16	16
2-Mar-18	-4,1	0	12,9	11,7
9-Mar-18	0,2	0,6	20,4	18,3
16-Mar-18	1	2	16,2	15,4
23-Mar-18	2	0,97	22,6	22,9
30-Mar-18	2,7	0,92	5,9	3,1
6-Apr-18	2,8	2,6	20	5,4
13-Apr-18	8,7	0,43	23,9	20
20-Apr-18	9,7	1,13	19,57	19,5
27-Apr-18	7,55	2	22,6	21
4-May-18	7,6	2,53	24,4	22,2
11-May-18	14,53	6	24,2	23
18-May-18	14,7	0	25,7	21,5

Appendix G, shows the measured total phosphorus and phosphate (PO_4^{-3}) with average temperature and precipitation of sampling week at outlet of Madlabekken constructed wetland.

Table A-7-Total phosphorus and PO_4^{-3} concentrations of Madlabekken constructed wetland at outlet

Outlet				
weeks	weekly mean T	Precipitation (mm)	Total phosphorous (mg/L)	PO_4^{-3} (mg/L)
13-Oct-17	19,3	8,3	0,04	0,03
20-Oct-17	11,49	5,39	0,09	0,07
1-Dec-17	2,31	6,26	0,05	0,04
12-Jan-18	2,5	0,9	0,03	0,03
19-Jan-18	1,2	2	0,03	0,03
26-Jan-18	3,4	4,1	0,13	0,08
2-Feb-18	3,1	11,3	0,03	0,03
9-Feb-18	-0,63	5	0,16	0,12
16-Feb-18	2,2	5,6	0,028	0,028
23-Feb-18	1,6	2	0,06	0,04
2-Mar-18	-4,1	0	0,04	0,03
9-Mar-18	0,2	0,6	0,1	0,08
16-Mar-18	1	2	0,04	0,03
23-Mar-18	2	0,97	0,08	0,06
30-Mar-18	2,7	0,92	0,09	0,08
6-Apr-18	2,8	2,6	0,23	0,22
13-Apr-18	8,7	0,43	0,13	0,1
20-Apr-18	9,7	1,13	0,073	0,053
27-Apr-18	7,55	2	0,07	0,04
4-May-18	7,6	2,53	0,08	0,07
11-May-18	14,53	6	0,04	0,03
18-May-18	14,7	0	0,08	0,03

Appendix H, shows the measured total nitrogen and NH_4^+ with average temperature and precipitation of sampling week at outlet of Madlabekken constructed wetland.

Table A-8 Total nitrogen and NH_4^+ concentrations of Madlabekken constructed wetland at outlet

Outlet				
weeks	weekly mean T	Precipitation (mm)	Total nitrogen (mg/L)	NH_4^+ (mg/L)
13-Oct-17	19,3	8,3	0,7	0,088
20-Oct-17	11,49	5,39	3,2	0,452
1-Dec-17	2,31	6,26	3,9	0,483
12-Jan-18	2,5	0,9	3	0,276
19-Jan-18	1,2	2	1,4	0,459
26-Jan-18	3,4	4,1	1,2	0,338
2-Feb-18	3,1	11,3	0,8	0,118
9-Feb-18	-0,63	5	1,1	0,246
16-Feb-18	2,2	5,6	0,9	0,164
23-Feb-18	1,6	2	0,8	0,47
2-Mar-18	-4,1	0	1	0,321
9-Mar-18	0,2	0,6	1,8	0,921
16-Mar-18	1	2	0,9	0,694
23-Mar-18	2	0,97	0,9	0,601
30-Mar-18	2,7	0,92	0,9	0,769
6-Apr-18	2,8	2,6	0,5	0,56
13-Apr-18	8,7	0,43	1,1	0,928
20-Apr-18	9,7	1,13	1,27	0,77
27-Apr-18	7,55	2	1,2	0,671
4-May-18	7,6	2,53	0,9	0,395
11-May-18	14,53	6	1	0,15
18-May-18	14,7	0	0,6	0,268

Appendix I, is showing the average TSS and nutrients in Madlabekken constructed wetland during the study period and their reduction percent.

Table A-9 Monthly average pollutant concentration at inlet and outlet during the study period and removal efficiency of Madlabekken wetland for each parameter

Month	Precipitation* (mm)	Temperature*	Parameter± Error	Influent	Madlabekken wetland	
					Effluent	Removal efficiency
October 2017	9,01	9,96	TSS ± 0,416	28,50	11,00	61,40
			Total COD± 0,249	27,75	18,50	33,33
			soluble COD ± 0,216	14,60	12,35	15,41
			Total phosphorus± 0,005	0,21	0,07	69,05
			Phosphate ± 0,005	0,19	0,05	72,97
			Total nitrogen ± 0,386	1,95	1,95	0,00
			Ammonium± 0,012	0,42	0,27	35,41
December 2017	6,65	3,49	TSS ± 0,416	6,67	0,87	86,96
			Total COD± 0,249	17,2	11,46	33,37
			soluble COD ± 0,216	8,2	9,8	-19,51
			Total phosphorus± 0,005	0,16	0,05	68,75
			Phosphate ± 0,005	0,14	0,04	71,43
			Total nitrogen ± 0,386	3,10	3,9	-25,81
			Ammonium± 0,012	0,67	0,48	28,23
January 2018	4,49	2,74	TSS ± 0,416	9,89	1,43	85,54
			Total COD± 0,249	23,17	14,97	35,39
			soluble COD ± 0,216	14,50	14,67	-1,17
			Total phosphorus± 0,005	0,35	0,06	82,86
			Phosphate ± 0,005	0,23	0,05	78,26
			Total nitrogen ± 0,386	0,84	0,36	57,62
			Ammonium± 0,012	1,70	1,87	-9,80
February 2018	3,80	0,23	TSS ± 0,416	16,83	0,50	97,03
			Total COD± 0,249	35,18	13,32	62,13
			soluble COD ± 0,216	13,38	12,33	7,85
			Total phosphorus± 0,005	0,17	0,07	57,88
			Phosphate ± 0,005	0,10	0,05	44,10
			Total nitrogen ± 0,386	1,05	0,90	14,29
			Ammonium± 0,012	0,46	0,25	46,18

*Monthly average

Table A-9 continued

Month	Precipitation* (mm)	Temperature*	Parameter± Error	Influent	Madlabekken wetland	
					Effluent	Removal efficiency
March 2018	1,23	0,86	TSS ± 0,416	4,93	1,00	79,73
			Total COD± 0,249	22,04	15,60	29,22
			soluble COD ± 0,216	15,82	14,28	9,73
			Total phosphorus± 0,005	0,11	0,07	37,50
			Phosphate ± 0,005	0,10	0,06	44,00
			Total nitrogen ± 0,386	1,26	1,10	12,70
			Ammonium± 0,012	0,71	0,66	6,32
April 2018	1,37	7,87	TSS ± 0,416	1,92	2,11	-10,14
			Total COD± 0,249	21,00	21,52	-2,46
			soluble COD ± 0,216	17,73	16,48	7,05
			Total phosphorus± 0,005	0,07	0,13	-86,30
			Phosphate ± 0,005	0,04	0,10	-175,33
			Total nitrogen ± 0,386	1,00	1,02	-1,75
			Ammonium± 0,012	0,38	0,73	-93,72
May 2018	4,15	12,00	TSS ± 0,416	4,00	3,56	11,08
			Total COD± 0,249	31,90	24,77	22,36
			soluble COD ± 0,216	24,17	22,23	8,00
			Total phosphorus± 0,005	0,08	0,07	13,04
			Phosphate ± 0,005	0,06	0,04	27,78
			Total nitrogen ± 0,386	0,63	0,83	-31,58
			Ammonium± 0,012	0,07	0,27	-308,54

*Monthly average