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OPTIMIZING AN INDOOR CONSTRUCTED WETLAND TREATING GREYWATER

Master thesis
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submitted by:
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Table of contents

Abstract

The Human Right to Water and Sanitation was recognised as a human right by the United Nations General Assembly on 28 July 2010. Nevertheless increases the disparity between water demand and water supply day by day. Proper Sanitation can relieve the problems of water supply and wastewater management. A safe reuse of treated greywater can reduce the need for freshwater withdrawals.

The objective of this thesis was the analysis and optimisation of a constructed wetland treating greywater. The laboratory scale indoor constructed wetland system with horizontal flow was artificial aerated. The aim was to understand the effect the artificial aeration had on the treatment efficiency as well as the reduction of aeration with proper degradation still in place. The treatment unit consists of three horizontal subsurface flow tanks which were aerated continuously. In three test series the aeration of one or more tanks was turned off, while two test series were carried out with an intermittent aeration mode.

The experimental setup was loaded with artificial greywater. One part of this thesis was to amend the artificial greywater formula to include ammonia. Therefore, a chemical substance had to be found which completely dissolves into ammonia within the mixing tank as well as the required amount to get the sought concentration of ammonium nitrogen.

The removal rates of the constructed wetland system with full aeration were very good. More than 95 % of carbon based parameters were degraded. Also 92 % of ammonia was converted, which usually is only reached by vertical flow wetlands. While the aeration had only little (< 10 %) effect on the treatment efficiency of TSS, COD and BOD_5, the degradation of nitrogen based parameters was affected by the aeration intensity. It was also attempted to increase denitrification, but no satisfying results could be achieved. It was not possible to create the required conditions within this experimental setup.

Zusammenfassung (in German)

Das Recht auf Zugang zu sauberem Wasser und Sanitärversorgung ist am 28. Juli 2010 von der Vollversammlung der Vereinten Nationen als Menschenrecht anerkannt worden. Trotzdem wird die Differenz zwischen Wasserbedarf und Wasserdargebot täglich größer. Ein angemessenes Abwassersystem kann dazu beitragen die Probleme der Wasserversorgung und der Abwasserreinigung zu lösen. Eine sinnvolle und angepasste Wiederverwendung von gereinigtem Grauwasser kann dabei helfen den Bedarf an Trinkwasser zu reduzieren.

Der Zweck dieser Masterarbeit war die Untersuchung und Optimierung einer in-door Pflanzenkläranlage zur Reinigung von Grauwasser. Die untersuchte Pflanzenkläranlage im Labormaßstab wurde horizontal durchströmt und künstlich belüftet. Das Ziel war es den Einfluss der Belüftung auf die Abbauleistung zu verstehen sowie die Belüftungsintensität nur soweit zu reduzieren dass auch weiterhin eine ausreichende Reinigung erfolgt. Die Anlage besteht aus drei Filtern in Serie die konstant belüftet wurden.

Der Versuchsaufbau wird in regelmäßigen Abständen mit einem künstlichen Grauwasser beschickt. Ein Teil dieser Arbeit war es das Rezeptur für das künstliche Grauwasser um den Parameter Ammonium zu erweitern. Dazu musste eine passende Chemikalie gefunden werden die sich schnell und vollständig in Ammonium umwandelt sowie die benötige Menge herausgefunden werden um die benötigte Konzentration zu erreichen.

Die Anlage erreichte bei voller Belüftung sehr gute Eliminationsraten. Der Abbau von Kohlenstoffbasierten Parametern lag über 95 %. Ammonium wurde zu 92 % umgewandelt, was normalerweise nur von vertikal durchflossenen Pflanzenkläranlagen erreicht wird. Die Belüftung hat auf die Abbauleistung von AFS, CSB und BSB_5 nur eine geringe (< 10 %) Auswirkung. Auf die Abbauleitung der untersuchten stickstoffhaltigen Parameter hatte die Varianz der Belüftungsintensität sehr wohl eine Auswirkung. Es ist jedoch nicht gelungen Bedingungen für eine vollständige Denitrifikation zu schaffen.

Abbreviations

BOD_5	Biochemical Oxygen Demand in 5 days [mg O_2 L^{-1}]
COD	Chemical Oxygen Demand [mg O_2L^{-1}]
CW	Constructed Wetland
DOC	Dissolved Organic Carbon [mg L^{-1}]
EFL1, 2, 3	Effluent of Level 1, 2 or 3
GW	Greywater
HL	Hach-Lange DR-1900 (photometer)
SL	spectro::lyser (spectrometer probe by s::can)
TOC	Total Organic Carbon [mg L^{-1}]
TSS	Total Suspended Solids [mg L^{-1}]
TURB	Turbidity [NTU]

1. Introduction

According to the European Commission more than 40'000 million m³ of wastewater are treated every year in Europe, but only 964 million m³ (2.4 %) of this treated wastewater is reused. That is less than 0.5 % of the annual European freshwater withdrawal (demEAUmed policy brief 2017).

Although Europe, on generally, is not classified as a water-stressed area, the effects of population growth, urbanism and tourism have influenced countries in the Mediterranean region in recent years (European Environment Agency 2018). The issues which concern the Mediterranean countries are the limited water resources on the one hand, as well as the fact that the region is one of the world's top tourist destinations. The activities of tourists increase the pressure on water resources as a tourist consumes 3 to 4 times more water per day than a permanent resident (European Environment Agency 2016). This is because tourist-related water consumption is not limited to food, drink and personal hygiene, but also includes consumption related to other activities such as swimming pools, irrigation of golf courses, laundry, etc. At the European level there are no legal instruments available concerning water reuse. Some European countries have implemented their own regulations for the uses of treated wastewater. Accepted reuse possibilities are irrigation, cleaning, fire hydrants, aquifer recharge, etc. An increase in water reuse in tourist facilities could lessen the environmental impact of the increasing tourism rate in the Mediterranean region.

The demEAUmed project (demEAUmed, 2017), co-funded by the European Union's Seventh Programme for research, technological development and demonstration, was investigating an optimal and versatile water reuse strategy within a hotel. The project connected eight innovative technologies to reduce the freshwater consumption within touristic facilities.

As part of the demEAUmed project and in cooperation with the Viennese company alchemia-nova Institute for innovative phytochemistry & closed loop processes an indoor constructed wetland – vertECO: constructed vertical ecosystem – has been studied. The vertECO can be considered a hybrid constructed wetland as it combines a horizontal subsurface flow with artificial aeration.

Six different test series has been carried out between 14th July 2016 and 27th January 2017 in order to analyze the effect of different aeration intensities on the degradation process of carbon based and nitrogen based parameters.

2. Objectives

The content of this thesis is focused around the following two research objectives:

1. The first objective aimed at introducing nitrogen into the artificial greywater – because in comparison to the thesis of Alexander Hack (2016) – the parameter NH_4-N was measured in greywater of hotels in a significant amount. Therefore the artificial greywater formula had to be amended to include ammonia.
2. The second objective was to determine how much oxygen can be saved compared to the currently used aeration strategy while still ensuring an adequate or at least sufficient treatment performance. The limiting values were determined by the legal regulations in place.

Structure of the thesis:

In chapter 3 the fundamentals of the main areas of this master thesis are described: The different types of greywater as well as the characteristics of pollution are presented in chapter 3-1. The different types of constructed wetlands are defined in the following. Chapter 3-3 points out the main elimination processes of wastewater treatment which are of relevance for this thesis. The mode of operation and the theoretical background of UV-VIS spectroscopy are presented. A short overview of the legal background conclude chapter 3.

Chapter 4, Material and Methods, starts with the description of the adaptation of the greywater recipe regarding the nitrogen parameter. The constructed wetland, probes and the different test series are explained as well.

In chapter 5 the results of the test series are presented and discussed.

Finally, in chapter 6 the results are summarized and in chapter 7 suggestions for further test series are provided.

3. Fundamentals

3.1 Greywater

The wastewater stream can be divided by two origins: domestic (household) wastewater and industrial wastewater (Ertl 2008). Household wastewater can further be separated into blackwater and greywater (Langergraber 2016).

Greywater is commonly further defined as all of the wastewater produced in a household without faecal contamination (blackwater) (Oldenburg et. al. 2008). Typically, this includes wastes from bathroom sinks, baths, and showers, and may also include wastes from laundry facilities and dishwashers. Some definitions include wastes from kitchen sinks, although there is no consensus on this (Gross et. al. 2008). Ghaitidak and Yadav (2013) further divide greywater according to the level of pollution into dark and light greywater (Figure 3-1).

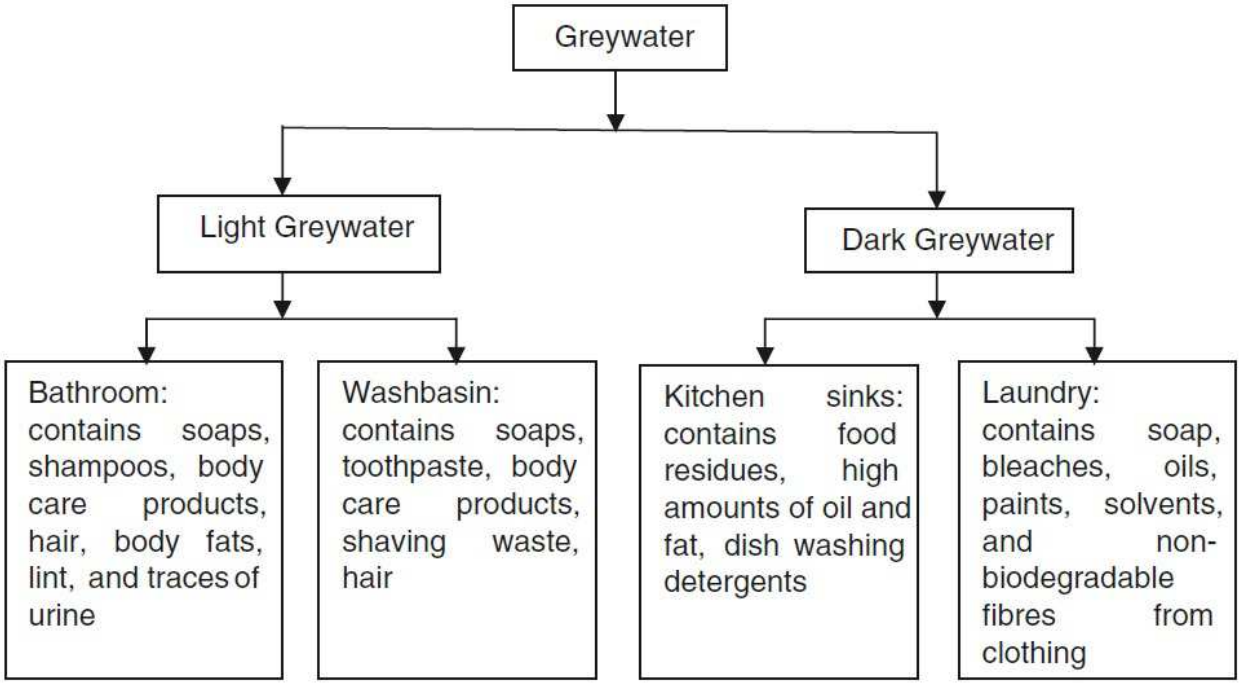


Figure 3-1: Greywater sources and their constituents (Ghaitidak & Yadav 2013)

The quality of greywater depends on the sources and the constituents. The Hawaii State Department of Health stated that in 2009 that the characteristics of greywater are in direct dependency of the number of users, their age distribution, their life-style and water usage patterns, the living standard as well as the cultural habits. The characteristics depend on which soaps, toothpastes, shampoos and the quantity of household chemicals are used. Further also the time of storing the greywater significantly influences the quality. Characteristics of domestic greywater in selected countries can be seen in Table 3-1.

Greywater originating from laundry can contain high concentrations of chemicals (sodium, phosphorus, surfactants and nitrogen) from the washing powder. This greywater can be hot water, contain bleaches, oils, paints, solvents and can contain non-biodegradable fibres from clothing (Morel and Diener, 2006).

The greywater from kitchen sinks is characterized by containment of food particles as well as significant amounts of oil and grease (Morel and Diener 2006).

The quantity of generated greywater depends on the number of users, their lifestyle and the water usage patterns. In areas where there is no or only a limited water supply service the

amount of greywater generation is reduced. A typical amount of greywater in households with piped water (without water scarcity) is 90-120 l/p/d (Morel and Diener 2006).

It is estimated that 60-75 % of wastewater volume accounts for greywater (Tilley et al. 2008 and Ghaitidak and Yaday 2013).

Table 3-1: Domestic greywater characteristics in selected countries (Morel and Diener 2006)

Parameter	Costa Rica	Palestine	Israel	Nepal	Malaysia	Jordan
Q (l/p/d)	107	≈50	≈100	72	≈225	≈30
TSS (mg/l)	-	1396	330	98	76	316
COD (mg/l)	-	1270	822	411	212	-
BOD_5 (mg/l)	167	590	477	200	129	275-2287
NH_4-N (mg/l)	-	3.8	1.6	13.3	13	-

Greywater usually contains microorganisms (E. coli, Faecal coliforms) due to its contact with the human body. The concentration of these microorganisms is much lower compared to concentrations in blackwater (Chung and White 2009).

Although the risks and the inconsistent conditions greywater has an international recognition as substitute as alternative water resource (Ghaitidak and Yadav 2012). Recycling greywater can reduce the load on wastewater treatment plants, reduce freshwater consumption by reusing treated greywater (irrigation, toilet flushing) and thereby reduce emissions (Morel and Diener 2006). According to Prathapar et al. (2005) up to 50 % of freshwater can by saved by using recycled greywater.

3.2 Constructed wetlands

Constructed wetlands are artificial wetlands that are designed to optimise processes found in natural environments to treat different types of polluted water. Treatment wetlands are considered as an environmental friendly and sustainable way of treating wastewater. The special characteristics of these wetlands are to lower operation and maintenance requirements compared to other waste water treatment technologies. Constructed wetlands are robust to variation of influent and can be used for different wastewater types (Dotro et. al 2017).

The artificial installation can be divided into different types, due to its function on improving and cleaning different wastewater types. Hoffmann et al. (2011) divided constructed wetlands after the water flow regime into surface flow (FWS CWs) and subsurface flow (SSF CWs). Subsurface constructed wetlands can further be divided depending on their flow direction into Horizontal flow (HF) and Vertical Flow (VF) wetlands. Hybrid systems can combine different types of constructed wetlands to make use of the specific benefits of the different systems.

Compared to other wastewater treatment systems, constructed wetlands need less energy and maintenance but require more land. They are considered a suitable solution for smaller and decentralised wastewater treatment systems (Hoffmann et al. 2011).

3.2.1 Horizontal Flow Wetlands

In a Horizontal Flow Wetland (Figure 3-2) the wastewater enters on one end, flows horizontal through porous media (sand or gravel) and gets collected on the opposite end. The water level

is controlled by a standpipe outside the wetland and should be 5 – 10 cm below the surface. The gravel depth is 0.5 – 0.7 m while a freeboard of 0.2 m (for secondary treatment) and 0.5 m (for tertiary treatment) for water storage of high flows or storm water. The gravel bed is separated from the surrounding media by plastic liner and/or geotextile membrane (Dotro et al. 2017).

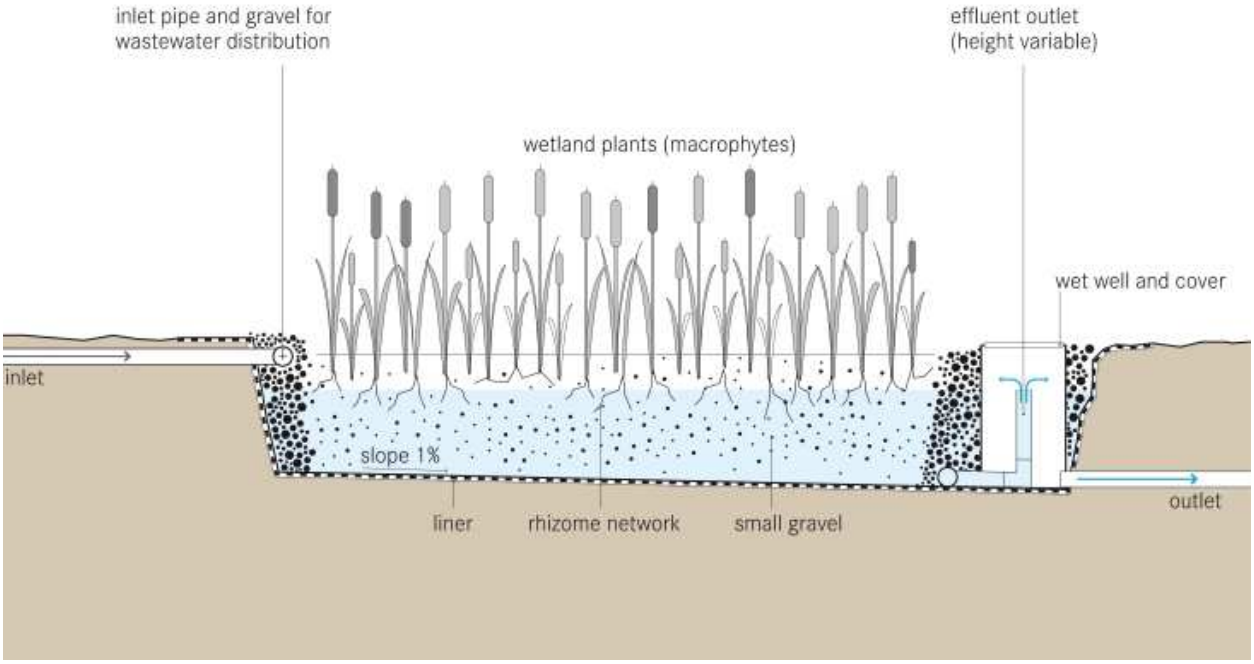


Figure 3-2: Schematic of Horizontal Flow Wetland (Tilley et. al 2014)

Horizontal Flow Wetlands are easier to design and to build than Vertical Flow Wetlands and primarily used for secondary or tertiary treatment of domestic or industrial wastewater. The most common error is clogging of the filter, which results in surface run-off. Clogging can be prevented by primary treatment to remove suspended solids, prevent an undersized inlet area and the grain size of the filter media should be large enough. The water –saturated conditions result in mainly anaerobic conditions where bacteria on the surface of the porous media and plant roots remove the organic matter. The limiting factor is the external oxygen transfer (Hoffmann et al. 2011).

3.2.2 Vertical Flow Wetlands

In a Vertical Flow Wetland (Figure 3-3) the wastewater drains vertically from the planted surface down through the substrate towards the drainage system on the ground. Vertical flow wetlands are loaded intermittently by pump or if the landscape allows it with a siphon. The intervals between the loadings should be between 3 and 6 hours. The time between the loadings allows air to re-enter the Wetland. Thereby enough oxygen is in the filter whereby anaerobic microbial processes take place. Vertical Flow Wetlands are considered to have higher treatment efficiency and need less space than Horizontal Flow Wetlands. They are commonly used for secondary or tertiary treatment of domestic wastewater as they remove organic carbon very efficient and in contrast to Horizontal Flow Wetlands are able to perform Nitrification and Denitrification processes.

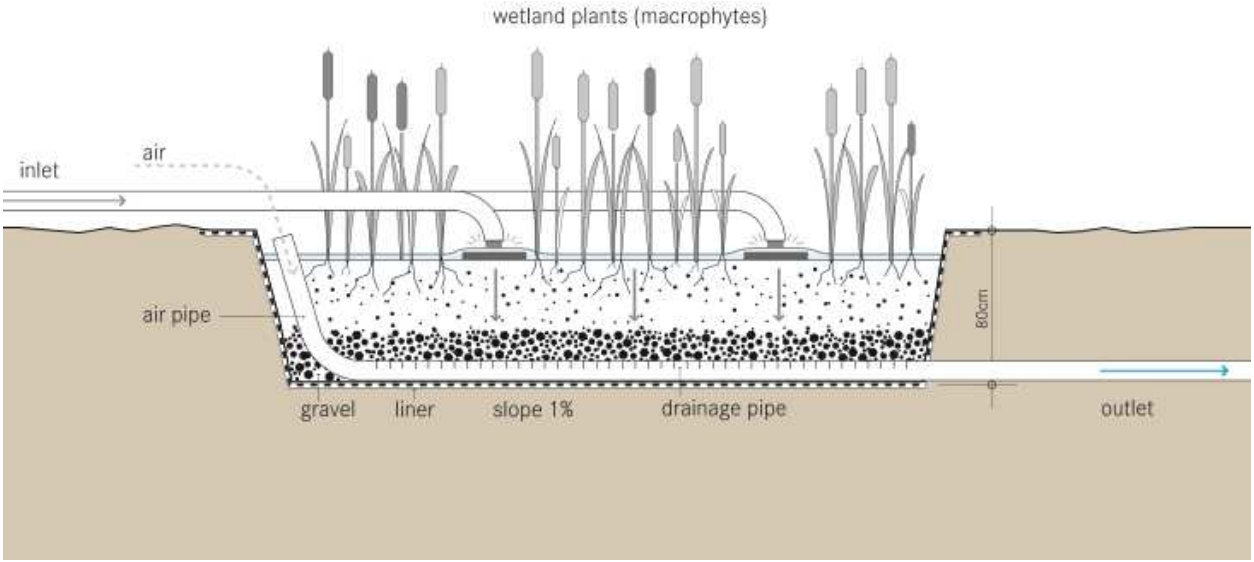


Figure 3-3: Schematic of Vertical Flow Wetland (Tilley et. al 2014)

The substrate used for the filter layer affects the hydraulic retention time as well as the removal efficiency. Fine material increases the hydraulic retention time and this often results in higher treatment efficiency. The potential for clogging is increased using a finer filter substrate.

A Vertical Flow Wetland consists of a drainage layer on the bottom, where coarse gravel is used for good drainage. A transition layer prevents the migration process of fine material from the filter layer to the drainage layer. For the filter layer usually sand is used and the depth should at least be 0.5 m. On top of the filter layer a layer of gravel can be used to prevent erosion and a free water surface during the loading process.

Mostly emergent macrophytes are used for planting Vertical Flow wetlands. The vegetation has mostly an effect on the physical processes in the wetland as the roots provide surface for the microbial growth and improve the hydraulic properties of the filter (Dotro et al 2017 & Hoffmann et al. 2011).

3.2.3 Free Water Surface Wetlands

Free Water Surface Wetlands (Figure 3-4) are commonly used as a tertiary wastewater treatment or as polishing step or treat water from non-point sources like urban stormwater or agricultural runoff. Water treated by Free Water Surface Wetlands are characterized by a high flow volume and low pollutant concentrations. There are less attachment sites for microbial biofilms and therefore the reaction rates for pollutant removal are slower compared to subsurface wetlands. The depth of Free Water Surface Wetlands depends on the maximum level the planted vegetation can endure under flooded conditions. The average depth is around 30 cm while the upper limit for most plant species about 60 cm. They can contain deep zones, which promote open water areas. Wide ranges of pollutant removal mechanism take place in Free Water Surface Wetlands: Sedimentation at the inlet zone, photo-degradation through sunlight in open water areas as well as aerobic and anaerobic processes. The presence of anaerobic or aerobic conditions depends on the organic matter loading, depth of water and distance from the inlet. The wetland should be designed the upper layer of the water column is always aerobic to prevent odour problems. The removal of nutrients by plant uptake is more

significant in Free Water Surface Wetlands compared to other Treatment Wetlands (Dotro et al 2017).

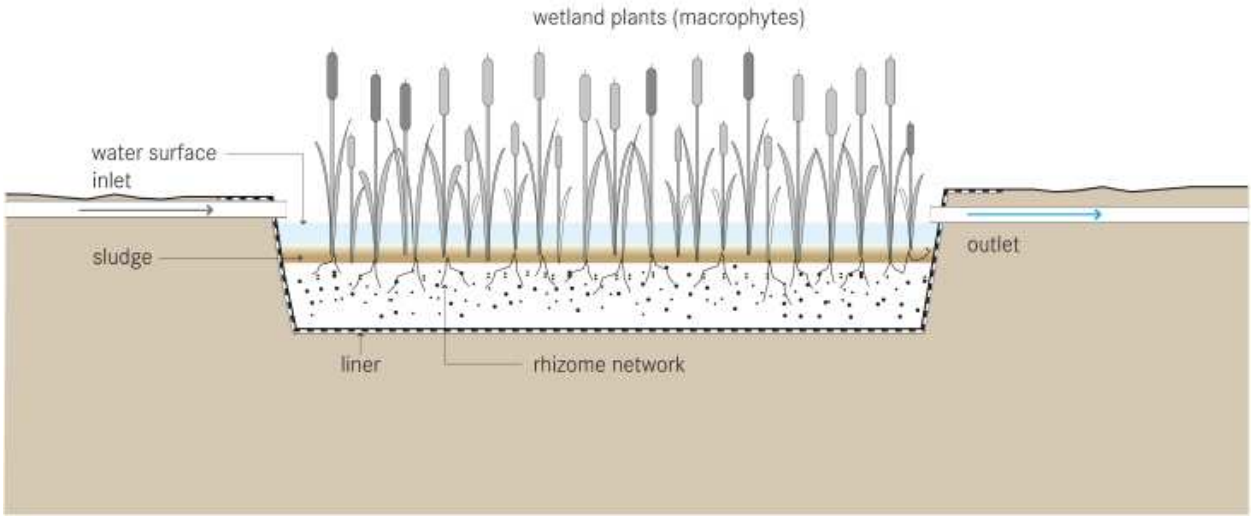


Figure 3-4: Schematic of Free Water Subsurface Wetland (Tilley et. al 2014)

3.2.4 Removal efficiencies

Table 3-2 compares removal efficiencies and specific treatment area requirements per population equivalents of typical designs of the above-described types of constructed wetlands:

Table 3-2: Removal ratios (in %) of Constructed Wetlands main types treating Domestic Wastewater or Greywater (Dotro et al. 2017 & Hoffmann et. al. 2011)

Parameter	**Horizontal Flow Wetland**	**Vertical Flow Wetland**	**Free Surface Flow Wetland***
Total Suspended Solids	80 – 95	90 – 99	80
Organic matter (BOD_5)	80 –- 90	90 – 99	80
Ammonia nitrogen	20 – 30	90	80
Total nitrogen	15 – 40	30	30 – 50
Coliforms	2 log_{10}	2 – 4 log_{10}	1 log_{10}
Treatment area required (m^2/PE)	3 – 10	1.2 – 2.5	> 10

* For tertiary treatment only

Constructed wetlands are not primarily designed for phosphorus removal and a reliable design has not been developed by now. Phosphorus removal happens through adsorption and precipitation. Therefore many constructed wetlands have a high removal rate for a period of time. This rate declines during the lifetime due to the limited adsorption sites of the filter material. If phosphorus removal is necessary a separate soil filter can be used where the substrate can be changed of the phosphorus adsorption capacity is reached.

Hybrid system can achieve even higher removal rates for nitrogen and pathogen removal as they combine different advantages of Horizontal Flow and Vertical Flow Wetlands. Usually they are more expensive to build and more complicated to operate than non-hybrid systems (Hoffmann et al. 2011).

3.3 Elimination processes

The removal process of constructed wetlands depends on a variety of different processes. A cooperation of physical, chemical and biological processes within the wetland degrades and eliminates the pollutants. The elimination happens as the wastewater passes through the wetland medium and the plants rhizosphere. Different processes depend on different conditions and some of them are linked to each other. The main parameters and their degradation processes are described in this chapter.

3.3.1 Organic matter and suspended solids

Organic matter is a heterogeneous mixture of diverse organic compounds. The main components are proteins, carbohydrates and lipids (von Sperling 2007). Organic matter originates from the remains of organisms like plants, animals, humans and their waste products, as well as chemical reactions. The carbon compounds exist either in dissolved or particular forms in wastewater. The 0.45 µm filter is usually considered the dividing line (von Sperling 2007).

The Total Suspended Solids (TSS) are a part of organic and inorganic solids that are non-filterable (von Sperling 2007) and measured by a gravimetric analysis after filtration and drying (Kadlec & Wallace 2009).

3.3.1.1 Total Suspended Solids

The elimination of suspended sediments is a major function of wetlands and a result of a number of internal processes. The suspended solids mostly get eliminated by sedimentation through low water velocities in the constructed wetland and interception within the filter media. Thereby the suspended solids get transferred from the water to the sediment bed of the wetland.

The removal of suspended matter is important for the ecosystem of the wetland as many pollutants like metals and organic chemicals are associated with suspended solids (Kadlec & Wallace 2009).

A high load of suspended solids can have effects on the hydraulic conductivity of Horizontal Flow Wetlands. The inlet zone removes a significant portion of the suspended solids. Due to design errors or insufficient pre-treatment clogging can occur as mentioned in the beginning of the thesis. That can result in a surface run-off (Hoffmann 2011).

3.3.1.2 BOD_5 & COD

A large fraction of pollutants in domestic waste or greywater are carbon compounds. There are several hundred different of these carbon based compounds which can be divided in terms of biodegradability into two groups: inert organic matter and biodegradable organic matter:

1. The inert organic matter does not change its form while passing through the wetland. The non-biodegradable soluble organic matter leaves wetland with the same concentration as it entered because it does not undergo any transformation. While the non-biodegradable organic matter is part of the biomass and can be removed by removing the sludge.
2. The biodegradable organic matter is transformed while passing through the wetland. It can be differed by their biodegradability. The rapidly biodegradable fraction consists of simple molecules and can be used by heterotrophic bacteria right away. It usually occurs in soluble form. The slowly biodegradable fraction consists of complex molecules which cannot be used by molecules directly.

Extracellular enzymes are necessary to convert the particularly organic matter into soluble matter. This process is called hydrolysis.

Two groups of biomass are present in biological treatment systems. They can be divided according to their viability into: inert residue and active biomass:

1. The inert residue consists of slowly degradable products and particulate products which are inert to biological attacks. They are the result of biomass decay processes like endogenous metabolism, death of biomass, predation and others.
2. The active biomass can be divided into heterotrophic and autotrophic. They differ in their source of carbon and are responsible for biological degradation. The carbon source of the active heterotrophic is the rapidly biodegradable carbonaceous matter. The heterotrophic biomass can grow under aerobic conditions, where oxygen is used as an electron acceptor, as well as anoxic conditions where nitrate is used as electron acceptor. Therefore aeration is necessary.

The active autotrophic biomass uses carbon dioxide as carbon source, while ammonia is the source of energy. Autotrophic biomasses are considered a chemoautotrophic organism, which means the use inorganic matter as their energy source. Autotrophic biomass needs aerobic conditions to convert ammonia into nitrite and nitrate.
Both heterotrophic and autotrophic decay generates inert residue and slowly degradable matter, which needs to undergo hydrolysis before it can be used again (von Sperling 2007).

There are four important steps of aerobic conversion in sewage treatment (von Sperling 2007 cf. Branco 1976):

- The stabilisation of organic matter (Conversion into inert products like carbon dioxide or water)
- The utilisation of oxygen
- The production if carbon dioxide
- And the release of energy

The aerobic respiration can be expressed in this general and simplified equation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy \quad (3.1)$$

The anaerobic conversion takes place in two stages. The acidogenic phase where the organic matter converts into organic acids (in this stage there is no removal, only conversion) and the methanogenic phase where the methanogenic organisms convert the organic acids into methane, carbon dioxide and water. The removal of organic matter is performed through the release of CH_4 into the atmosphere. The anaerobic conversion can be expressed by this general and simplified equation: (Sperling 2007):

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2 + Energy \quad (3.2)$$

3.3.2 Nitrogen

Nitrogenous matter can be divided by its organic state into inorganic and organic matter. Ammonia characterizes the inorganic nitrogen. It can occur either in its free form NH_3 or in its ionised form ${NH_4}^+$. The organic nitrogen is divided by its biodegradability into inert and biodegradable. The soluble inert fraction is insignificant and therefore not further considered. The particulate inert organic nitrogen is part of the non-biodegradable carbonaceous matter. It gets removed by with the excess sludge.

The biodegradable organic nitrogen can be divided into two components. The rapidly biodegradable organic nitrogenous matter is in soluble form and heterotrophic bacteria convert it into ammonia. This process is called ammonification. The slowly-biodegradable organic nitrogenous matter is in particulate form and gets transformed into the rapidly biodegradable form by hydrolysis. This process happens parallel with the hydrolysis of carbonaceous matter.

Neither ammonification nor hydrolysis changes the quantity of nitrogen in the wastewater. Both process are initiated without help and they are present until the nitrogen concentration is negligible small (von Sperling 2007).

3.3.2.1 Nitrification

Nitrification is an oxidation reaction where ammonia is transformed into nitrite and further into nitrate. The transformation is carried out by chemoautotroph microorganisms. Carbon is used in form of carbon dioxide and the energy is gained from oxidation of inorganic substrate like ammonia.

Ammonia is transformed into nitrite by bacteria of the *Nitrosomonas* genus according to this reaction:

$${NH_4}^+ + 3O_2 \rightarrow 2{NO_2}^- + 4H^+ + 2H_2O \quad (3.3)$$

Bacteria of the genus *Nitrobacter* further oxidize the nitrite into nitrate according this equation:

$$2{NO_2}^- + 2O_2 \rightarrow 2{NO_3}^- \quad (3.4)$$

The equation of the global reaction of nitrification:

$${NH_4}^+ + 2O_2 \rightarrow {NO_3}^- + H^+ + H_2O \quad (3.5)$$

The nitrification process is characterised by the consumption of free oxygen and the release of H^+ which consumes the alkalinity of the medium and can reduce the pH (von Sperling, 2007).

3.3.2.2 Denitrification

Denitrification is a microbial process where nitrate is reduced in anoxic conditions to nitrogen gas, which is then released into the atmosphere. The heterotrophic organisms use nitrate as electron donor instead of oxygen. Denitrification needs a low oxygen concentration as well as organic carbon to take place. The Denitrification process can be expressed by the following reaction:

$$2{NO_3}^- + 2H^+ \rightarrow N_2 + 2.5O_2 + H_2O \quad (3.6)$$

Further, it can be noted that Denitrification can save energy as organic matter is stabilised in the absence of oxygen and the consumption of H^+increases the buffer capacity of the medium (von Sperling, 2007).

3.4 UV-VIS Spectroscopy

Two different instruments have been used throughout the measurement period of this master thesis: the *spectro::lyser* a spectrometer probe from *s::can* for the parameter TSS, COD and BOD_5 and the DR1900 a spectrophotometer from *Hach-Lange* for the parameters NH_4-N and NO_3-N. Both instruments work with the UV/VIS Spectroscopy.

The Ultraviolet-visible spectroscopy is an absorption spectroscopic method, which measures the absorption of visible (VIS) and ultraviolet (UV) light by organic matter. The UV/VIS spectroscopy uses the fact that radiation of electromagnetic waves of light between 200 and 800 nm can be absorbed by atoms and molecules (Perkampus 1992). Thereby the valence electrons can reach an excited state. The chemical characteristics of the molecule (C-C double bonds, C-O bonds, C-N as well as aromatic structures) have a typical absorbance spectra (Langergraber et al.2017) Hence the contained compounds can be identified by measuring the absorption spectrum.

The mathematical-physical basis of light-absorption measurements on gases and solutions in the UV-VIS and IR-region is formed by the Bouger-Lambert-Beer law (Perkampus 1992):

$$"lg\left(\frac{I_0}{I}\right)_{\bar{\nu}} = \lg\left(\frac{100}{T(\%)}\right)_{\bar{\nu}} \equiv A_{\bar{\nu}} = \varepsilon_{\bar{\nu}} \times c \times d \quad (3.7)$$

In this equation

$$A_{\bar{\nu}} = \left(\frac{I_0}{I}\right)_{\bar{\nu}} (3.8)$$

is the absorbance and

$$T_{\bar{\nu}} = \frac{I}{I_0} \times 100 \text{ (3.9) in \%}$$

is the transmittance, $\varepsilon_{\bar{\nu}}$ is the molar decadic extinction coefficient.

Perkamus (1992) further elaborates that I_0 is the intensity of the monochromatic light entering the sample and I is the intensity of this light emerging from the sample. The value c describes the concentration of the light-absorbing substance and d measures the length of the path of the sample in cm. It is further described that

$$\varepsilon_{\bar{\nu}} = \frac{A_{\bar{\nu}}}{c \times d} \text{ (3.10)}$$

where the dimension for $\varepsilon_{\bar{\nu}}$ is $1\, mol^{-1}\, cm^{-1}$ for "c" in $mol\, l^{-1}$. It can also be $1000\, cm^2\, mol^{-1}$ when "c" is in $mol\, 10^{-3}\, cm^{-3}$. The molar decadic extinction coefficient $\varepsilon_{\bar{\nu}}$ is a quantity characteristic of the substance which also depends on wavenumber $\bar{\nu}$ (cm^{-1}) or on wavelength λ (nm).

In his book Perkampus (1992) further explains "the functional correlation between $\varepsilon_{\bar{\nu}}$ and wavenumber $\bar{\nu}$ is called the "absorption spectrum" of a compound. Since the extinction coefficient can vary by several orders of magnitude within the absorption spectrum of a single organic compound, the logarithmic value $lg\, \varepsilon = f(\tilde{\nu})$ can be used instead of $\varepsilon = f(\tilde{\nu})$ to plot an absorption spectrum."

"The Bouguer-Lambert-Beer law is a limiting law for dilute solutions, i.e. the assertion that the extinction coefficient ε is independent of a substance concentration at the given wavenumber $\bar{\nu}$ (wavelength λ) applies only to dilute solutions. E is no longer constant for concentrated

solutions but depends on the refractive index of a solution. At concentrations up to $c \leq 10^{-2}\, mol\, l^{-1}$, the effect is slight and lies at one or two powers of ten below the usual photometric accuracy."

UV/VIS Spectroscopy can be divided into three different types (Gottwald & Heinrich 1998):

1. The qualitative analysis can **identify a chemical** by measuring maxima and position of the absorption spectrum, which is further compared with already measured absorption spectrums. This method has not been used for this master thesis and therefore will not be explained in details.
2. The quantitative analysis can identify the **concentration** with high accuracy and the method is used by the s::can spectrometer. To quantify UV-VIS spectroscopy measurements a calibration is necessary. The calibration enables to calculate the searched concentration value (x-value) by measuring the extinction value (y-value) of the probe.

   Measuring the absorption of multiple calibration solutions does the calibration. The measured value of absorption is then dependent value y of the independent variable x. Moreover the user has to find a mathematical model, which describes the relationship between the two variables.

   The calibration of the s::can spectro::lyser used during the measurement period of this thesis has been carried out in his master thesis of Alexander Hack (Hack, 2016).
3. The underlying principle of the half-quantitative photometric analysis is the measurement of colour intensity. The sample gets mixed with reagents, which triggers a chemical reaction and leads to a change in colour of the solution. The intensity of the colorization depends on the concentration of the solution.

The principle design of photometers and spectrophotometers operates very similar. Both consist of a light source, a monochromator or a filter, a cuvette compartment, a detector and an amplifier with a visual display unit (Perkampus 1992).

Modern spectrophotometers are almost exclusively using two types of lamps for their source of radiation. Halogen lamps are used for the visible part of light (VIS) while deuterium lamps are used for light of the ultraviolet region (Gottwald & Heinrich, 1998).

3.5 Legal aspects

Although there is no international standard in place to control the quality of greywater for the purpose of reuse (Alkhatib et al. 2006), there are several international recommendations and guidelines. The most relevant are provided by the World Health Organization (WHO 2016) and national organizations like the United States Environmental Protection Agency (USWPA 2012). At European level several countries have developed individual guidelines for the use of reclaimed greywater for non-potable activities (Oh et. Al 2018). Several national standards are summarized and compared in Table 3-3:

Table 3-3: Treated greywater standard in various countries (Oh et. Al 20018):

Parameter	Australia	Israel	Italy	New South Wales	Canada
TSS [mg/l]	<30	<10	<10	<20	<20
BOD_5 [mg/l]	<20	<10	<20	<20	<20
COD [mg/l]	-	<100	<100	-	-
Total N [mg/l]	-	-	<15	-	-

The Spanish legislation (RD 1620/2007) regulates the water reuse including microbial load and what the final destination of the reclaimed water is. The different categories for final end use are: urban uses, agricultural uses, industrial uses, residential uses and environmental uses. The parameters Escherichia coli, TSS, Turbidity as well as total nitrogen, total phosphorous, Nitrates and others are defined as well as the analytical methods for each use (Atanasova et. al 2017). In May 2018 the European Commission has proposed a new regulation on minimum requirements for water reuse (European Commission 2018).

4. Material and methods

4.1 Artificial greywater

The formula for the artificial greywater had already been developed by alchemia-nova (Table 4-1). The experiments and comparisons, respectively, were already in place and operating in the demo testing facility in Barcelona. The previously measured parameters where: TSS, COD, BOD_5, TURB, TOC and DOC which are mostly carbon-based while hardly anyone had looked into nitrogen-related parameters. The s::can spectro::lyser was calibrated to measure the before mentioned parameters.

Table 4-1: Artificial greywater recipe:

Ingredient	Amount
Shower gel	80 ml
Toothpaste	10 ml
Bodymilk	40 ml
Shampoo	70 ml
Conditioner	50 ml
Household cleaning agent	40 ml
Liquid soap	80 ml
Deodorant	8 ml
Water	500 l
Ammonium chloride	20 (- 30*) g

* 30 g were used for test series 0 and 1

When we started taking probes at the beginning of this master thesis to compare the values TSS, COD, BOD_5, TURB, TOC and DOC in the greywater, aeration intensity and the cleaning performance of the demo with the constructed wetland of alchemia-nova, it became clear that another parameter had to be added – NH_4-N. This was due to the fact, that, since the previous thesis had been conducted, ammonium had been discovered as another relevant component in the greywater at the demo site.

In general greywater is not contaminated with high nitrogen concentrations (compare Table 3-1), but during measurements at a demo site in Barcelona, a high nitrogen concentration of over 25 mg/l was detected. The source of nitrogen in the greywater is not identified; nevertheless it is expected to be urine.

For the thesis experiments, two Chemicals (urea and ammonium chloride) have been used to add nitrogen artificially. To verify the measurement settings of the Hach Lange Spectrophotometer, the data was measured in the alchemia-nova and in the SIG laboratory. At first both chemicals have been tested how they dilute to gather the amount of chemicals necessary to reach the experiments level of 20 – 25 mg/l in the greywater tank. Secondly the chemicals behaviour was tested in situ at the experiment setting. To get the data of the testing

the chemicals were in the tank for two weeks and daily measurements have been performed. Finally ammonium chloride was used to extend the greywater composition.

4.2 Experimental setup

The underlying research for this thesis was conducted in the laboratory of *Alchemia-Nova – Institute for Innovative Phytochemistry & Closed Loop Processes* in Vienna, Austria. The design of the experimental setup was part of an earlier master thesis of Hack (2016).

My thesis builds upon this prior research especially because the construction and the essential equipment was already in place and could readily be used to perform the required tasks and to ensure the success of the objectives that were set out.

Subsequently, a closer description of the experimental setup of the laboratory, the greywater tanks, the constructed wetland and the aeration on-site is laid out in this chapter.

The constructed wetland system was situated indoors (Figure 4-1). Due to the lack of natural sunlight, an artificial lighting system was installed. The scheme consisted of LED lamps, which have a power consumption of 500 Watt and were used to reproduce a light-dark cycle. The LED lights – with a wavelength range of 400 - 730 nm – illuminated the plants for 16 hours a day. The air temperature in the laboratory was kept at 16 °C to 18 °C for the whole research period.

Figure 4-1: Experimental setup (alchemia nova 2016)

The artificial greywater was mixed and stored in two tanks with a combined capacity of 1000 litres. The outflow from the tank to the constructed wetland was controlled by a peristaltic pump which was operated by a timer clock. Water was pumped from the tank to the first level of the wetland for 15 minutes followed by another 15 minutes where the flow of water was disrupted.

This operation mode fed the plant with 500 litres per day during the week and half the amount throughout the weekend. Due to the size of the storage tank they were on a reduced operational mode during the weekends, with a hydraulic loading of 250 litres per day. The consolidated timetable for taking the necessary samples was initially set out every day. Owing to the reduced functionality during two days of the week it soon became clear that the results of the first day in full operation mode were not coherent with the main measurement recordings and therefore not practicable for the proceeding analysis.

The treatment unit itself consisted of six evenly sized stainless steel tanks, whereas in each case two tanks were connected below the surface to constituted one big tank on the same level. Thereby they are each regarded as one tank on one level. Those three big tanks were situated on three different height levels where the artificial greywater had to flow through the tanks in a subsurface flow. The outflow was situated about three centimetres below the top edge of the tank and ensured a steady water level of 25 centimetres within each tank.

At the time when the research was conducted the tank had already been modified to tackle the issue of varying residence times due to the siphon effect which caused excessive flow rates. One of the unintended consequences of an unsuccessful “fill-and-drain” experiment was some vegetation loss. Further details on the initial set-up can be found in Hack (2016).

The tanks were filled with expanded clay for hydro cultures with an 8/16 mm granulation. The special clay for hydro cultures was used because *alchemia-nova* traced high salt concentrations in the effluent when using cheaper expanded clay anticipated for construction purposes. Although the high salt and ions concentration were not clearly linked with the substrate, there were no associated problems with the expanded clay for hydro cultures.

A variety of plant species is planted in the tanks, for the aesthetic aspect when it comes to commercialization. However, the potential impact of every single plant species is not examined in this experiment setting. The selection ranged from typical wetland plants like rushes (*Juncus* sp.) and sedges (*Carex* sp., *Cyperis* sp.) to – in this connection – uncharacteristic ones like Ficus *pumila* and *Spathiphyllum* sp. During the time of research a small number of plants died off and were replaced by different plants.

A plastic air diffuser from the same air compressor, which is specified below, aerated both the greywater tank and the constructed wetland. As a result of changing the aeration of the tank to an intermitted operation mode, the aeration of the collection tank changed as well.

The installed air compressor had a nominal air output of 90l/min. As specified by the manufacturer, the performance curve (Figure 4-2) purports at 25cm of water head (= 0.0025MPa) the air compressor can deliver about 85 litres of air per minute. By deducting 5 l/min for the air resistance we calculate with an air output of 80l/min. The compressed air is equally split up between the artificial greywater tank and each of the aerated height levels of the testing plant. When fully aerated, every level receives about 20l/min of air.

Dry air contains about 21 % of oxygen. The multiplication of these numbers shows that the air compressor delivers about 4 litres of O2 per minute and height level.

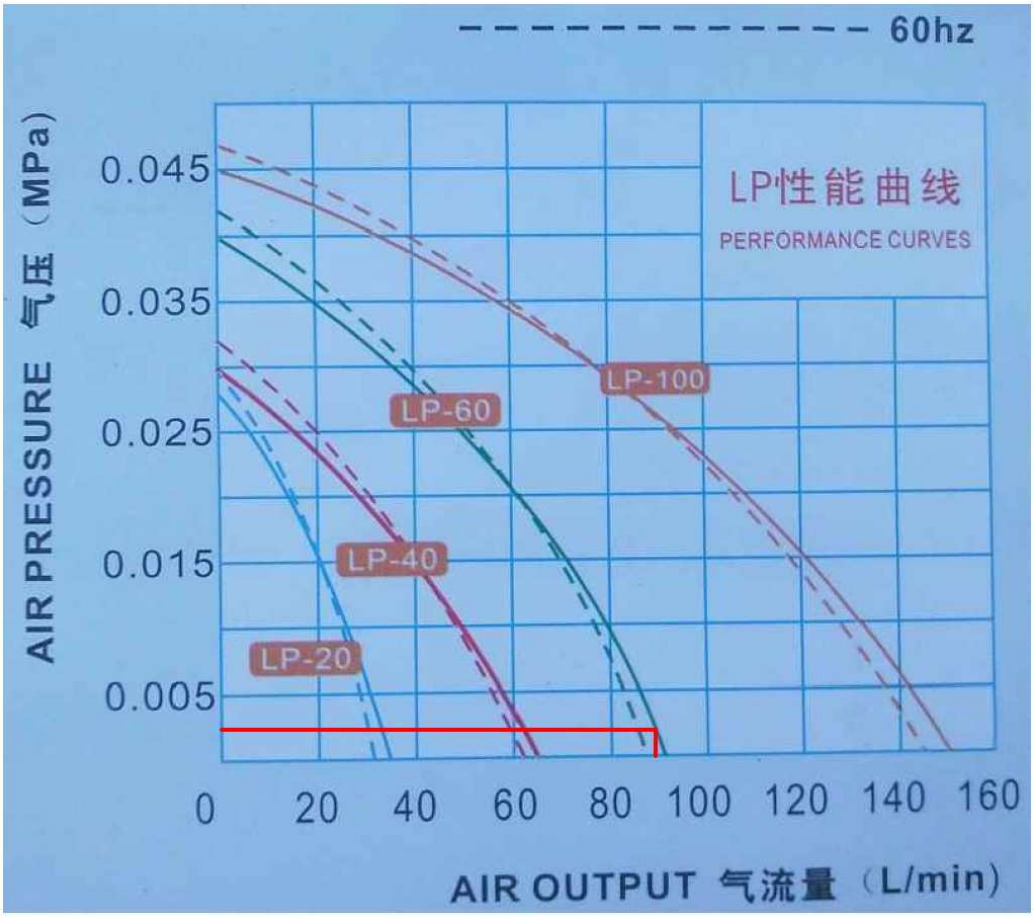


Figure 4-2: Performance curve air compressor

For each series of measurement the number of aerated levels respectively the amount of air was changed. The test series were carried out from July 2016 to January 2017. After changing the aeration mode there were no measurements for two weeks because the results varied too much from one day to the next. The variation in the results is most likely due to the bacteria, which needed time to adapt to the increasing oxygen supply.

The testing series were carried out for three consecutive weeks for every one of them. Due to the effects of the reduced hydraulic operation mode after the weekend, measurements have only been examined Tuesday to Friday.

4.3 Description of the test series

For meeting the second objective of this master thesis, six different measurement series were conducted. The first one was about assessing the status quo. This was necessary to obtain the relevant figures from which the research could start in order to measure the alteration by varying the aeration intensity.

Test series 0:

To achieve this, the aeration was on full operational mode with the same greywater values as on the demo site. These values were compared on all levels and in line with the figures from the related testing facility in Spain. The (artificial) greywater parameters, the aeration intensity and the cleaning performance were close to the same which was a satisfactory starting point for carrying out the subsequent testing series.

When exposing the degradation processes to closer scrutiny, it was observed that the carbon was degrading properly. Meanwhile, the NH_4-N was degrading under the measurability limits (2 mg per litre) and therefore it was not detectable any more. The anticipated effect – namely that the NH_4-N would degrade into NO_3-N or, in other words, that the ammonium would degrade into nitrate – occurred.

On this basis the first hypothesis was developed, upon which the following measurement series were conducted (Table 4-2):

Test series 1:

Test series 1 was concerned with the reduction of aeration. By disconnecting the aeration of level 3, which means a reduction of the aeration by 33 %, there should be anoxic conditions in place in which NO_3-N will degrade. Hence, the NO_3-N should be degraded into N2 which in turn should gasify.

Test series 2:

The NH_4-N concentration at the testing site concurred with the peak value, which was measured at the demo site. Since this maximum value is not representative, the second test series was aimed at reducing the NH_4-N pollution from approximately 25 mg/l to the average value of about 15 mg/l.

The rationale behind this is the idea that with a lesser NH_4-N concentration the degradation of NO_3-N would occur at a faster rate while a sufficient amount of carbon for the degradation would be available.

Test series 3:

Test series 3 aimed at further reduced aeration. This should be obtained through disconnecting the aeration of level 2, which would result in an additional reduction of aeration of 25 %, which results in a reduction of 66 % compared to test series 0.

The anticipated anaerobic conditions, in which simultaneously enough carbon is in place, degradation should be possible.

Test series 4:

The objective of test series 4 was to try a different approach by establishing an intermittent operating mode. In this mode an intermittent aeration regulation would provide 15 minutes of aeration followed by 15 minutes without aeration. Although the strategy is different, the aeration intensity was decreased by 50 % of the initial test series 0.

This should have the benefit of producing aerobic as well as anaerobic conditions in which the degradation of NO_3-N should happen while the degradation performance of the other parameters should be ensured as well.

Test series 5:

Test series 5 sought to further improve the intermittent operational mode by extending the aeration periods again. The new trial consists of longer periods of ventilation, which means 30 minutes with aeration are followed by 15 minutes without aeration. This operational mode means a reduction of the aeration in comparison with test series 0 by 33 %.

In theory, this should permit sufficient aeration to accomplish the degradation of NH_4-N while also allowing enough anaerobic periods to further have NO_3-N transform into N_2 which should then gasify.

Table 4-2: Overview of the different test series

Test series	Time of measurement	NH_4-N [mg/l]	Aeration			Time interval
			Level 1	Level 2	Level 3	
0	14th – 28th July 2016	25	On	On	On	-
1	16th August – 2nd September 2016	25	On	On	Off	-
2	20th September – 14th October 2016	15	On	On	Off	-
3	2nd – 11th November 2016	15	On	Off	Off	-
4	29th November – 2nd December 2016	15	Intermittent	Intermittent	Intermittent	15min
5	10th – 27th January 2017	15	Intermittent	Intermittent	Intermittent	30 min on 15 min off

To detect a possible influence of the aeration and pump times on the measurement time, extra tests have been conducted. For this reason a sample was taken in an interval of 15 minutes and in total for two hours, to recognize if the pump is leading to a flush, which further could influence the measurement time (Table 4-3).

Table 4-3: Conditions of the time series

Time of Measurement	Aeration	Pump
	Off	On
12:45		Off
13:00	On	On
13:15		Off
13:30	Off	On
13:45		Off
14:00	On	On
14:15		Off
14:30	Off	On
14:45		Off

4.4 Measurement devices

In this thesis, several measuring instruments were employed, which will be described in the following chapter. Among the equipment used was the *s::can spectro::lyser*, furthermore the *Hach-Lange DR-1900*, the *s::can ammo::lyser* and the *Thermo Scientific Orion Star A329*.

To get accurate measurements of each sampling point, the correct values were validated at the start of the testing series with the chemical analytical lab of the Institute of Sanitary Engineering and Water Pollution Control (SIG) at the University of Natural Resources and Life Sciences, Vienna.

It should be noted beforehand that when applying the different measurement devices in situ, it became apparent that due to technical problems the *s::can ammo::lyser* and the *Thermo Scientific Orion Star A329* did not produce any viable results. That's why the focus was put on the remaining instruments for the generation of feasible results that were in turn scrutinized to avoid biased outcomes.

Following this brief overview, the measurement tools and their characteristics are explained in greater detail while also addressing the issues that arose during the testing at the plant and the subsequent checking of the findings.

4.4.1 s::can spectro::lyser

S::can Messtechnik GmbH is an Austrian Company which was established in 1999 as a spin-off of BOKU *University* and is based in Vienna. The focus of the company is on the design and manufacture of digital sensors for online quality measurement.

The measuring principle of the *spectro::lyser* is the UV-VIS spectrometry with a measuring range of 190-720 nm wavelength (Figure 4-3) and is manly used by drinking water providers for raw water monitoring (s::can n.d.).

The parameters which can be measured by the *spectro::lyser™ UV-VIS are* TSS, turbidity, NO_3-N, COD, BOD_5, TOC, DOC, UV254, colour, BTX, O_3, H_2S, AOC, temperature and pressure (s::can n.d.). Whereas the parameters TSS, NO_3-N, COD, BOD_5, NH_4-N, pH and temperature were measured and only TSS, COD and BOD_5 were collected and evaluated.

The *spectro::lyser* probe was operated via a *s::can terminal* with *s::can software*, with different global calibrations already installed. For the sampling of this master thesis the following global calibrations were used:

- [INFLUBODV150] to monitor the influent concentrations (TSS, COD, BOD_5) of wastewater treatment plants.
- [EFFFLUBODV150] to monitor the effluent concentration (TSS, COD, BOD_5) of wastewater treatment plants.

Those global calibrations had to be adjusted by a local calibration based on the result of the master thesis of Hack Alexander (2016). The crosschecking with the laboratory showed that the specific local calibration of Hack Alexander (2016) had to be modified: the pair of values for very high and very low concentrations had to be excluded to get viable results. The crosschecking also showed that the locally calibrated [INFLUBODV150] calibration was eligible for measuring the artificial greywater and the EFL1, while the locally calibrated [EFFFLUBODV150] calibration had good results for EFL2 and EFL3.

The *s::can spectro::lyser* is able to measure NO_3-N and NH_4-N, but those parameters were not locally calibrated by Hack Alexander (2016). With the global calibration there were no viable results. Therefore another instrument was needed to gauge the nitrogen parameters.

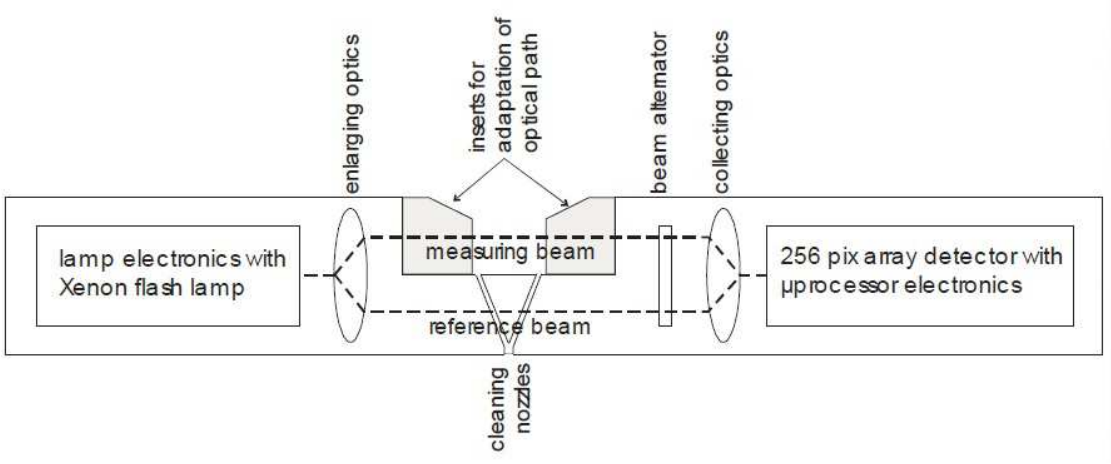


Figure 4-3: spectrometer probe (Langergraber et al. 2003)

The measurements with the s::can spectro::lyser have been carried out two times with different probes to increase the number of measuring results. During the measurement period there were two issues occurring with the s::can spectro::lyser where the sealing ring of the lamp has become porous. In order to repair the device it had to be sent to the s::can headquarters which unfortunately resulted in two time lags of about three weeks each.

4.4.2 s::can ammo::lyser pro

From previous experiments the alchemia-nova was in possession of a s::can ammo:lyser pro which is a multi-parameter probe for ammonium measurement. The measurement principle is an ion-selective electrode which converts the activity of an ion dissolved in a solution into an electrical potential. The electrode measures the electrical potential and thereby the required ionic concentration can be determined.

When applying the measurement devices in situ, it became apparent that the life span of the reference electrode from the s::can ammo::lyser was exceeded. According to s::can the life span of the ISE is typically 6 months (for applications <1mg/l NH4-N), resp. 1 to 2 years (for applications >1mg/l NH4-N). Unfortunately, the replacement of the electrode was too expensive, so another device for measuring NH4-N and NO3-N was chosen: Hach-Lange DR1900 Portable Spectrophotometer

The Hach Lange Spectrometer works with measuring the photometric wavelength light in a wavelength of 340 – 800 nm. To perform accurate measurements specific sample cells had to be used.

To measure the NH_4-N parameter LCK303 ammonium cuvette samples were used. The measurement range is 2.0 - 47.0 mg/L NH_4-N. When the result was below 2.0 mg/L NH_4-N (which was the case in most of the results of EFL3) there was no further testing as the cleaning capacity was verified.

NiraVer5 sachets filled with cadmium were used to measure the NO_3-N concentration. The measurement range is 0 - 50 mg/L NO_3-N (s::can n.d.). With a pipette a specific amount of the filtered sample had to be put into the sample cell where it was mixed with prepared reagents. Ten minutes after mixing through-mix the two substances with each other the sample cell changed its colour depending on the NH_4-N and NO_3-N concentration and is ready for measurement.

Despite the high price of the LCK303 sample cells the Hach Lange Spectrometer was subsequently used for the measurement of the nitrogen parameter as the results were very accurate. Due to financial reasons there was no further testing of other nitrogen parameter such as Organic Nitrogen or Nitrite Nitrogen.

4.4.3 Thermo Scientific Orion Star A329

The Thermo Scientific Orion Star A329 is a small handheld device which was used in the beginning to measure ph, electrical conductivity and dissolved oxygen. Due to technical problems and lack of significance of these metrics the Thermo Scientific Orion Star A329 was not further used throughout the sample taking.

4.5 Sampling

To ensure internal consistency within the measurement period a cleaning and sample drawing routine was implemented.
The first step was to take the samples. From each sampling point (shown in Figure 4-4) a measuring jug with a volume of 1 litre was taken. Due to the sedimentation of precipitated parts of the artificial greywater, the tanks were carefully stirred with a wooden stick prior to the sample taking. The withdrawal of the greywater was carried out below the water surface to get a better mixed sample.
The sampling of EFL 1 and EFL2 was carried out through a valve in the connection pipe from one level to the following. In the case that the first sample was highly contaminated with unsolved particles, it was disposed and a second sample was taken.

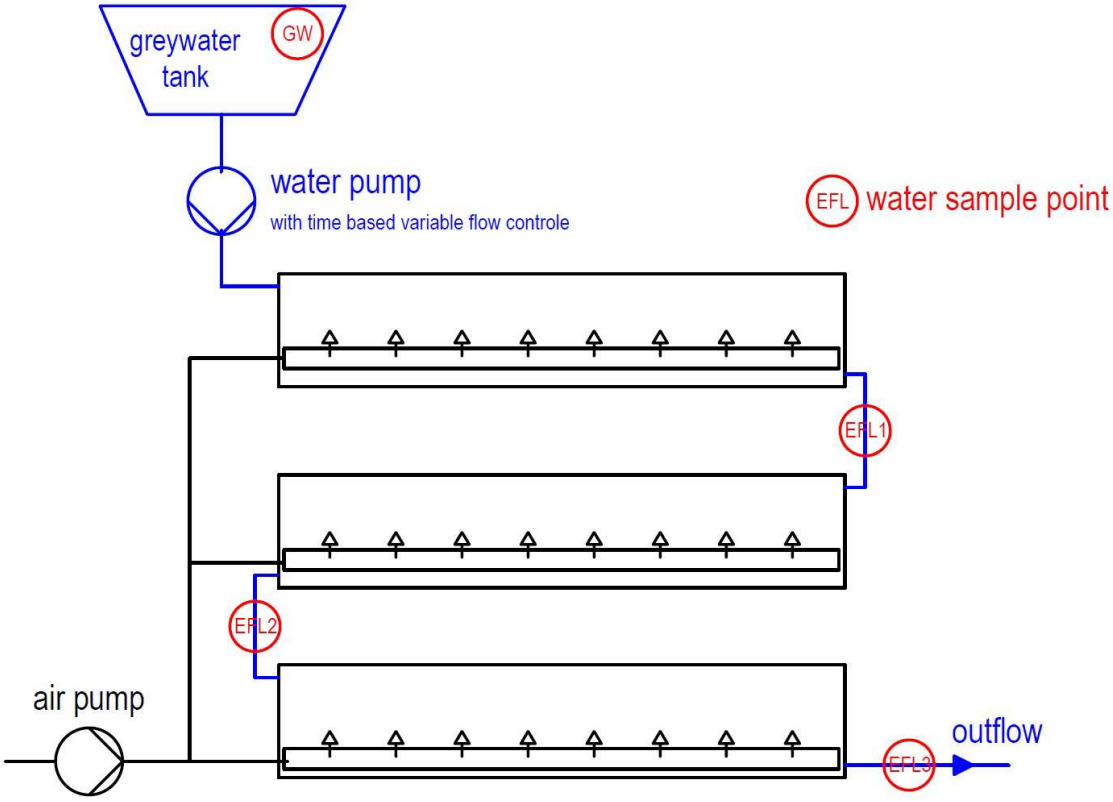


Figure 4-4: Schematic front view of constructed wetland system.

The EFL 3 sample was taken from the outflow of the constructed wetland. Due to small irregularities between measurement period and sample taking, sometimes it was only possible to extract a small EFL3 sample, due to small irregularities between measurement period and sample taking.

After sampling the probes, a small part of each sample was filtrated with a Büchner flask and stored in a measuring cylinder, which was cleaned with tap water before. The leftover samples

were kept until the whole measurement was performed in case more filtrated probe was needed. In order to avoid erroneous measurements, the low contaminated samples were measured first and then the more polluted ones. The filtration device was cleaned with hot water between the sampling.

Further the s::can spectro::lyser was cleaned, to remove organic and inorganic accretion from the lens:

1. Removal and cleaning of the multifunctional slide of the spectro::lyser with hot tap water
2. Flushing the measuring path of the spectro::lyser with hot tap water
3. Cleaning the measuring path with ethanol
4. Wiping the lens with a cotton bud which is saturated with 3 % acetic acid
5. Rinsing the measuring path with distilled water
6. Attachment of the multifunctional slide on the spectro::lyser
7. Testing with distilled water, if the cleaning was successful. If not repeating of steps 3 and 4.

The measurement sequence was also followed in this measurement (always ascending from the least polluted samples to the most polluted samples). Before the measurements, the chamber off the spectro::lyser was cleaned three times with the filtrated samples. Afterwards the measurement chamber was filled up with the filtrated sampling and after that, the measurement slide was turned 90° around to prevent stray light or other light influencing the measurement. Between the measurements of the different samplings the spectro::lyser and the multifunctional slide were flushed with hot tap water.

The test series were all measured and evaluated according to the same principle, which is explained in the following:

The test series lasted 3 weeks, whereby only the values of the weekdays except Monday were used for evaluation (as already explained in chapter 4.2). The parameters that were measured with the Hach-Lange Spectrophotometer were then used immediately. The s::can probe measurements (TSS, COD, BOD_5) were performed twice each to have a higher number of samples.

Comparing the measured values from the s::can probe and the SIG laboratory, the EFL3 and the greywater values were very similar and therefore the validation was completed. However, at EFL1 and EFL2 a big difference was found. (EFL2 lab to s::can -66 %; EFL1 lab to s::can -20 %).

Two methods have been developed for recalibration after the experiments:

- The measured values of EFL1 and EFL2 multiply by a factor, which resulted from the measured s::can and laboratory values.
- Develop a formula (based on the SIG Lab results) using those that can be used to calculate the EFL1 and EFL2 values.

For the first variation, only a few comparative measurements were available. We were not sure about the reliability of the test results therefore the s::can values were given only conditionally. The measurements of the SIG laboratory have shown that the degradation of carbon parameters is very linear, and from this a simple formula can be created using the values of it. Since we did not have to resort the bad measurements results of EFL1 and EFL2 in this variation, but decided on the reliable values of EFL3 and GW for this variation of the calibration.

The next step of the evaluation was to remove those values that have been identified as outliers. Reasons for such outliers were either problems with the s::can probe or problems in the experiment setting.

5. Results and discussion

5.1 Adding Nitrogen

Dilution series were used determined the required amount of the chemicals (Table 5-1). When using urea (CH_4N_2O) in the operating system, however, it was observed that the NH_4-N concentration at the measuring points of the greywater varies greatly. Higher concentrations of NH_4-N were measured in the operating system than in the greywater tank. The reason is that urea is only converted into NH_4-N by hydrolysis. As a result, a part of the NH_4-N gets dissolved as gas. The duration of the conversion would need to be investigated in order to measure Total Kjeldahl Nitrogen, which is very expensive and therefore not performed in this experiment. Urea is therefore not suitable as a source of NH_4-N due to the complex conversion to NH_4-N.

In the experiments with ammonium chloride (NH_4Cl) within the operating system, no problems occurred. The chemical dissolves in greywater and was immediately available as NH_4-N.

Table 5-1: Results of the dilution series for ammonium chloride:

Amount of Ammonium chloride [g/l]	Ammonium nitrogen concentration [mg/l]
40	21
20	14
10	8.9
5	3.9
2.5	1.1
1.25	0.6
0.63	0.2
0.31	0.2
0.16	0.1

The target was to get an ammonium nitrogen concentration of 25 mg/l in the artificial greywater. During the preliminary tests it turned out that only 30 g of ammonium chloride were necessary to achieve this concentration. During the test series the ammonium concentration was reduced to 15 mg/l, therefore only 20 g of ammonium chloride where necessary for 500 l of artificial greywater.

5.2 Treatment performance

5.2.1 Test series 0

Test series 0 was carried out from 14th to 28th of July 2016 and had nine days of measurements. The results of test series 0 define the defaults vales for subsequent test series and can be seen in Table 5-2 and box plots of each parameter in Figures 5-1 to 5-5.

Table 5-2: Mean values test series 0

	TSS	COD	BOD_5	NH_4-N	NO_3-N
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
GW	85	267	138	25.4	0.9
EFL1	62	182	93	22.9	2.0
EFL2	12	96	49	17.7	0.6
EFL3	7	9	4	2.1	7.8

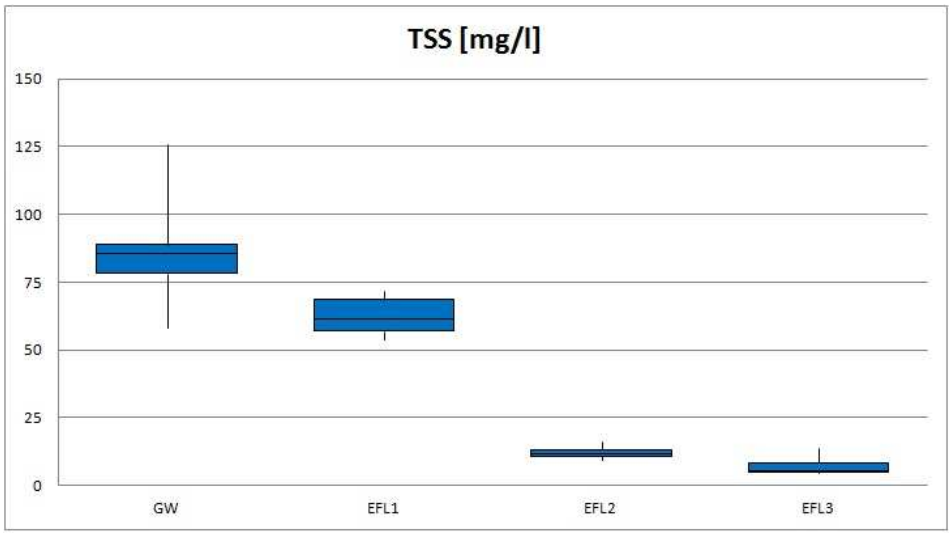


Figure 5-1: degradation of TSS at test series 0

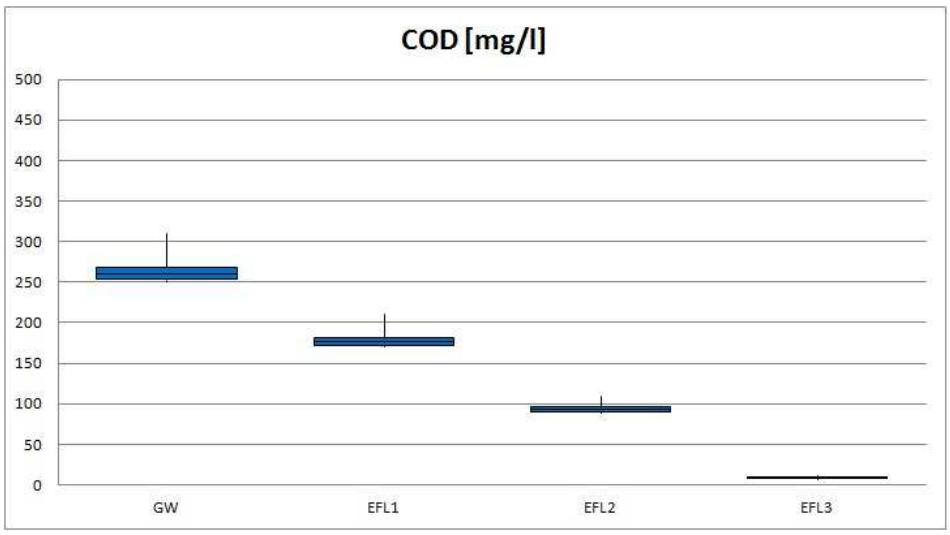


Figure 5-2: degradation of COD at test series 0

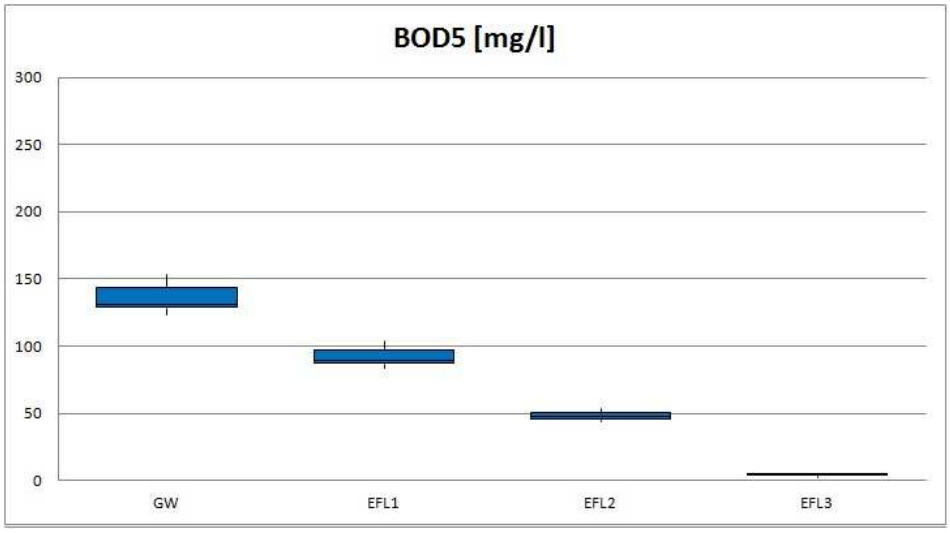


Figure 5-3: degradation of BOD_5 at test series 0

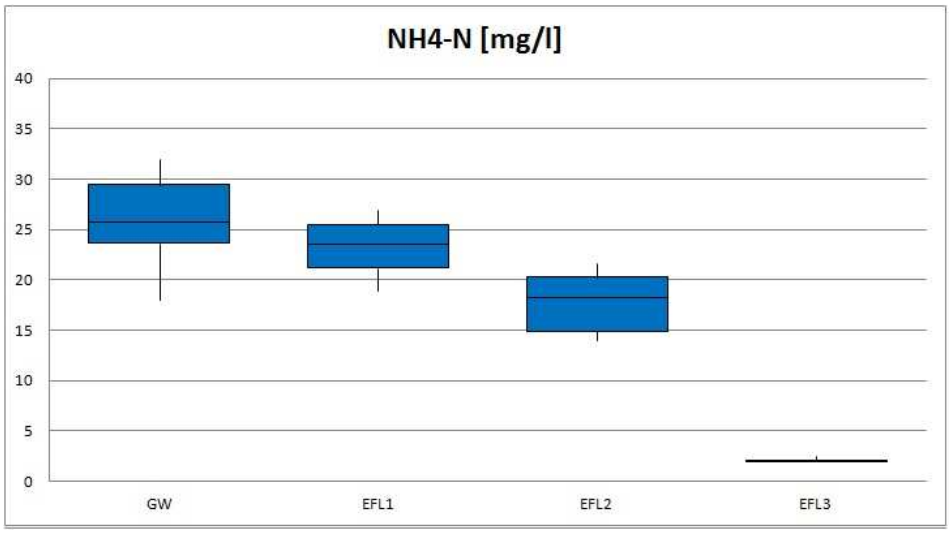


Figure 5-4: degradation of NH_4-N at test series 0

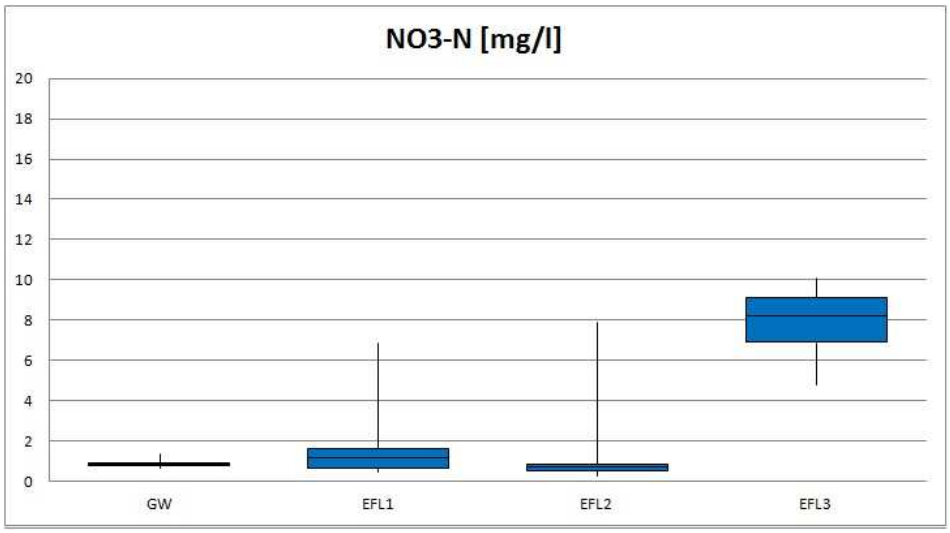


Figure 5-5: degradation of NO_3-N at test series 0

Table 5-3: Treatment efficiency for test series 0

	TSS	COD	BOD_5	NH_4-N	NH_4-N + NO_3-N
Treatment efficiency [%]	92	97	97	92	62

As you can see in Table 5-3, test series 0 showed that the existing setting had very good cleaning results regarding carbon-based parameter TSS, COD and BOD_5. A total of 92 % of TSS was removed within the wetland, while most of the sedimentation of suspended solids took place in the first and second level. The fact that most of the suspended solids are removed in the first stage of constructed wetlands has often been reported (e.g. Vymazal & Kröpfelová 2015). The treatment efficiency for BOD_5 and COD with 97 % is higher as in typical horizontal flow wetlands (see Table 3-2, chapter 3).

The nitrogen-based parameter showed that the aerobic nitrification process also works out very well. The results of NH_4-N were, except for one result, all below the measurement limit of 2.0 mg/l. As seen in the high vales for NO_3-N, the boundary conditions for the denitrification process were not in place. It was not clear whether the missing anoxic conditions or the organic carbon source limited the process.

In the tasks of the following test series of this master thesis were to reduce the aeration as well as improving the conditions for the Denitrification process.

5.2.2 Test series 1

Test series 1 was carried out from 16th August to 2nd September 2016 and had eleven days of measurements. The results of test series 1 are the consequence of turning of aeration at level 3 and can be seen in Table 5-4 and box plots of each parameter in Figures 5-6 to 5-10.

Table 5-2: Mean values test series 1

	TSS	COD	BOD_5	NH_4-N	NO_3-N
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
GW	108	287	144	20.0	0.9
EFL1	76	196	87	23.7	1.1
EFL2	21	105	52	19.7	0.6
EFL3	9	14	6	3.0	8.3

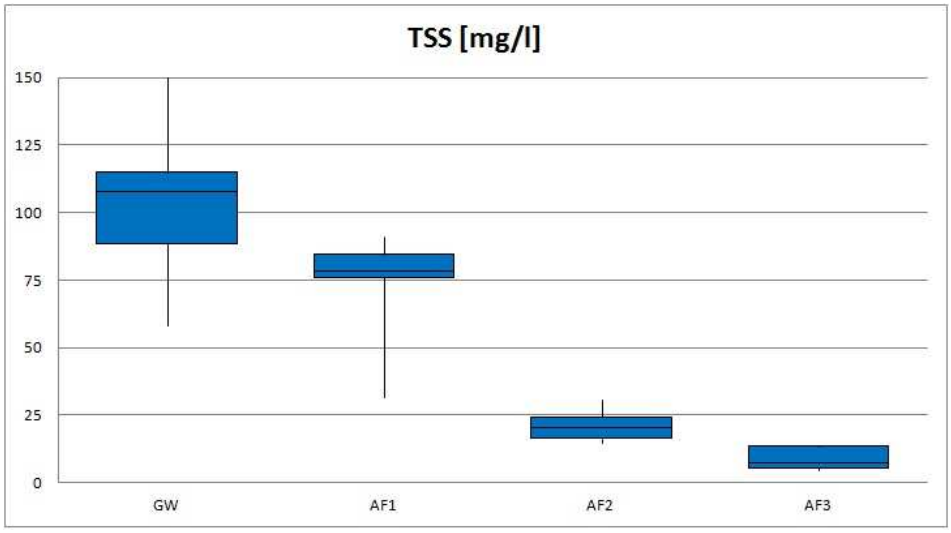


Figure 5-6: degradation of TSS at test series 1

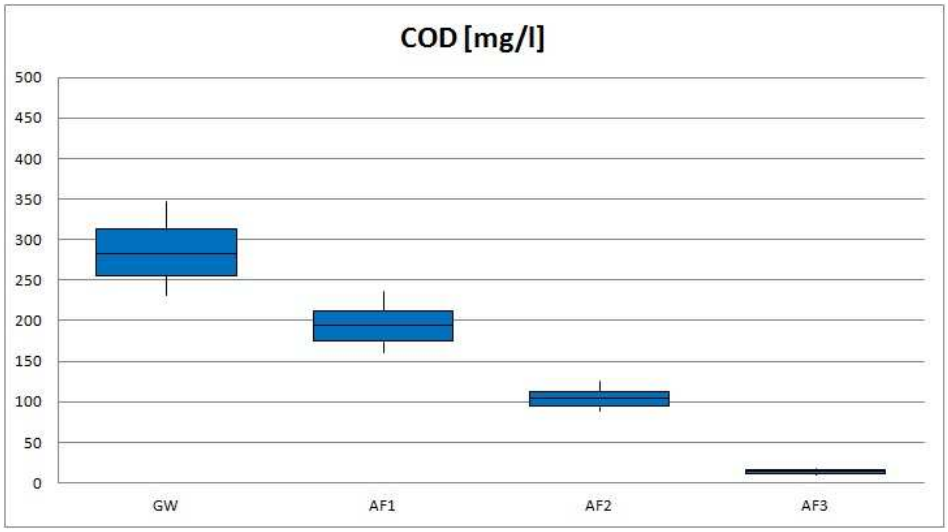


Figure 5-7: degradation of COD at test series 1

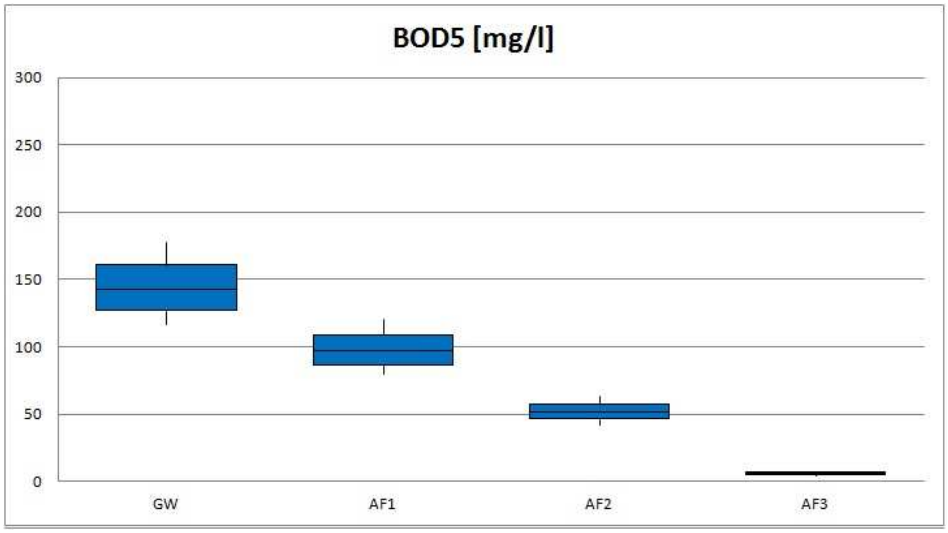


Figure 5-8: degradation of BOD_5 at test series 1

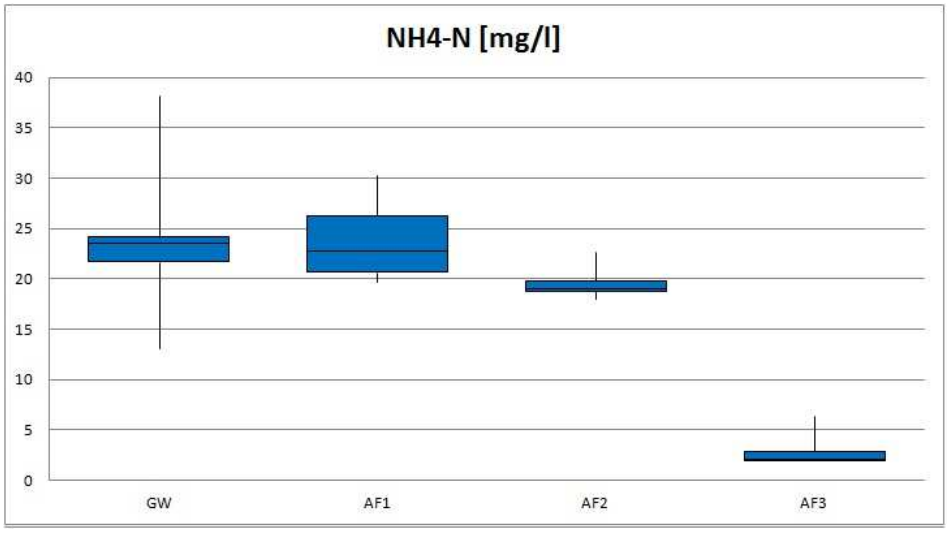


Figure 5-9: degradation of NH_4-N at test series 1

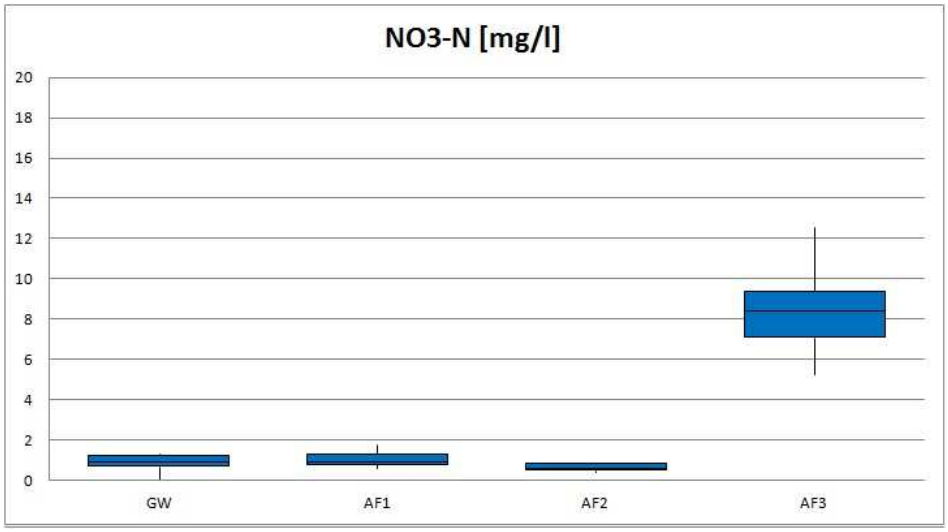


Figure 5-10: degradation of NO_3-N at test series 1

Table 5-5: treatment efficiency for test series 1

	TSS	**COD**	**BOD_5**	**NH_4-N**	**NH_4-N + NO_3-N**
Treatment efficiency [%]	92	95	96	85	46

The reduction in level 3 ventilation had virtually no impact on the carbon degradation process (Table 5-5). Both removal efficiency and the final values were very satisfactory. Although there was no oxygen input in level 3, COD and BOD_5 were still degraded, which indicates that there was still enough dissolved oxygen in the water provided for aerobic conditions. The measured nitrogen values in the greywater tank were subject to a large fluctuation range during this series of measurements.

Values up to 40 mg/l were measured and in addition, the values for NH_4-N are on average almost 4 mg/l higher than in the greywater tank at the measurement point of level 1. Despite this irregular input, the experiment rates were very good. The values for NH_4-N were below the measurable limit of 2.0 mg/l on four out of nine of the measurement days.

An improvement in the denitrification performance could not be determined. This may be due to the fact that the NH_4-N charge was very high and only in level 3 an orderly nitrification took place and therefore there was no time for a further denitrification.

However, it may also be possible that the intensive aeration in level 2 has taken so much dissolved oxygen into level 3 that no anoxic conditions necessary for denitrification could arise there.

5.2.3 Test series 2

Test series 2 was carried out from 20th September to 14th October 2016 and had ten days of measurements. The results of test series 2 are the result of no aeration of level 3 and a reduction of NH_4-N in the greywater. The results can be seen in Table 5-6 and box plots of each parameter in Figures 5-11 to 5-15.

Table 3-6: Mean values test series 2

	TSS	**COD**	**BOD_5**	**NH_4-N**	**NO_3-N**
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
GW	123	378	208	13.0	1.0
EFL1	74	256	141	10.3	0.9
EFL2	21	133	73	8.8	0.6
EFL3	11	11	5	2.0	4.8

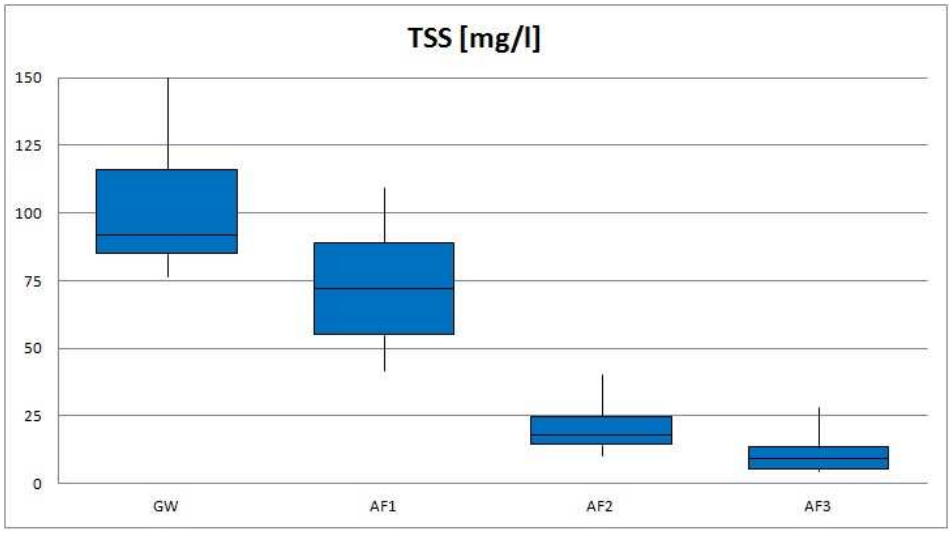


Figure 5-11: degradation of TSS at test series 2

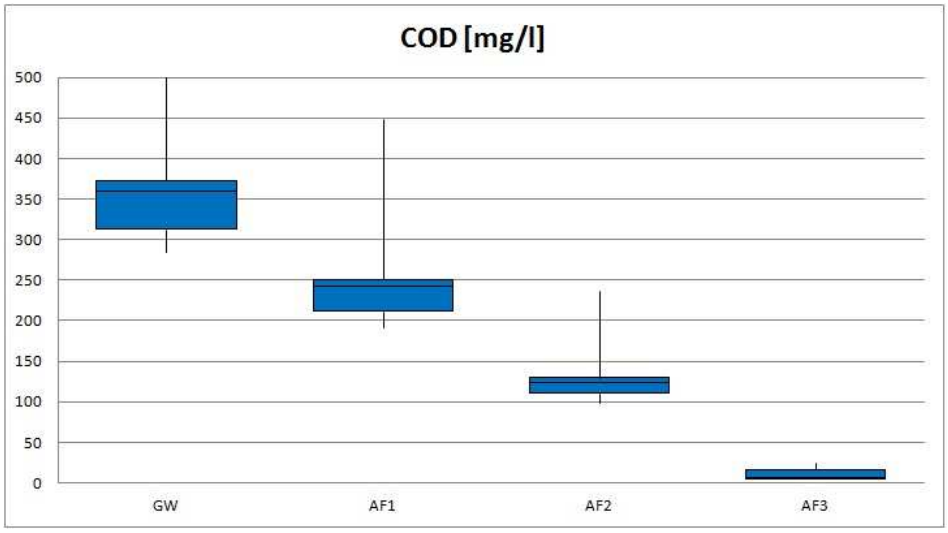


Figure 5-12: degradation of COD at test series 2

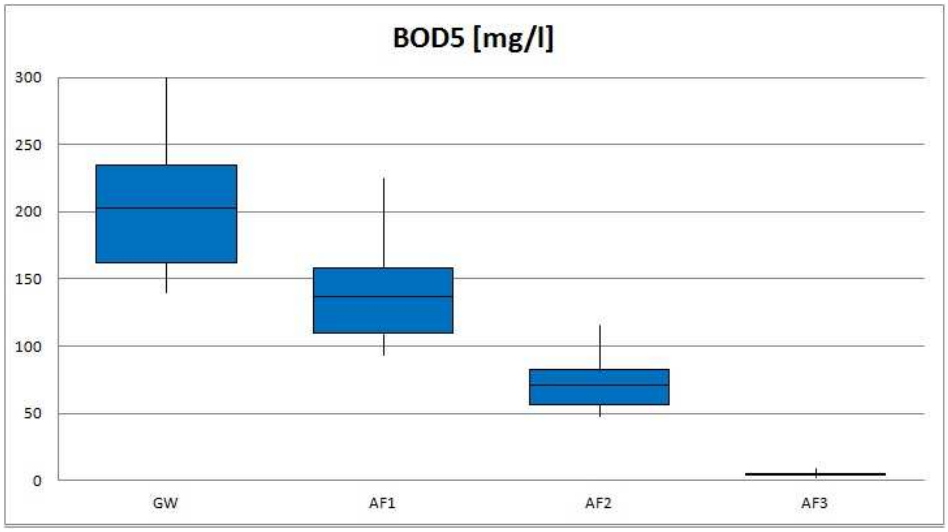


Figure 5-13: degradation of BOD_5 at test series 2

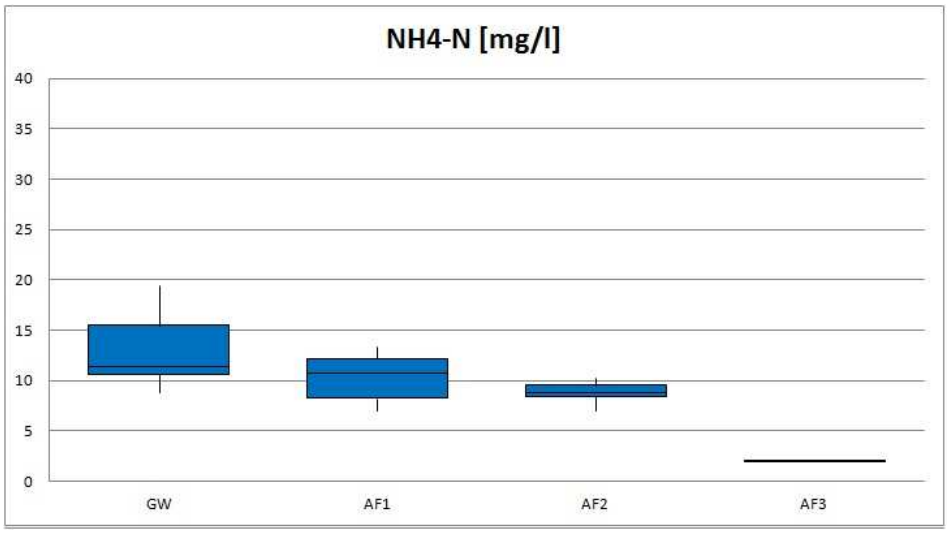


Figure 5-14: degradation of NH_4-N at test series 2

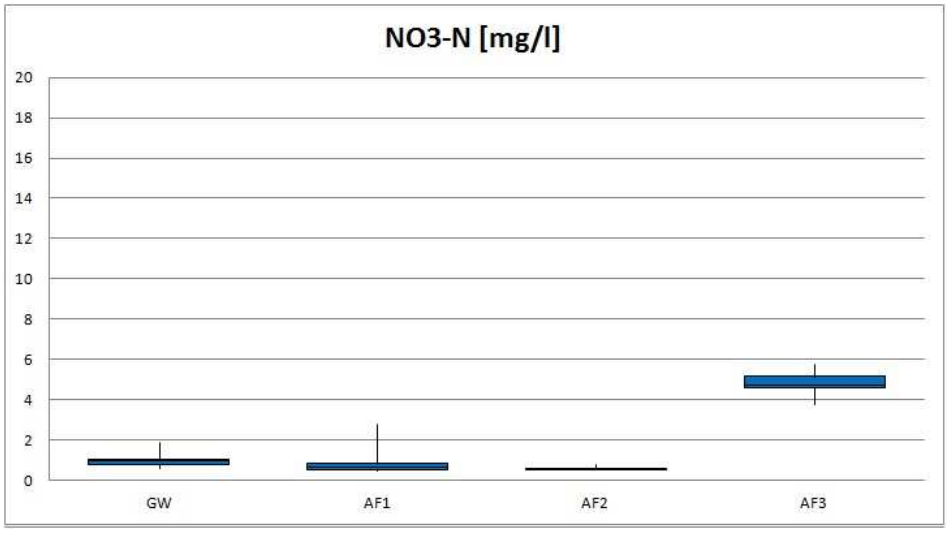


Figure 5-15: degradation of NO_3-N at test series 2

Table 5-7: treatment efficiency for test series 2

	TSS	COD	BOD_5	NH_4-N	NH_4-N + NO_3-N
Treatment efficiency [%]	91	97	98	85	51

As you can see in Table 5-7, the reduction of NH_4-N had no impact on the degradation of the carbon. The treatment efficiency and the end values continued to be very satisfactory and at a high quality.

The nitrification was very good. All readings for NH_4-N in the effluent were below the measurability limit of 2.0 mg/l. For the calculation of the degradation intensity of NH_4-N, 2.0 mg/l was taken as discharge value. With a more accurate measurement, this value could possibly be increased again.

It can be observed that nitrification mostly takes place in level 2 and 3 where most of the carbon is already degraded and the food source for the heterotrophic bacteria gets less. Therefore the conditions allow *Niterosoma* and *Niterobacter* to spread.

The requirements for a full denitrification are not in place as most of the ammonium gets transformed to Nitrate in level 3 where the BOD_5 is already below 5 mg/l and therefore no carbon source to perform a denitrification.

5.2.4 Test series 3

Test series 3 was carried out from 2nd November to 11th November 2016 and had seven days of measurements. The results of test series 3 are the result of turning of the aeration of level 2 and 3, and further the results can be seen in Table 5-8 and box plots of each parameter in Figures 5-16 to 5-20.

Table 5-8: Mean values test series 3

	TSS	COD	BOD_5	NH_4-N	NO_3-N
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
GW	88	358	199	14.4	0.7
EFL1	53	247	137	12.8	0.8
EFL2	18	137	75	12.0	0.8
EFL3	8	26	12	11.3	1.2

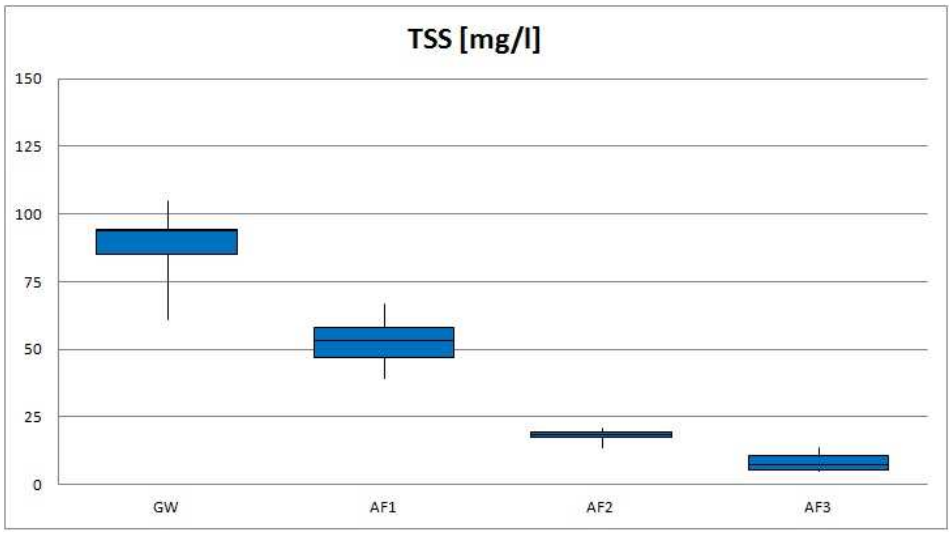


Figure 5-16: degradation of TSS at test series 3

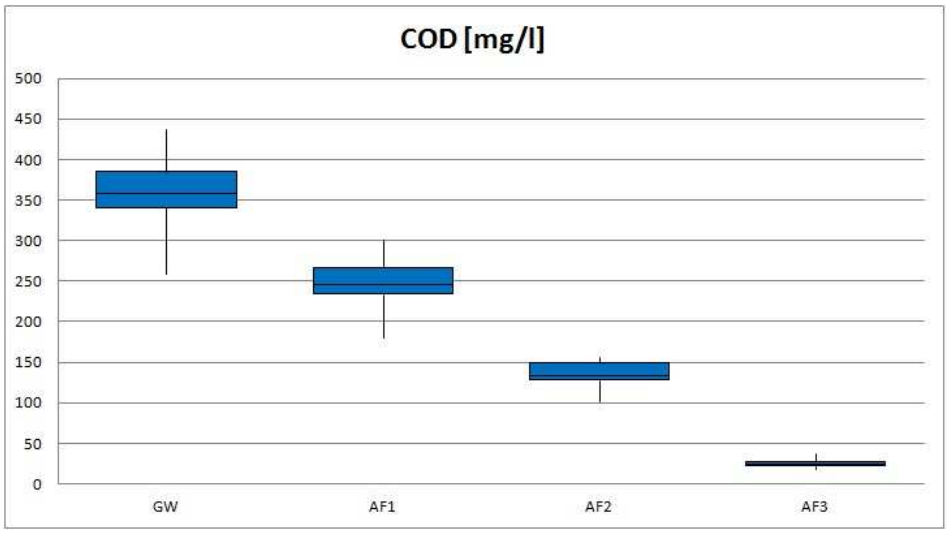


Figure 5-17: degradation of COD at test series 3

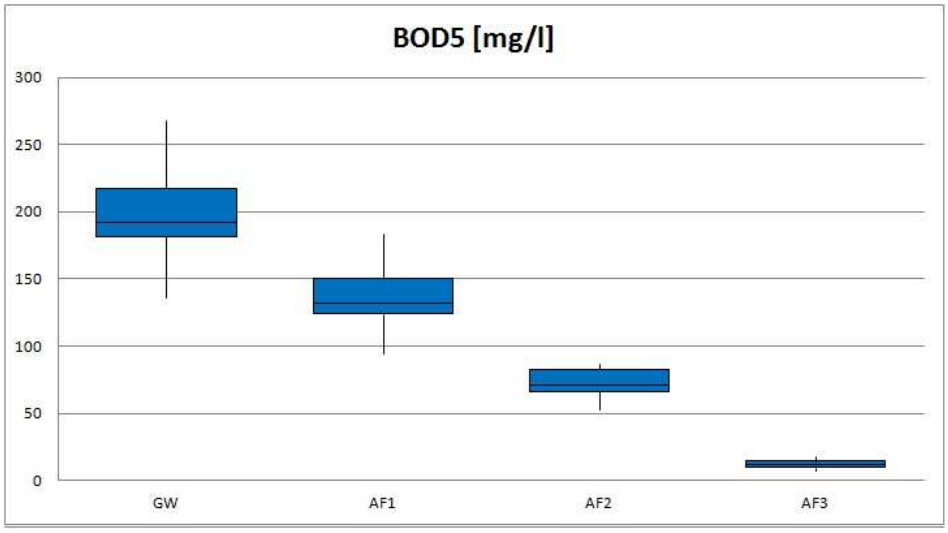


Figure 5-18: degradation of BOD_5 at test series 3

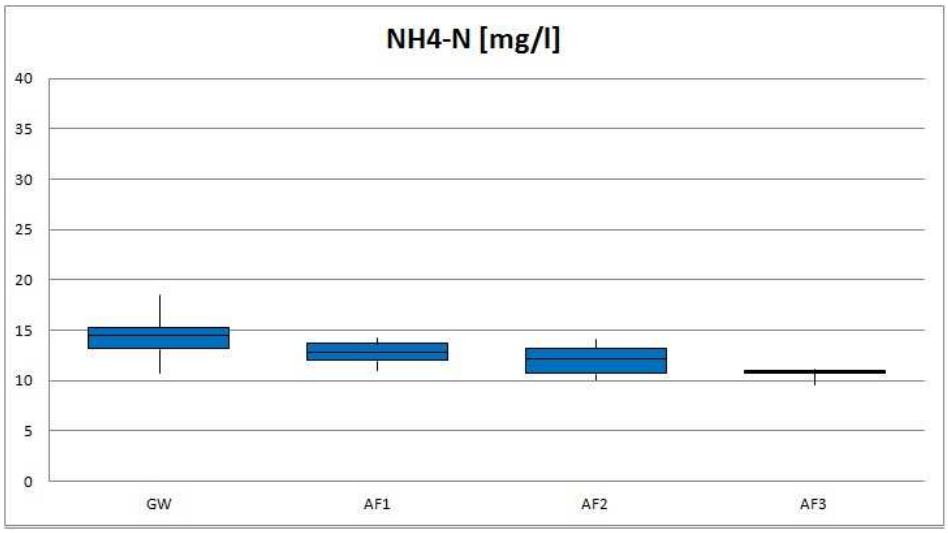


Figure 5-19: degradation of NH_4-N at test series 3

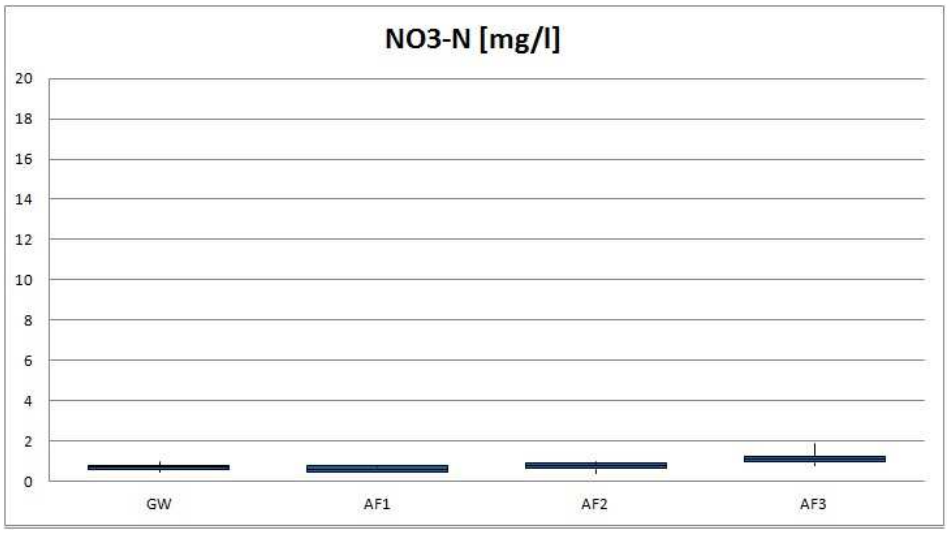


Figure 5-20: degradation of NO_3-N at test series 3

Table 5-9: treatment efficiency for test series 3

	TSS	COD	BOD_5	NH_4-N	NH_4-N + NO_3-N
Treatment efficiency [%]	91	93	94	22	17

The reduction of aeration in level 2 only had a low impact on the degradation of carbon based parameter. The values are a little bit higher than in the previous testing series, but the treatment efficiency is still above 90 %. Especially in level 3 the degradation is not as good as in previous test series. It is to be presumed that this is due to a lack of dissolved oxygen (Table 5-9).

The aeration intensity of test series 3 did not put enough oxygen in the system for the nitrification process. The major part of nitrification in previous test series took place in level 2 and level 3, where in this set-up not enough oxygen was left to perform nitrification. Without nitrification a denitrification process is not possible. This testing series was prematurely discontinued since no sufficient removal of the nitrogen parameters was achieved.

5.2.5 Test series 4

Test series 4 was carried out from 29th November 2016 to 9th December 2016 and seven days of measurements were performed. The results of test series 4 are the result of an intermittent aeration mode (15 min on / 15 min off) and can be seen in Table 5-10 and box plots of each parameter in Figures 5-21 to 5-25.

Table 5-10: Mean values test series 4

	TSS	COD	BOD_5	NH_4-N	NO_3-N
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
GW	78	313	155	19.8	0.9
EFL1	40	212	105	15.2	1.0
EFL2	15	111	56	13.8	1.4
EFL3	8	9	6	6.7	3.1

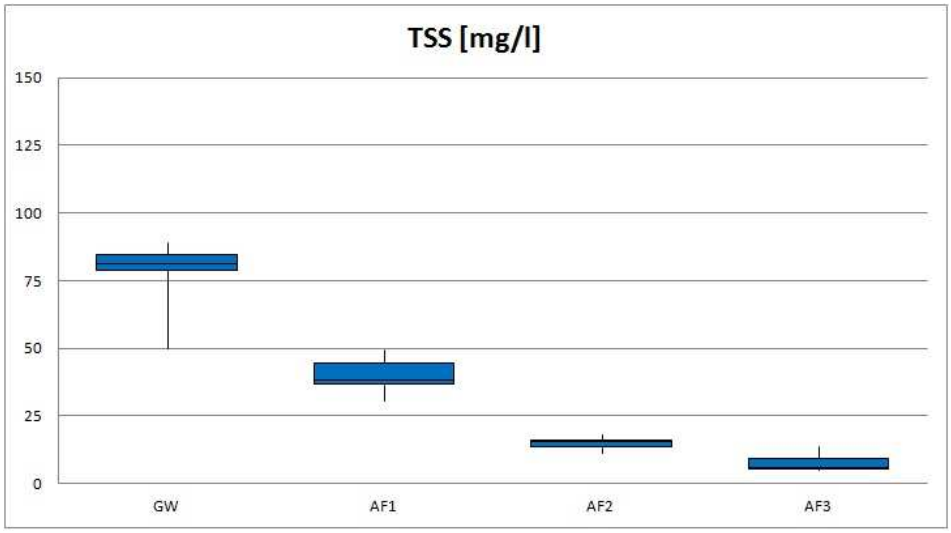


Figure 5-21: degradation of TSS at test series 4

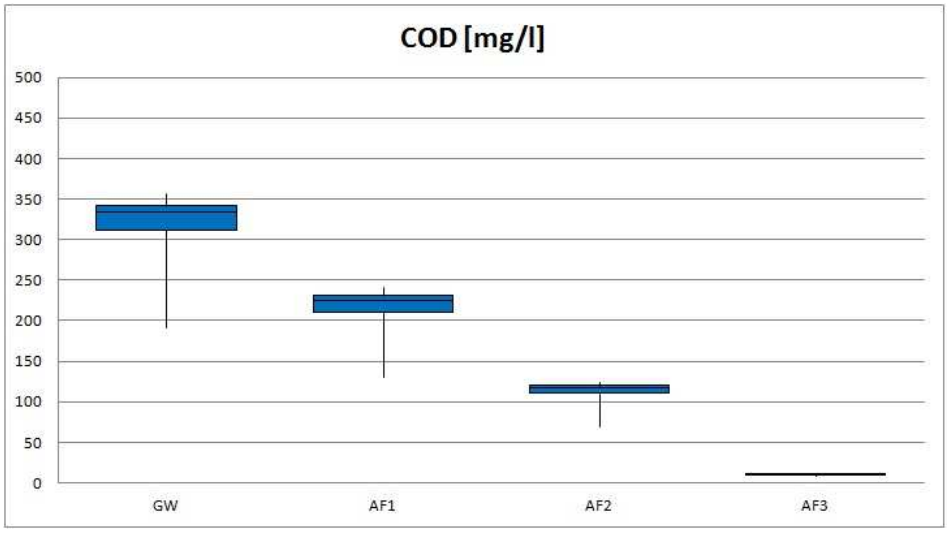


Figure 5-22: degradation of COD at test series 4

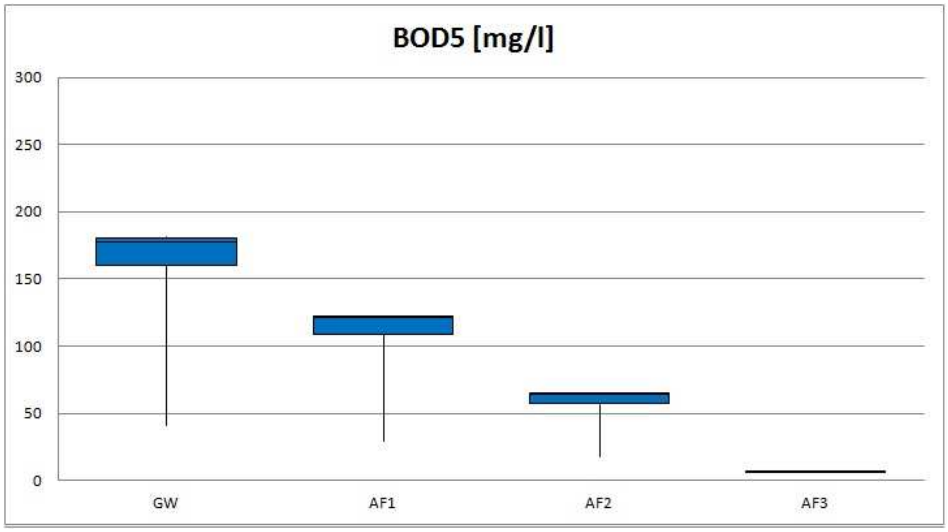


Figure 5-23: degradation of BOD_5 at test series 4

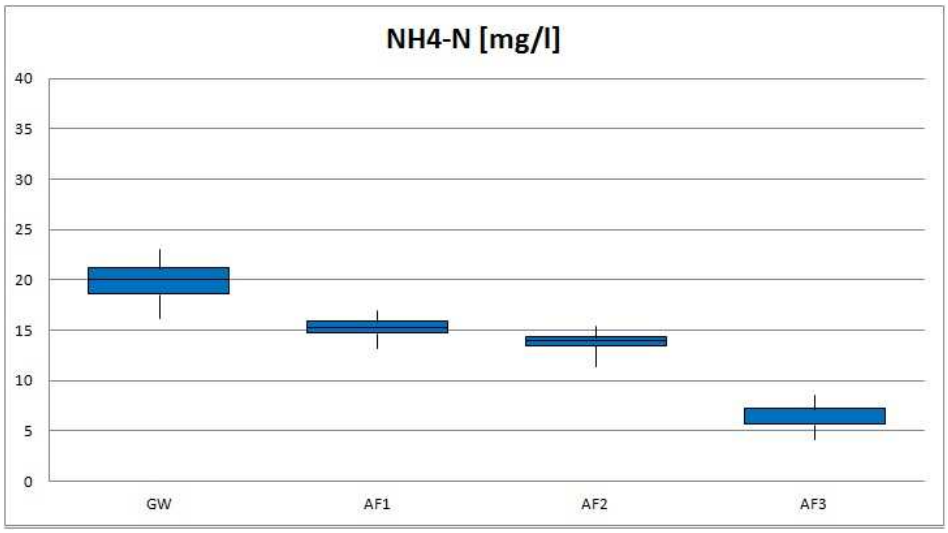


Figure 5-24: degradation of NH_4-N at test series 4

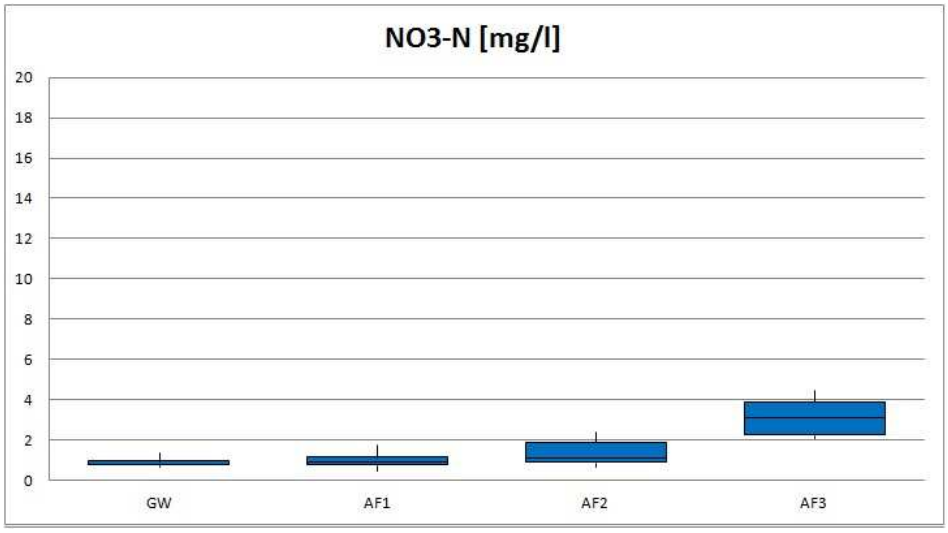


Figure 5-25: degradation of NO_3-N at test series 4

Table 5-11: treatment efficiency for test series 4

	TSS	COD	BOD_5	NH_4-N	NH_4-N + NO_3-N
Treatment efficiency [%]	90	97	96	66	53

In spite of the new intermittent aeration mode, the results for the carbon-based parameters were satisfying. As in the previous testing series the results were very good as the treatment efficiency was above 95 % and the discharge values for COD and BOD_5 below 5 mg/l (Table 5-11)

The results for the nitrification are not as good as previous test series. Compared to the other test series NH_4-N gets degraded worse in level 2 and level 3. The reason can be either a problem with the amount of oxygen or the temporal fluctuation of oxygen. If the reason is the small amount of oxygen can be identified in test series 6.

The aeration interval of this test series had the lowest results for NO_3-N. It is supposed that the reason therefore is the balanced split in times with aerobic conditions and anoxic conditions.

5.2.6 Test series 5

Test series 5 was carried out from 10th January to 27th January 2017 and in total ten days of measurements were performed. The results of test series 5 are the result of an intermittent aeration mode (30 min ON / 15 min OFF) and can be seen in Table 5-12 and box plots of each parameter in Figures 5-26 to 5-30.

Table 5-12: Mean values test series 5

	TSS	COD	BOD_5	NH_4-N	NO_3-N
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
GW	114	293	137	20.1	0.9
EFL1	49	203	99	14.9	0.6
EFL2	8	102	52	12.1	0.5
EFL3	2	5	4	3.2	7.1

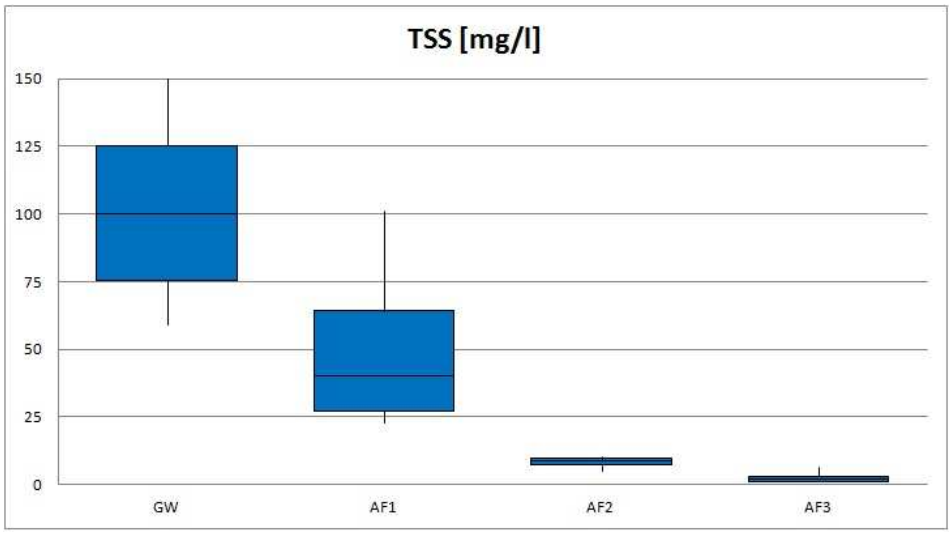


Figure 5-26: degradation of TSS at test series 5

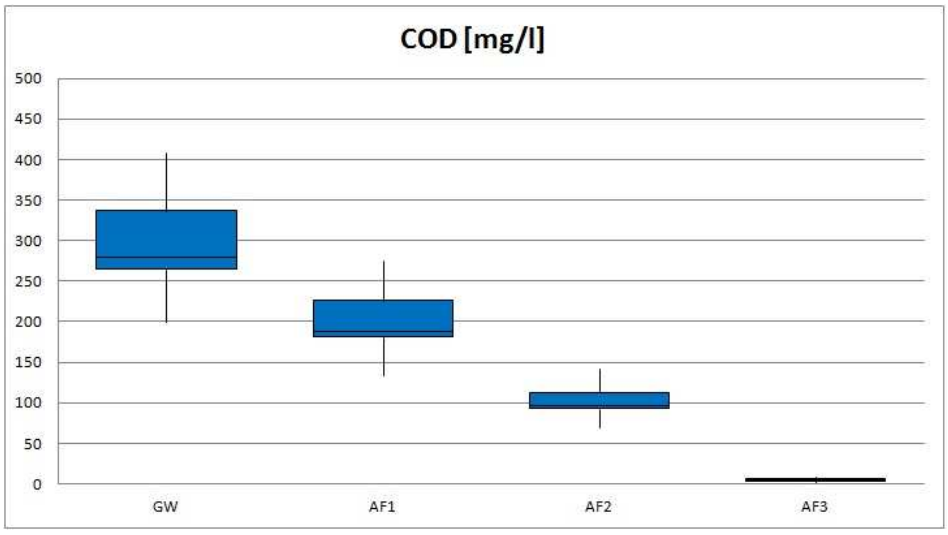


Figure 5-27: degradation of COD at test series 5

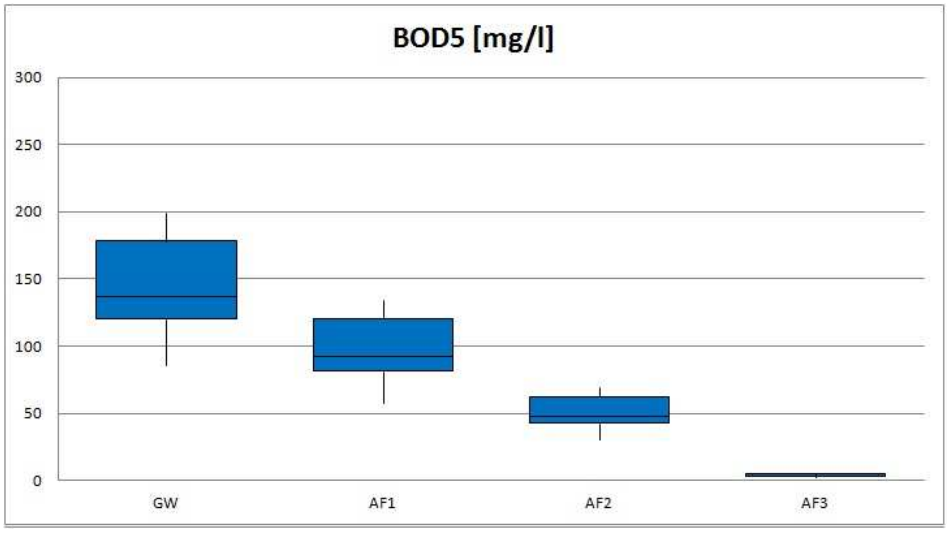


Figure 5-28: degradation of BOD_5 at test series 5

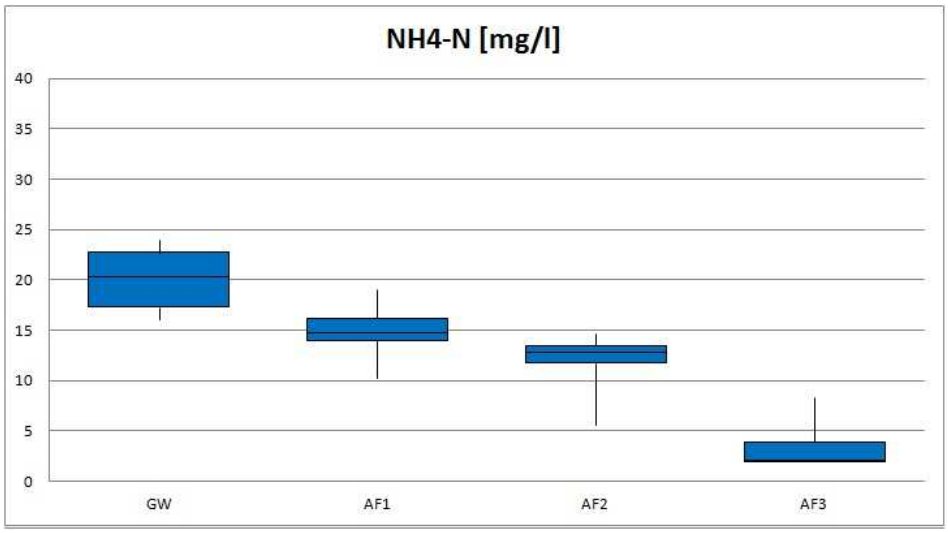


Figure 5-29: degradation of NH_4-N at test series 5

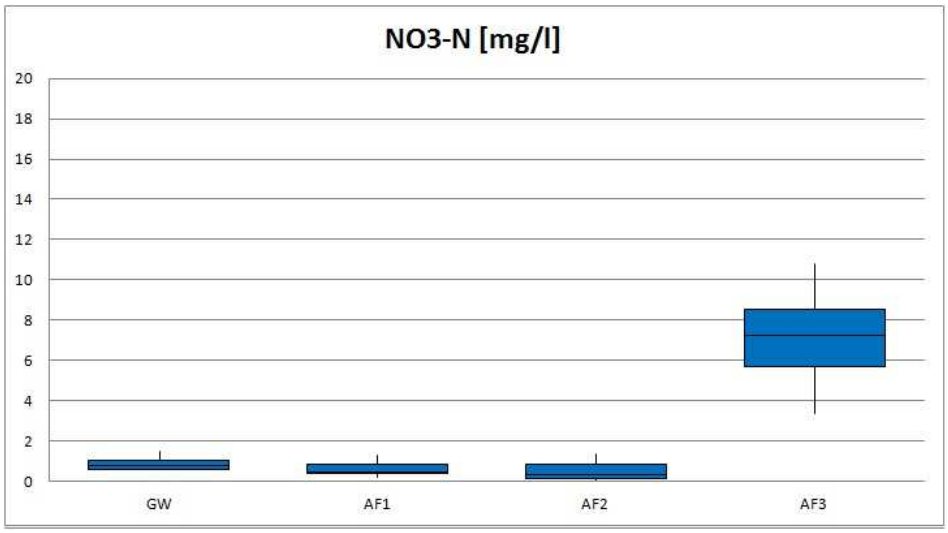


Figure 5-30: degradation of NO_3-N at test series 5

Table 5-13: treatment efficiency for test series 5

	TSS	COD	BOD_5	NH_4-N	NH_4-N + NO_3-N
Treatment efficiency [%]	98	98	97	84	51

The results for the carbon-based parameters were also in this test series very satisfying (Table 5-13). The increase in aeration time also increased the NH_4-N degradation process. The treatment efficiency is nearly 20 % higher than in test series 4 where the intermittent aeration had longer periods of no aeration.

Due to the increased aeration intensity the time of anoxic conditions is reduced and therefore the Denitrification is decreased.

5.2.7 Comparison of the test series

The measurement results show that the examined aeration intensity has nearly no effect on the degradation of TSS (Figure 5-31). The sedimentation takes place mostly in level 1 and level 2 which are aeration in all but one test series. Only in test series 3 one of those levels was not aerated, but the results of test series 3 showed no significant difference to the other test series.

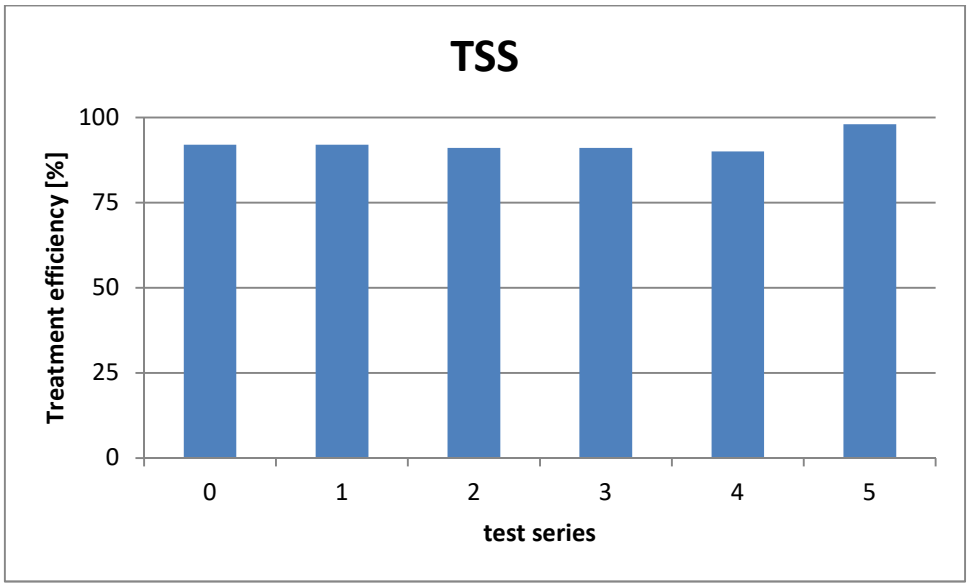


Figure 5-31: comparison of TSS degradation

When comparing the results of this wetland with treatment performances of other constructed wetlands found in the literature it can be said that the artificial aeration of a horizontal flow wetland has a positive effect on the degradation of COD (Figure 5-32) and BOD_5 (Figure 5-33). Treatment efficiencies of more than 90 % are only found within vertical flow wetlands. The aeration intensity needed for this effect is not high, as the effect already took place in test series 3 when only one level was aerated.

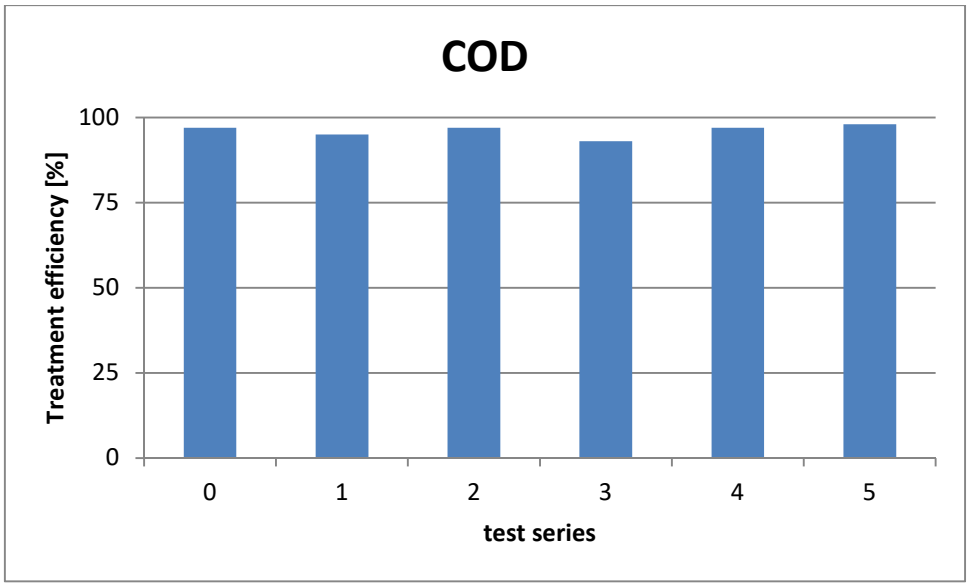


Figure 5-32: comparison of COD degradation

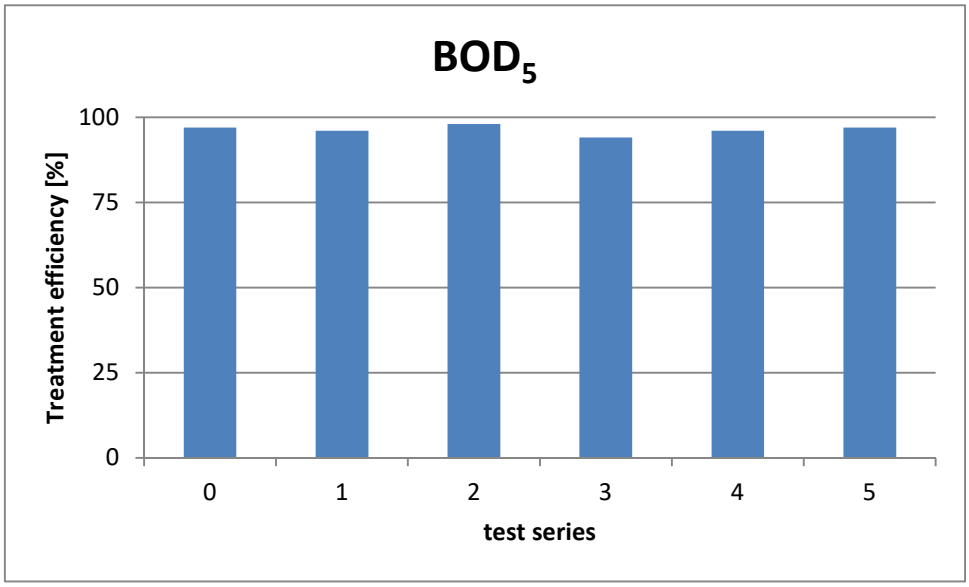


Figure 5-33: comparison of BOD_5 degradation

The most obvious effects the aeration had on a horizontal flow wetland were on the degradation of nitrogen (Figure 5-34). It was observed that the more oxygen was available the faster NH_4-N was degraded to NO_3-N. When enough oxygen was present NH_4-N was degraded below the limit of detection of 2.0 mg/l. All test series had a removal ratio concerning ammonium nitrogen of more than 80 %. That removal ratio is a much higher than the 20 - 30 % which horizontal flow wetlands typically have. Removal ratios of this size can usually only be reached by vertical flow wetlands.

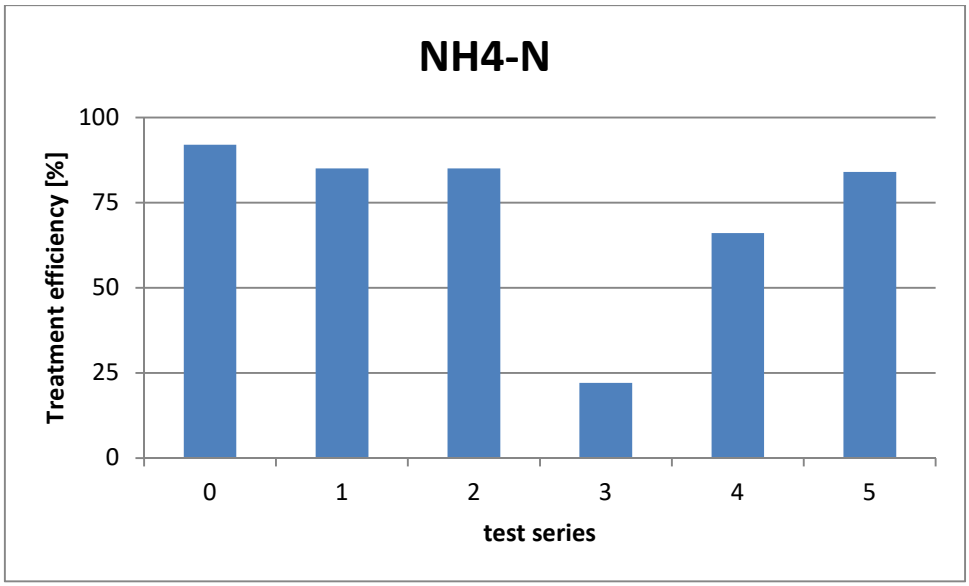


Figure 5-34: comparison of NH_4-N degradation

The exact level of denitrification cannot be determined with these measurement results because only the parameter NH_4-N and NO_3-N were measured. Nevertheless it turned out that the aeration mode had little to no effect on the NH_4-N + NO_3-N degradation (Figure 5-35). It can be noted that a proper nitrification is key to a good degradation of Nitrate. The reason why test series 0 has a better treatment efficiency of NH_4-N + NO_3-N is that a higher ammonium input was treated.

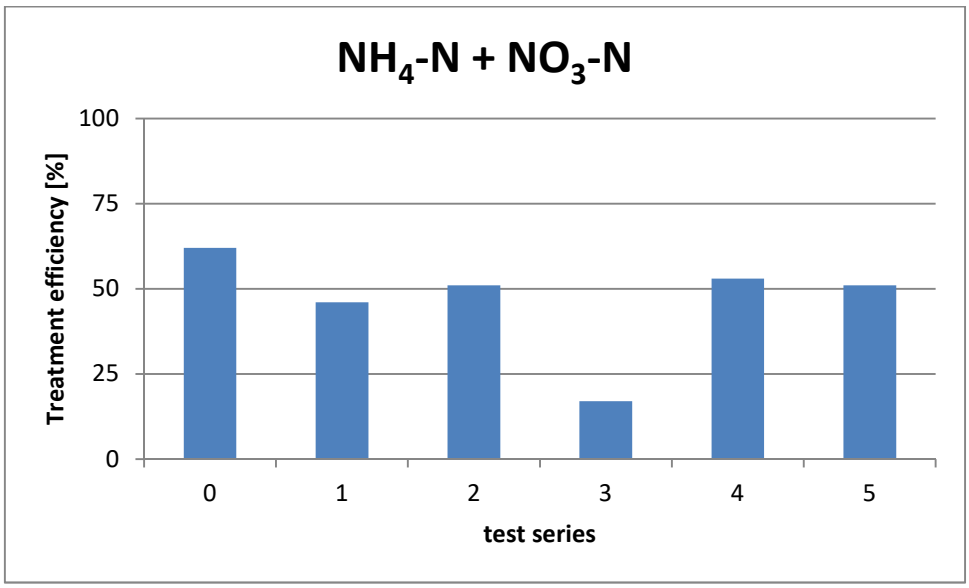


Figure 5-35: comparison of NH_4-N + NO_3-N degradation

It can further be said that those test series with enough periods without aeration had a lower NO_3-N concentration in the outflow than test series with a permanent aeration (Figure 5-36).

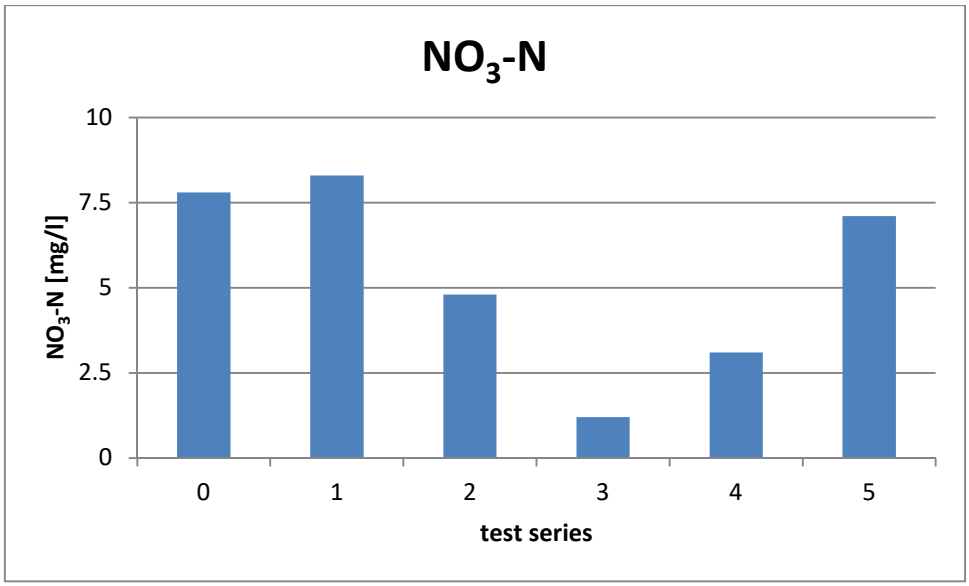


Figure 5-36: comparison of NO_3-N values in EFL3

6. Conclusion and outlook

The first objective of this master thesis aimed at introducing ammonia into the artificial greywater. Two Chemicals have been tested to add nitrogen artificially. Ammonium chloride was used to extend the greywater composition as it had good results for both the dilution test and the behaviour in situ at the experiment setting. For the measurements of the nitrogen parameter a Hach-Lange photometer was used. This photometer was easy to handle and the results were conform to the results from the BOKU laboratory. It can be concluded that ammonium chloride provides a reliable source of ammonium nitrogen.

The main aim of this thesis was to identify how much of the artificial aeration in the vertECO constructed wetland system could be reduced and still get satisfying treatment performances. A UV-VIS spectrometer probe of the Viennese company *s::can* was used to measure the treatment capacity of the carbon based parameter. The global calibration of the spectrometer was adapted to conditions of this application area by DI Alexander Hack in an earlier master thesis (Hack, 2016). The starting conditions were full aeration of all levels. Under these conditions the wetland degrades 92 % of TSS, 97 % of COD and BOD_5 were degraded and 92 % of ammonium was degraded to Nitrate. Compared to horizontal flow wetlands without aeration these treatment efficiencies are very high. The change of the aeration intensity had little to none effect on the degradation of carbon based parameter. Even a reduction of 66 % had no big impact. In contrast the transformation from NH_4-N to NO_3-N is heavily dependent on the intensity of aeration. If the operation mode is intermittent or steady has little effect on the nitrification. The attempts to establish conditions, in which denitrification is possible and Nitrogen get gasified, did not work out. The testing series with an intermitted aeration made showed the biggest potential for denitrification. Future work should focus on the degradation of NO_3-N as total nitrogen and Nitrates are parameters which define the allowed reuse categories. Also the pollution of greywater with pathogens and their removal was not part of this thesis. Prior to reusing the treated greywater and possible contact with human further testing concerning this matter is necessary.

During comparison specimen at the laboratory of the BOKU it has been noticed these calibrations only provide validated results for two out of four measuring points. The two points were Inflow and Outflow which allowed us to use the measuring results to calculate the treatment performance with satisfactory accuracy. Due to a lack of more measuring points, it is not possible to make further statements about the degradation process within the constructed wetland. Also due to the lack of further results within the wetland it is not possible to assign a reason for the failed denitrification. A global calibration of the spectro::lyser for the use within greywater that is able to produce reliable data for all sampling points should be considered for the future until then it should be noted that this spectro::meter is not suitable for single shot measurements within laboratory conditions.

7. Summary

The aim of this master thesis was the analysis and optimisation of an existing constructed wetland treating greywater of a hotel complex. The recycled water will be reused for toilet flush, irrigation or laundry and thereby reduces the need for freshwater.

To avoid any potential odour nuisance, the constructed wetland is artificially aerated. The aeration improves the degradation process treating the greywater. Within this thesis it should be identified how much the aeration can be reduced and still get satisfying cleaning results.

The necessary research was carried out in an experimental plant in the laboratory of alchemia-nova in Vienna. The treatment efficiency was evaluated on the basis of the parameter TSS, COD, BOD_5, NH_4-N and NO_3-N. It was monitored which effects a reduction of aeration intensity had on these parameters.

The constructed wetland consists of three evenly sized levels whereat at the end of each level measurements were taken. The reduction of aeration was carried out by either turning off the aeration for a whole level or reducing the aeration time for the whole wetland. Between the different test series were breaks of two weeks so the bacteria in the wetland can adjust to the new oxygen availability. After the status quo was determined five test series were carried out, which were tested for at least two weeks. The results of these test series are presented in the following Table 7-1 where the aeration intensity is opposed to the treatment efficiency.

Table 7-1: Removal ratios (in %):

Aeration [l O_2/min]	**Treatment efficiency [%]**		
	COD	BOD_5	NH_4-N
12	97	97	92
8	95	96	85
4	93	94	22
6 (intermittent)	97	96	66
8 (intermittent)	98	97	84

The artificial aeration of a horizontal flow wetland increases the treatment efficiency of both carbon based and nitrogen based parameters. COD and BOD_5 degradation is slightly increased compared to unaerated horizontal flow wetlands while the treatment of ammonium nitrogen is as effective as in a vertical flow wetland.

In the course of this thesis an increase of denitrification was attempted, but no satisfying results were achieved. It was not possible to create the required conditions within this experimental setup.

8. References

Alkhatub, r., Roesner, L., Marjoram, C., 2006: An overview of graywater collection and treatment systems. World Environmental and Water Resource Congress 2006.

Al-Jayyousi, O. R., 2003: greywater reuse: towards sustainable water management. Desalination 156 181-192

Atanasova, N., Dalmau, M., Comas, J., Poch, M., Rodriguez-Roda, I., Buttiglieri G., 2017: Optimized MBR for greywater reuse systems in hotel facilities. Journal of Environmental Management 193 503 - 511

Branco, S.M. (1976). Biologia da polui¸c˜ao. In: CETESB (1976). Ecologia aplicada eprote¸c˜ao do meio ambiente. S˜ao Paulo (in Portuguese)

Chung K., White M., (2009) Greywater Reuse: Understanding Greywater Reuse Systems in the Current and Future Urban Contexts and How Individuals can Promote Greywater Reuse.,

https://courses.cit.cornell.edu/crp384/2009reports/White&Chung_Gray%20Water%20Reuse.pdf (date of visit: 07. January 2019).

demEAUmed (2017): demEAUmed policy brief, http://www.demeaumed.eu/index.php/diss/publications/send/30-pubdev/371-demeaumed-policy-brief (date of visit: 16. March 2019).

Dotro, G., Langergraber, G., Molle, P., Nivala, J., Puigagut, J., Stein, O., Von Sperling, M. (2017) Treatment Wetlands. *Biological Wastewater Treatment Series (Volume 7*), IWA Publishing, London, UK; doi: 10.2166/9781780408774.

Ertl T. (2008): 811.108 - VU Siedlungswasserbau und Gewässerschutz, Teil B: Abwasserentsorgung

European Commission (2018): Wate reuse. http://ec.europa.eu/environment/water/reuse.htm (Date of visit: 30.March 2019).

European Environment Agency (2016): Tourism. https://www.eea.europa.eu/soer-2015/europe/tourism (Date of visit: 16. March 2019).

European Environment Agency (2018): Use of freshwater resources. https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-3 (Date of visit: 16. March 2019).

Ghaitidak D.M., Yadav K. D., 2013: Characteristics and treatment of greywater – a review. Environ Sci Pllut Res 20:2795-2809

Gottwald W., Heinrich K.H. (1998): UV/VIS –Spektroskopie für Anwender, Weinheim, WILEY-VCH Verlag GmbH. ISBN: 3-527-28760-4 [*in German*]

Gross A., Wiel-Shafran A., Bondarenko N., Ronen Z., 2008: Reliability of small scale greywater treatment systems and the impact of its effluent on soil properties. International Journal of Environmental Studies, 65:1, 41-50

Hack, A.P. (2016): Modelling of an indoor constructed wetland. Master thesis, Institute of Sanitary Engineering and Water Pollution Control, Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences, Vienna.

Hawaii State Department of Health (2009): Guidlines for the reuse of gray water. http://health.hawaii.gov/wastewater/files/2013/06/graywater_guidelines.pdf (date of visit: 04 January 2019)

Hofmann H., Platzer C., Winker M., von Muench E., 2011: Technology review of constructed wetlands. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Eschborn, Germany.

Kadlec R.H., Wallace S. D., 2009: *Treatment Wetlands* (Second Edition). CRC Press, Boca Raton, USA. ISBN: 978-1-56670-526-4

Langergraber G. (2016): 811.362 – On Site Solutions for Water Supply and Sanitation. Lecture notes, Winter term 2015/2016, Institute of Sanitary Engineering and Water Pollution Control, BOKU University Vienna, Austria

Morel A., Diener S., 2006: Greywater management in low and middle income-countries, Review of different treatment systems for households or neihbourhoods. Eawag, Dübendorf, Switzerland. ISBN: 3-906484-37-8

Noah M., 2002: Greywater use still a gray area. J Environ Health, 64(10):22-25

Oldenburg M. (2008): Kennzahlen zur Zusammensetzung von Teilströmen neuartiger Sanitärsysteme. KA – Korrespondez Abwasser, Abfall, 55(10), pp.1113-1119.

Oh, K.S., Leong, J.Y.C., Poh, P.E., Chong, M.N., Lau, E.V.: A review of greywater related issues: Challenges and future prospects in Malaysia. Journal of Cleaner Production 171 (2018) 17-29

Perkampus H.-H. (1992): UV-VIS Spectroscopy and Its Applications. Springer-Verlag, Berlin. ISBN: 0-387-55421-1

Prathapar S.A., Jamrah A., Ahmed M., Al adawi S., Al Sidairi S., Al Harassi A., 2005: Overcoming constraints in treated greywater reuse in Oman. Desalination 186(1-3) 177-186

Prillwitz M., Farwell L., (1995): Graywater guide,

http://www.water.ca.gov/wateruseefficiency/docs/graywater_guide_book.pdf (date of visit: 12 December 2018).

Tilley, E. et al, 2008: Compendium of Sanitation Systems and Technologies. Swiss Federal Institute of Aquatic Science and Technology (Eawag). Dübendorf, Switzerland. ISBN: 978-3-906484-44-0

von Sperling M., 2007: Wastewater Characteristics, Treatment and Disposal. *Biological Wastewater Treatment Series (Volume 1*), IWA Publishing, London, UK, ISBN: 1843391619

Vymazal, J., Kröpfelová, L., 2015: Multistage hybrid constructed wetland for enhanced removal of nitrogen. Ecological Engineering 84 202 – 208.

9. Appendix

9.1 Measurements test series 0

Table 9-1: measured values test series 0 without outliner:

EFL3

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
14.07.2016	5	5	8	9	4	4	-	2.0
15.07.2016	10	18	9	12	4	4	-	2.0
19.07.2016	6	9	8	10	4	4	-	2.0
20.07.2016	13	9	12	11	4	4	4.8	2.0
21.07.2016	5	5	8	8	3	3	7.6	2.4
22.07.2016	6	6	9	9	5	5	10.1	2.0
26.07.2016	5	5	7	7	3	4	8.8	2.0
27.07.2016	5	5	9	8	4	4	0.0	2.0
28.07.2016	-	-	-	-	-	-	1.5	-

EFL2

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
14.07.2016	13	13	99	98	52	52	-	16.2
15.07.2016	10	12	110	111	54	54	-	15.0
19.07.2016	10	11	90	91	44	44	-	14.0
20.07.2016	11	11	100	97	46	45	0.5	14.7
21.07.2016	14	12	90	89	45	45	0.9	17.0
22.07.2016	16	16	91	90	48	47	0.7	21.6
26.07.2016	12	12	93	93	49	50	0.7	19.5
27.07.2016	10	9	95	95	53	53	7.9	20.0
28.07.2016	14	14	98	95	48	48	0.3	21.1

EFL1

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
14.07.2016	59	57	189	186	101	99	-	19.7
15.07.2016	71	73	212	210	104	104	-	20.0
19.07.2016	65	60	173	172	85	83	-	19.0
20.07.2016	64	57	188	184	87	87	6.9	23.4
21.07.2016	64	74	173	170	88	87	1.8	21.6
22.07.2016	58	57	173	172	90	90	0.5	27.0
26.07.2016	65	72	179	180	96	96	1.2	25.0
27.07.2016	54	54	180	181	101	102	0.5	27.0
28.07.2016	55	56	176	172	89	88	1.2	23.7

GW

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
14.07.2016	77	73	280	275	149	147	-	21.1
15.07.2016	129	123	313	309	154	154	-	18.0
19.07.2016	85	83	255	253	125	123	-	24.0
20.07.2016	85	77	276	270	129	128	0.9	27.5
21.07.2016	90	86	255	251	130	129	0.8	24.0
22.07.2016	71	68	255	253	133	132	1.4	30.8
26.07.2016	87	88	265	266	142	142	0.8	29.0
27.07.2016	58	59	266	268	149	151	0.9	32.0
28.07.2016	93	89	254	250	129	129	0.7	22.6

Figure 9-1: box plot of effluent 3 of test series 0

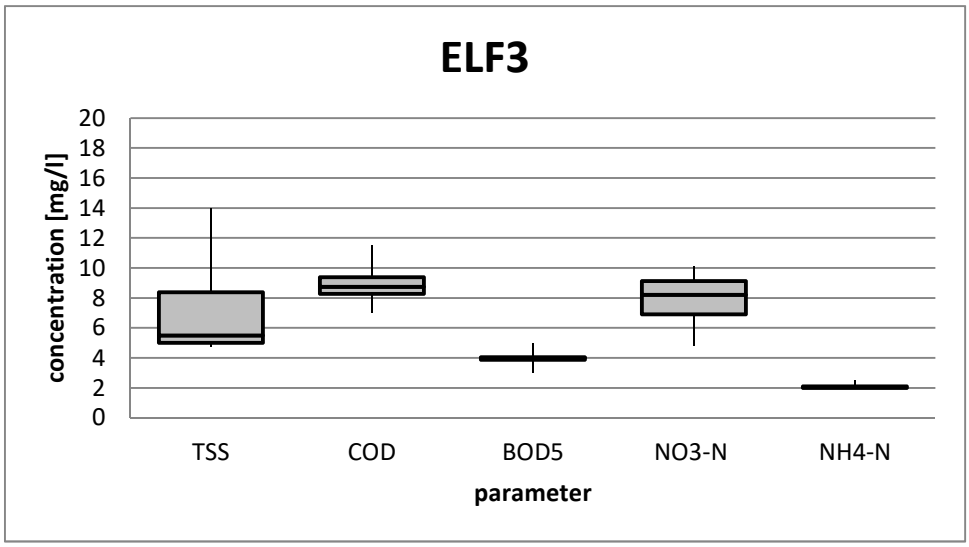


Figure 9-2: box plot of effluent 2 of test series 0

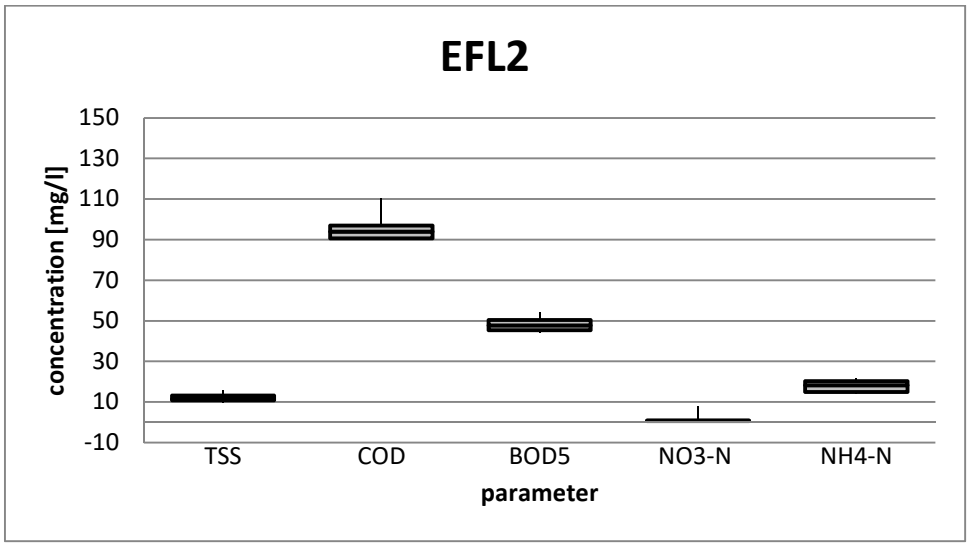


Figure 9-3: box plot of effluent 1 of test series 0

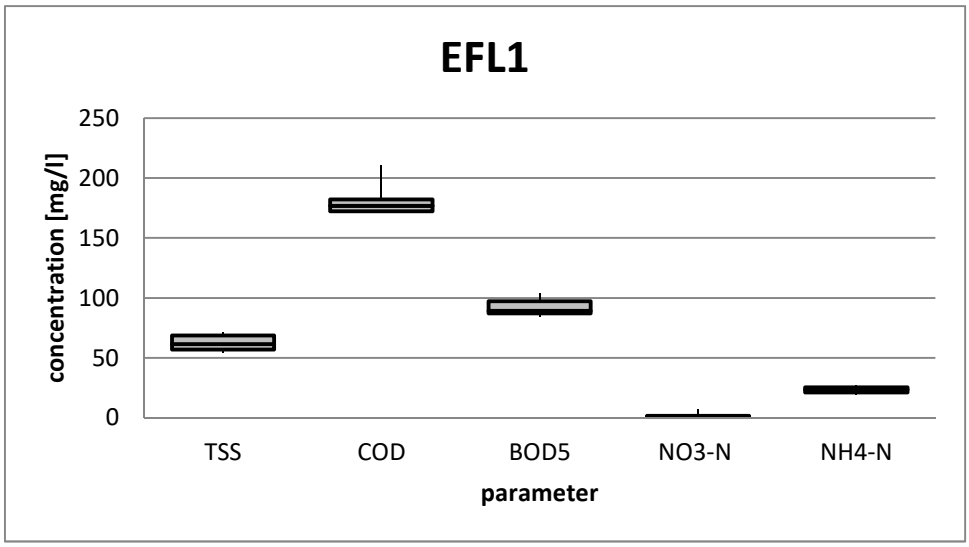
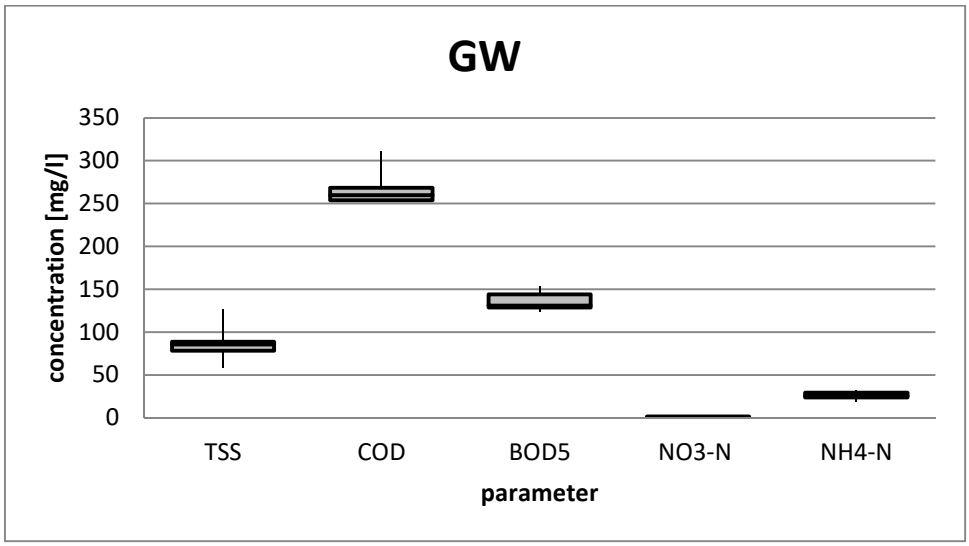


Figure 9-4: box plot of greywater of test series 0



9.2 Measurements test series 1

Table 9-2: measured values test series 1 without outliner:

EFL3

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
16.08.2016	6	6	12	12	6	6	6.2	4.7
17.08.2016	10	18	16	18	6	6	12.6	3.0
18.08.2016	6	9	22	16	7	7	8.4	2.2
19.08.2016	13	9	11	10	5	5	9.6	2.0
23.08.2016	5	5	11	10	5	4	6.7	2.0
25.08.2016	6	6	13	12	6	6	9.2	-
26.08.2016	5	5	13	16	6	7	7.6	-
30.08.2016	5	5	11	11	5	5	10.0	2.0
31.08.2016	19	8	16	15	7	7	7.5	2.9
01.09.2016	19	8	16	16	6	6	5.3	6.6
02.09.2016	19	8	14	14	5	6	8.4	2.0

EFL2

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
16.08.2016	15	15	90	89	46	46	0.5	22.7
17.08.2016	22	21	100	99	46	46	0.8	19.7
18.08.2016	22	19	94	86	45	44	0.5	18.6
19.08.2016	17	16	90	89	42	42	0.6	18.8
23.08.2016	15	16	109	108	60	59	0.9	19.8
25.08.2016	16	19	107	105	54	55	0.4	-
26.08.2016	32	29	116	118	52	53	0.7	-
30.08.2016	16	16	102	98	50	49	0.4	19.0
31.08.2016	28	26	127	125	64	64	0.9	22.0
01.09.2016	21	21	106	104	52	51	0.9	19.0
02.09.2016	28	26	123	122	62	62	0.5	18.0

EFL1

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
16.08.2016	32	31	167	166	87	87	0.8	23.3
17.08.2016	83	70	183	180	87	86	0.9	23.2
18.08.2016	93	84	166	156	82	80	0.7	20.4
19.08.2016	80	71	168	169	80	80	1.8	21.4
23.08.2016	79	78	207	205	116	115	1.5	29.2
25.08.2016	87	58	200	197	103	103	0.9	30.3
26.08.2016	93	89	218	220	97	98	0.9	29.4
30.08.2016	80	74	193	185	94	93	1.1	20.7
31.08.2016	91	85	239	234	121	120	1.7	22.7
01.09.2016	81	81	197	191	98	97	0.6	19.7
02.09.2016	76	85	233	231	118	119	0.8	20.6

GW

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
16.08.2016	60	57	245	243	127	127	1.2	24.3
17.08.2016	91	86	267	261	127	126	0.6	24.0
18.08.2016	83	79	238	226	120	117	0.8	20.7
19.08.2016	88	89	247	248	117	117	0.4	23.5
23.08.2016	111	105	305	303	171	170	1.3	38.2
25.08.2016	115	106	294	290	151	152	1.3	29.9
26.08.2016	202	196	321	322	143	144	0.0	13.1
30.08.2016	117	97	284	272	139	137	1.3	22.7
31.08.2016	129	116	350	344	178	177	0.9	24.0
01.09.2016	114	102	287	279	144	142	0.8	20.2
02.09.2016	121	118	342	339	175	175	1.2	23.3

Figure 9-5: box plot of effluent 3 of test series 1

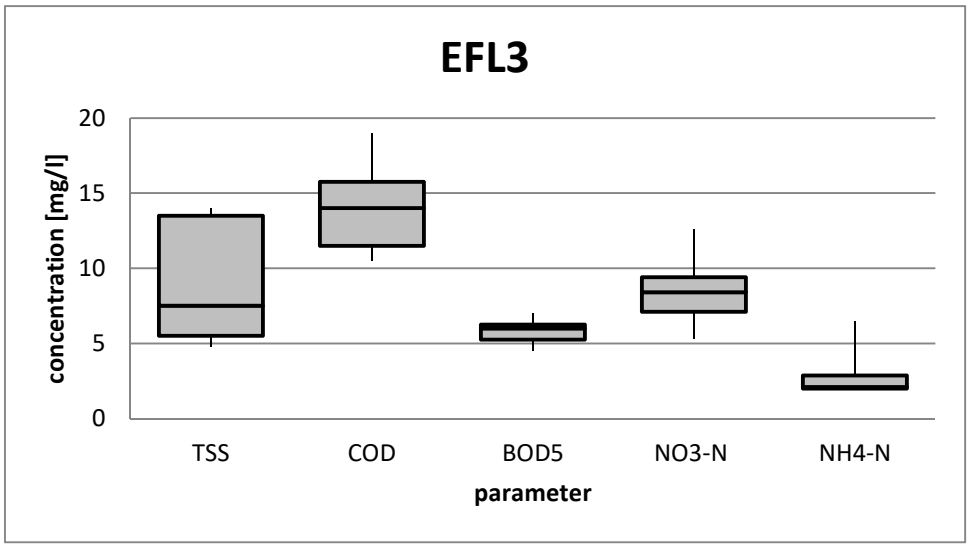


Figure 9-6: box plot of effluent 2 of test series 1

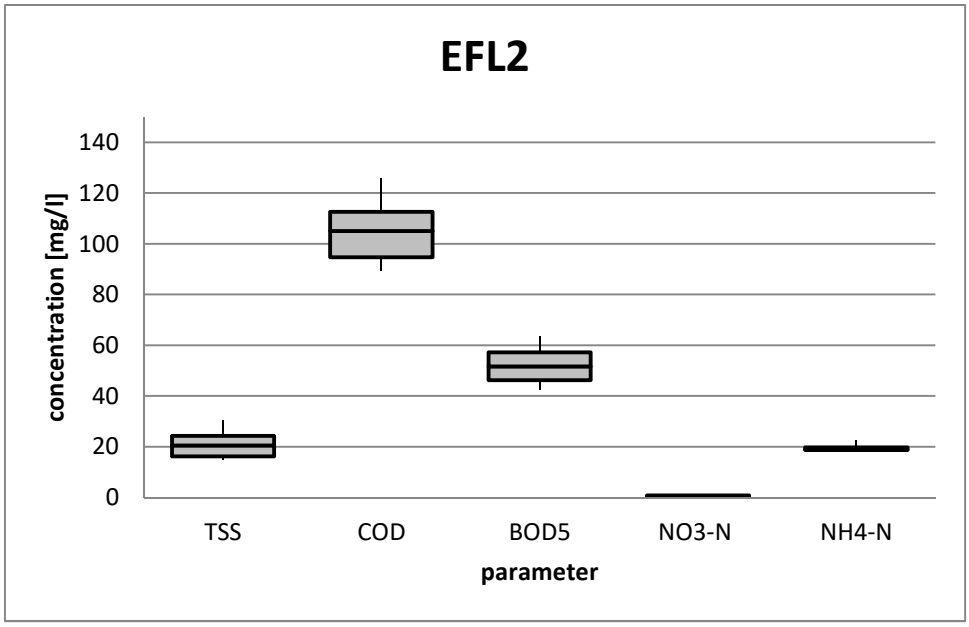


Figure 9-7: box plot of effluent 1 of test series 1

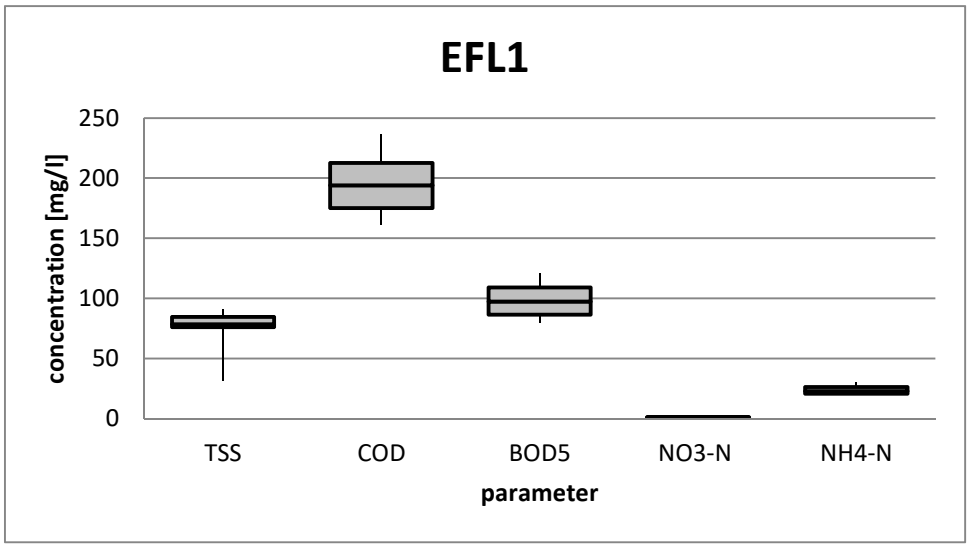
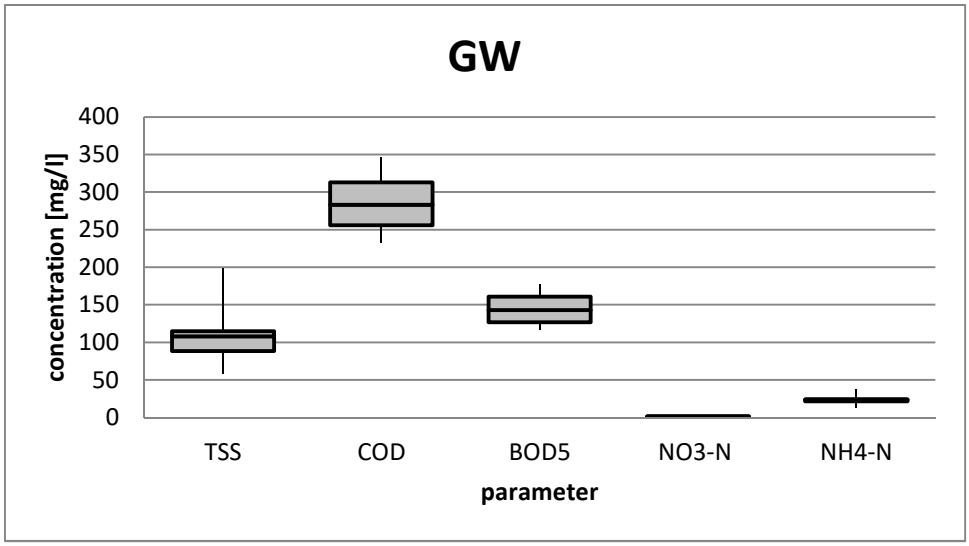


Figure 9-8: box plot of greywater of test series 1



9.3 Measurements test series 2

Table 9-3: measured values test series 2 without outliner:

EFL3

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
20.09.2016	29	28	16	16	4	4	4.8	2.0
21.09.2016	10	18	25	24	6	6	5.2	2.0
27.09.2016	6	9	-	-	-	-	4.7	2.0
28.09.2016	13	9	7	7	2	2	4.6	2.0
29.09.2016	5	5	-	-	-	-	5.8	2.0
05.10.2016	6	6	5	6	4	4	5.3	2.0
11.10.2016	5	5	5	6	4	4	4.1	2.0
12.10.2016	5	5	18	18	9	10	5.0	2.0
13.10.2016	19	8	5	6	4	5	3.8	2.0
14.10.2016	19	8	5	5	5	4	4.6	2.0

EFL2

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
20.09.2016	36	34	113	109	51	50	0.8	8.2
21.09.2016	42	39	239	234	116	115	0.6	7.1
27.09.2016	-	-	-	-	-	-	0.6	10.3
28.09.2016	19	19	99	99	48	48	0.6	9.4
29.09.2016	-	-	-	-	-	-	0.6	8.5
05.10.2016	17	17	109	110	59	59	0.5	13.0
11.10.2016	10	11	126	127	80	81	0.5	4.6
12.10.2016	21	21	137	136	88	87	0.5	9.1
13.10.2016	14	15	119	123	70	72	0.5	8.5
14.10.2016	14	14	128	127	71	70	0.7	9.8

EFL1

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
20.09.2016	108	104	209	202	98	97	0.6	8.2
21.09.2016	111	108	453	444	227	224	0.5	7.9
27.09.2016	-	-	-	-	-	-	0.5	12.3
28.09.2016	66	67	192	192	94	94	0.9	10.4
29.09.2016	-	-	-	-	-	-	1.3	8.4
05.10.2016	55	99	213	213	114	114	2.8	12.4
11.10.2016	47	44	246	249	156	157	0.6	7.1
12.10.2016	84	83	256	254	166	165	0.7	12.0
13.10.2016	42	42	234	239	135	138	0.7	11.1
14.10.2016	58	58	251	249	137	135	0.5	13.4

GW

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
20.09.2016	167	148	306	296	145	144	1.0	11.8
21.09.2016	301	285	667	654	337	333	1.0	10.7
27.09.2016	-	-	-	-	-	-	1.9	9.9
28.09.2016	78	75	285	284	139	140	0.8	8.9
29.09.2016	-	-	-	-	-	-	1.4	11.0
05.10.2016	80	81	317	317	168	168	0.6	10.6
11.10.2016	85	88	366	370	231	233	1.0	19.4
12.10.2016	89	91	375	372	244	242	0.9	17.8
13.10.2016	91	97	348	356	201	205	0.8	15.8
14.10.2016	103	102	374	371	203	201	0.8	14.6

Figure 9-9: box plot of effluent 3 of test series 2

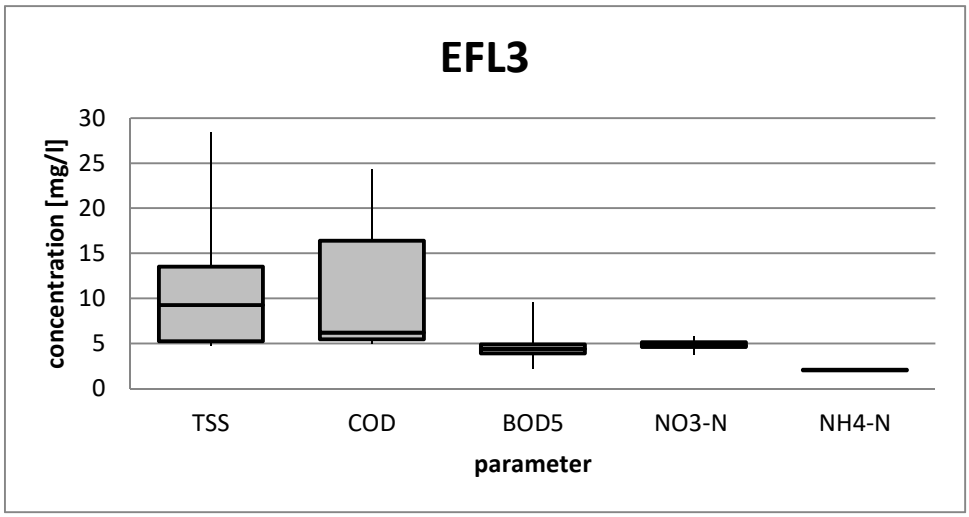


Figure 9-10: box plot of effluent 2 of test series 2

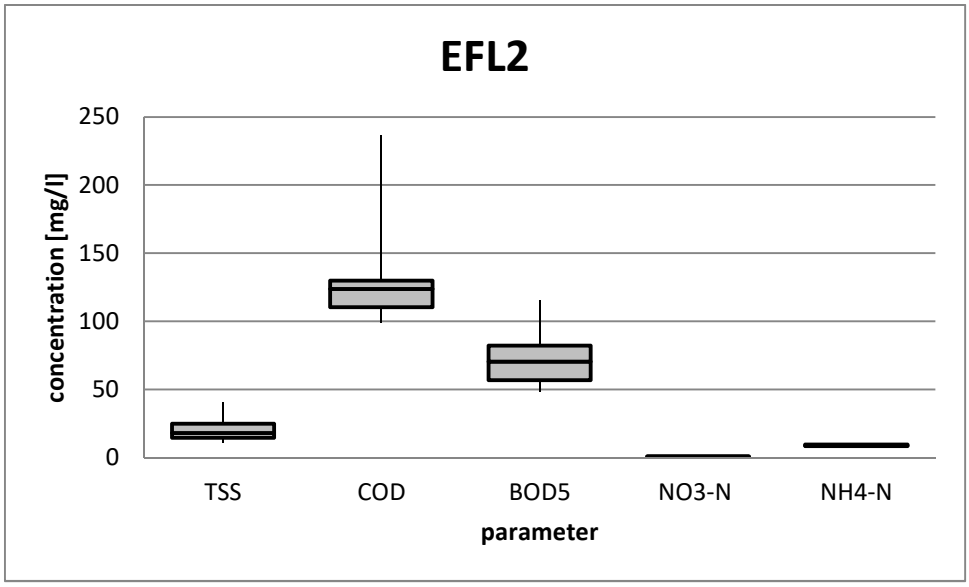


Figure 9-11: box plot of effluent 1 of test series 2

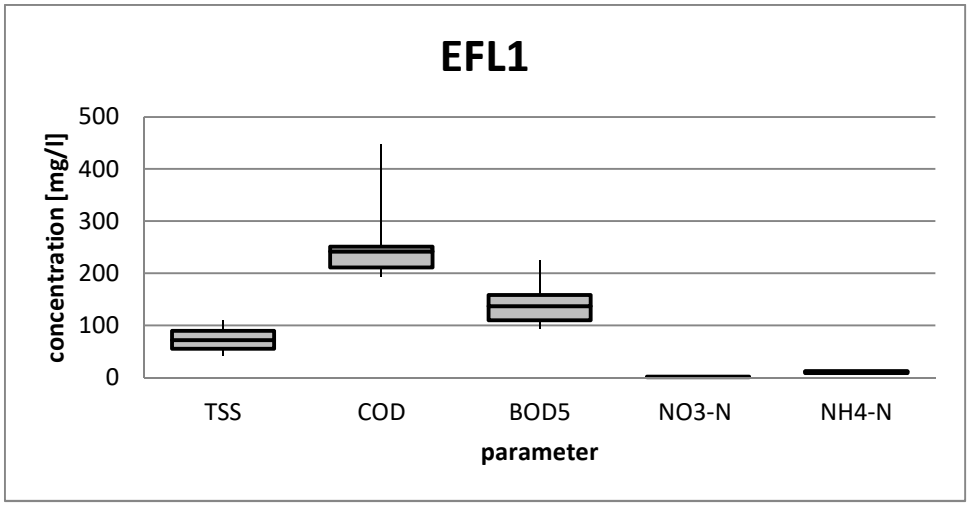
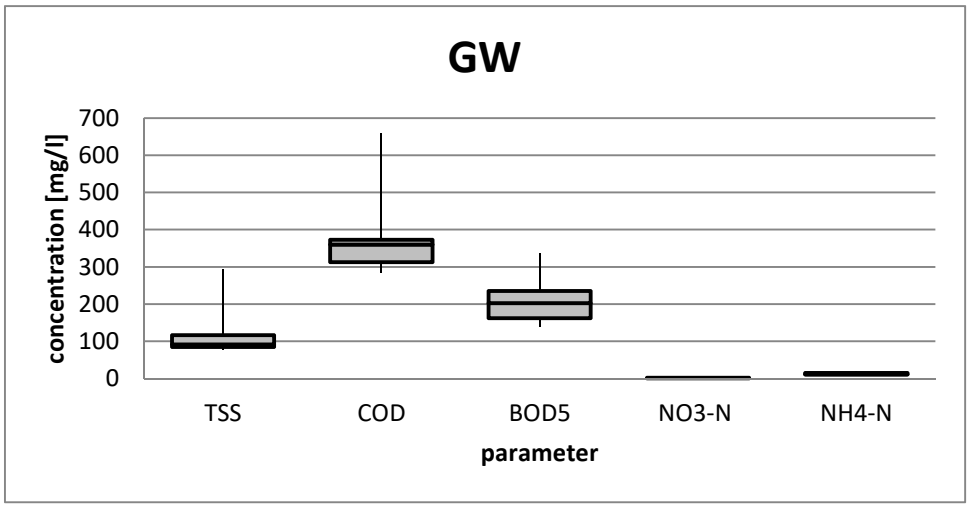


Figure 9-12: box plot of greywater of test series 2



9.4 Measurements test series 3

Table 9-4: measured values test series 3 without outliner:

EFL3

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
02.11.2016	10	10	29	30	15	16	1.4	12.0
03.11.2016	10	18	36	39	18	18	0.9	11.8
04.11.2016	6	9	25	25	13	13	0.8	11.7
08.11.2016	13	9	23	24	11	12	1.0	11.2
09.11.2016	5	5	19	19	9	10	1.9	12.1
10.11.2016	6	6	23	29	8	7	1.1	10.3
11.11.2016	5	5	21	22	10	10	1.1	9.7

EFL2

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
02.11.2016	19	19	165	166	99	101	0.8	11.3
03.11.2016	18	19	156	157	87	87	0.5	13.2
04.11.2016	21	21	142	142	79	79	0.4	13.2
08.11.2016	22	18	100	105	52	54	0.8	14.2
09.11.2016	14	14	130	126	70	68	1.0	12.2
10.11.2016	18	15	132	126	65	62	0.9	10.1
11.11.2016	18	19	132	135	70	71	0.9	10.1

EFL1

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
02.11.2016	61	63	300	303	183	185	0.8	12.8
03.11.2016	54	55	276	275	156	155	0.5	13.3
04.11.2016	67	67	258	260	144	145	0.6	14.3
08.11.2016	41	38	177	185	94	95	0.7	14.0
09.11.2016	47	47	242	232	130	127	0.4	11.6
10.11.2016	59	47	242	222	122	117	0.8	11.1
11.11.2016	46	48	244	248	131	133	0.4	12.4

GW

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
02.11.2016	104	106	436	439	267	270	0.6	14.3
03.11.2016	95	93	396	393	225	224	1.0	18.5
04.11.2016	82	85	375	377	210	211	0.9	15.3
08.11.2016	54	68	254	266	135	137	0.6	12.0
09.11.2016	92	82	353	339	191	185	0.7	10.7
10.11.2016	117	71	351	319	179	172	0.7	14.5
11.11.2016	93	96	355	361	191	194	0.5	15.3

Figure 9-13: box plot of effluent 3 of test series 3

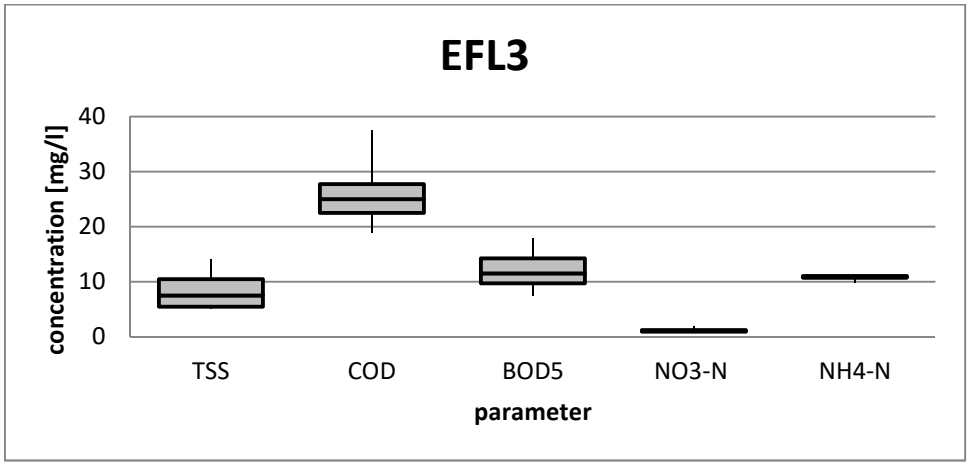


Figure 9-14: box plot of effluent 2 of test series 3

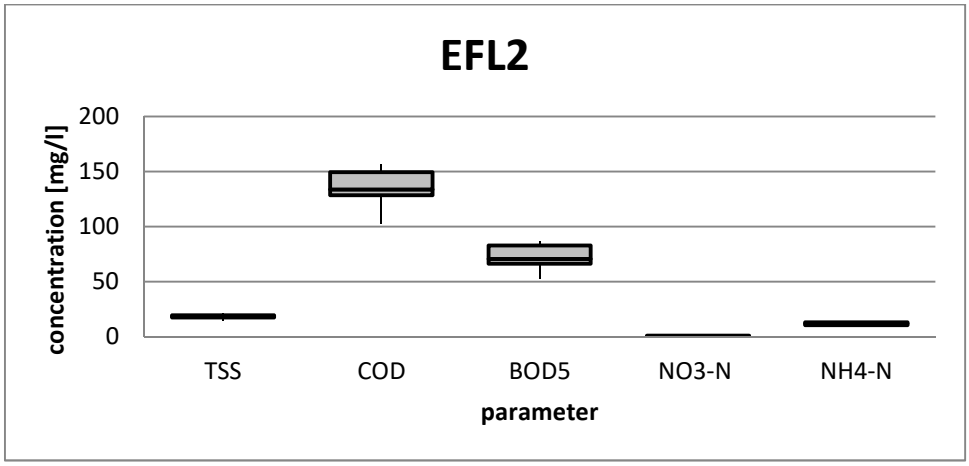


Figure 9-15: box plot of effluent 1 of test series 3

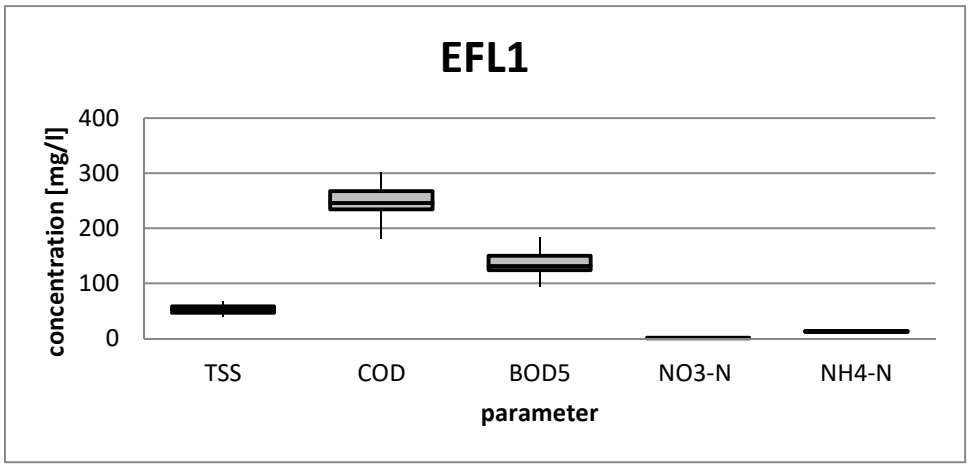
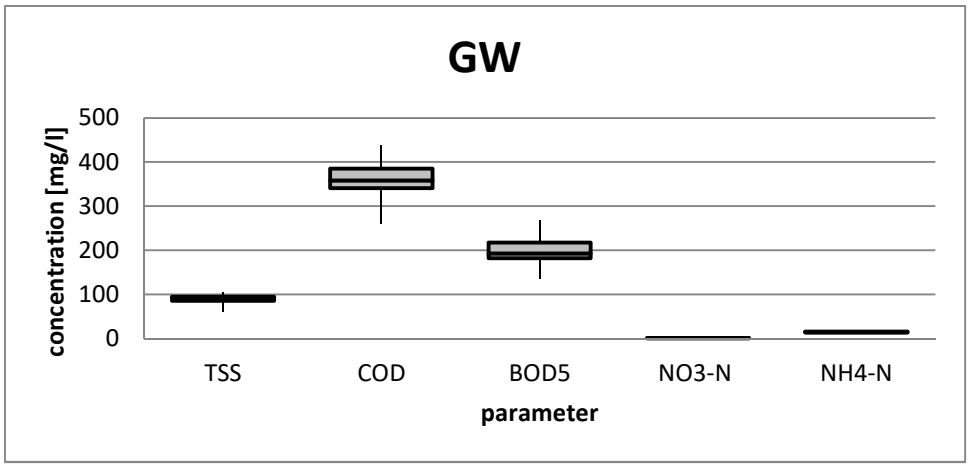


Figure 9-16: box plot of greywater of test series 3



9.5 Measurements test series 4

Table 9-5: measured values test series 4 without outliner:

EFL3

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
29.11.2016	6	6	10	9	5	5	4.5	4.2
30.11.2016	10	18	10	10	6	6	3.5	6.3
01.12.2016	6	9	10	10	6	6	2.1	9.2
02.12.2016	13	9	9	9	6	6	4.3	5.4
06.12.2016	5	5	10	9	6	6	2.3	5.9
07.12.2016	6	6	8	9	6	5	3.1	7.0
09.12.2016	5	5	10	9	8	7	2.2	8.6

EFL2

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
29.11.2016	18	13	111	106	57	56	0.9	11.5
30.11.2016	15	16	118	118	64	64	1.1	14.0
01.12.2016	15	14	118	118	64	64	2.3	14.2
02.12.2016	12	13	70	70	18	18	0.9	14.4
06.12.2016	11	12	115	109	58	57	2.4	15.5

07.12.2016	16	20	123	127	64	65	1.5	14.0
09.12.2016	16	16	126	120	66	63	0.7	13.0

EFL1

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
29.11.2016	37	37	211	204	108	108	1.8	15.8
30.11.2016	39	37	227	225	123	123	0.9	15.0
01.12.2016	37	36	225	226	121	123	0.8	14.4
02.12.2016	30	31	130	132	29	29	1.4	17.0
06.12.2016	44	44	219	210	111	109	0.5	16.0
07.12.2016	50	49	238	244	121	125	0.7	15.2
09.12.2016	45	45	242	230	123	118	0.9	13.2

GW

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
29.11.2016	96	82	312	301	160	159	0.8	19.9
30.11.2016	80	77	335	333	181	181	1.0	21.3
01.12.2016	78	81	333	334	179	181	1.4	23.0
02.12.2016	50	50	191	193	41	41	0.8	20.1
06.12.2016	90	76	324	310	163	160	0.7	21.0
07.12.2016	84	89	353	362	179	185	0.9	17.3
09.12.2016	80	82	358	341	181	174	0.7	16.2

Figure 9-17: box plot of effluent 3 of test series 4

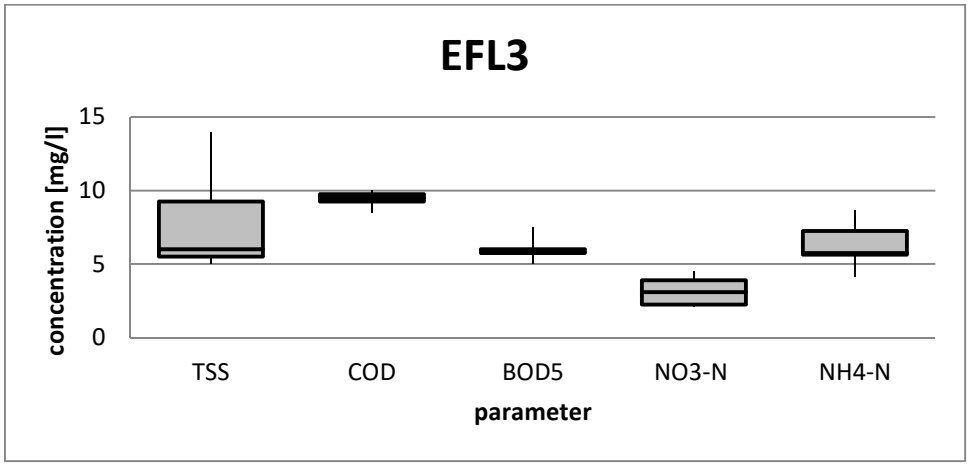


Figure 9-18: box plot of effluent 2 of test series 4

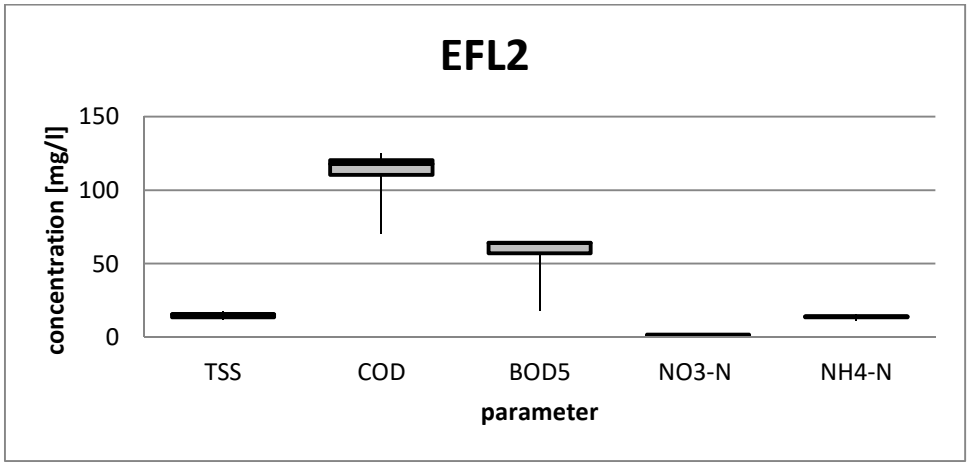


Figure 9-19: box plot of effluent 1 of test series 4

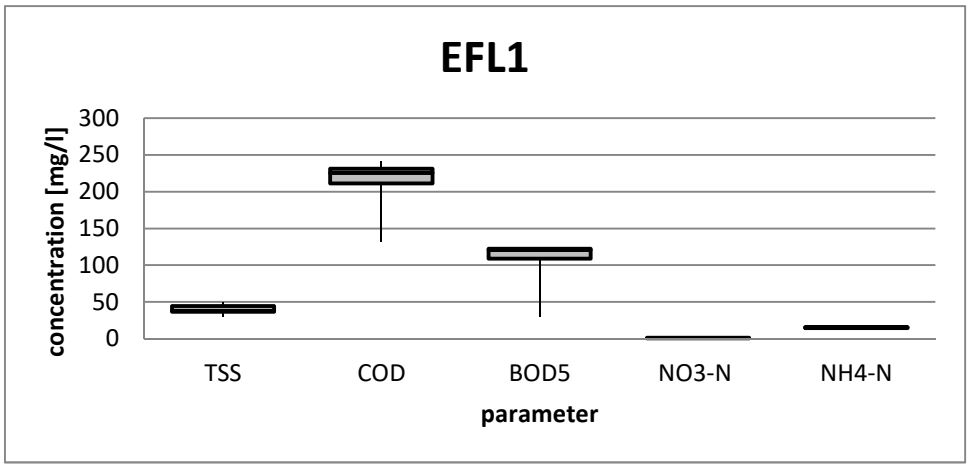
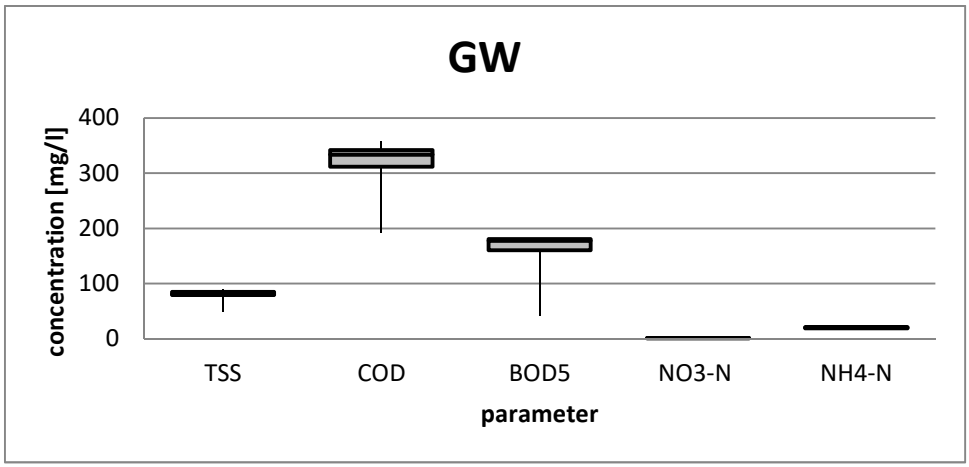


Figure 9-20: box plot of greywater of test series 4



9.6 Measurements test series 5

Table 9-6: measured values test series 5 without outliner:

EFL3

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
10.01.2017	1	1	5	5	5	5	-	2.0
12.01.2017	1	1	3	3	2	2	-	2.0
13.01.2017	2	2	4	4	3	3	-	2.0
17.01.2017	1	1	4	4	3	3	8.7	2.0
18.01.2017	4	3	10	9	5	5	3.4	8.3
19.01.2017	26	26	16	16	4	4	4.8	4.8
20.01.2017	7	7	7	7	3	3	10.8	2.0
24.01.2017	43	43	24	25	6	5	7.2	3.1
25.01.2017	3	3	6	6	4	4	8.4	2.0
27.01.2017	2	3	5	5	3	3	6.6	4.1

EFL2

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
10.01.2017	5	5	111	113	69	70	-	5.7
12.01.2017	5	5	117	114	61	60	-	10.4

13.01.2017	8	8	98	97	48	47	-	11.8
17.01.2017	9	9	101	86	50	45	1.4	14.1
18.01.2017	8	8	149	136	72	66	0.9	13.7
19.01.2017	27	32	98	98	42	42	0.8	14.7
20.01.2017	8	12	96	95	41	41	0.3	12.6
24.01.2017	69	45	142	139	64	62	0.2	12.9
25.01.2017	9	10	92	90	44	45	0.1	13.0
27.01.2017	9	10	69	71	29	32	0.1	11.7

EFL1

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
10.01.2017	22	24	218	220	134	135	-	10.3
12.01.2017	26	23	231	226	120	119	-	14.0
13.01.2017	-	-	193	191	92	92	-	
17.01.2017	66	62	198	168	97	88	1.2	16.6
18.01.2017	40	40	289	263	139	126	0.4	16.2
19.01.2017	86	71	181	180	79	81	1.3	15.4
20.01.2017	67	32	185	183	78	79	0.5	14.7
24.01.2017	108	94	259	252	122	120	0.4	14.8
25.01.2017	35	36	178	174	84	86	0.5	19.1
27.01.2017	26	28	132	137	54	62	0.2	13.0

GW

day	TSS [mg/l]		COD [mg/l]		BOD_5 [mg/l]		NO_3-N [mg/l]	NH_4-N [mg/l]
10.01.2017	67	68	324	327	199	200	-	21.8
12.01.2017	130	121	345	337	179	177	-	17.9
13.01.2017	89	83	287	284	137	136	-	16.9
17.01.2017	112	67	296	250	144	130	1.2	20.1
18.01.2017	169	135	429	390	206	187	1.5	20.6
19.01.2017	126	123	263	262	117	119	0.9	16.2
20.01.2017	116	106	273	271	116	118	0.6	17.1
24.01.2017	198	185	377	366	180	177	0.6	23.2
25.01.2017	79	65	263	259	124	127	0.8	23.0
27.01.2017	54	64	196	203	80	91	0.6	24.0

Figure 9-21: box plot of effluent 3 of test series 5

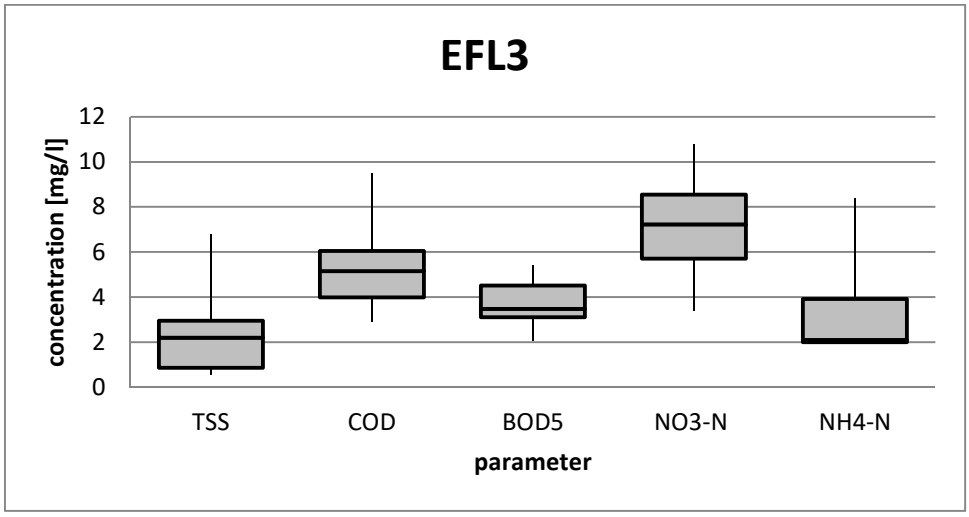


Figure 9-22: box plot of effluent 2 of test series 5

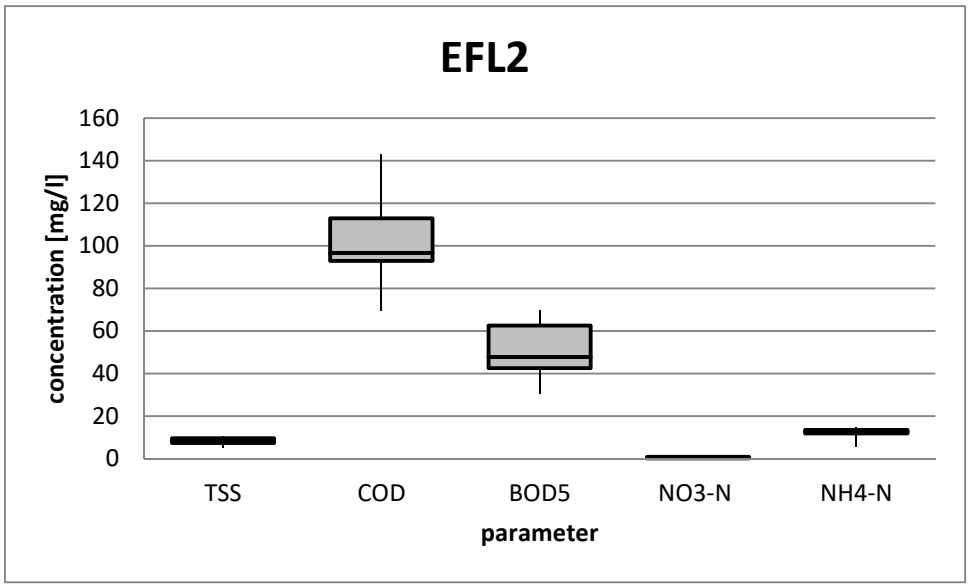


Figure 9-23: box plot of effluent 1 of test series 5

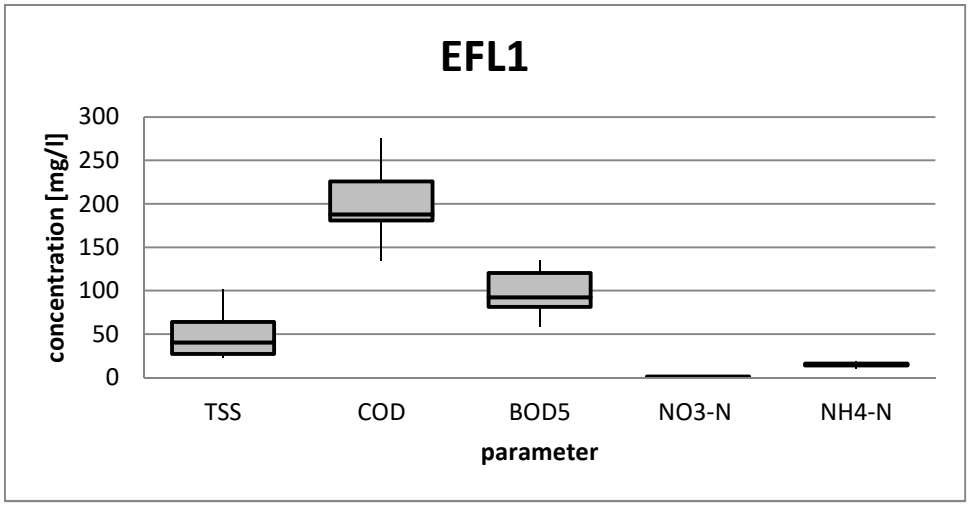
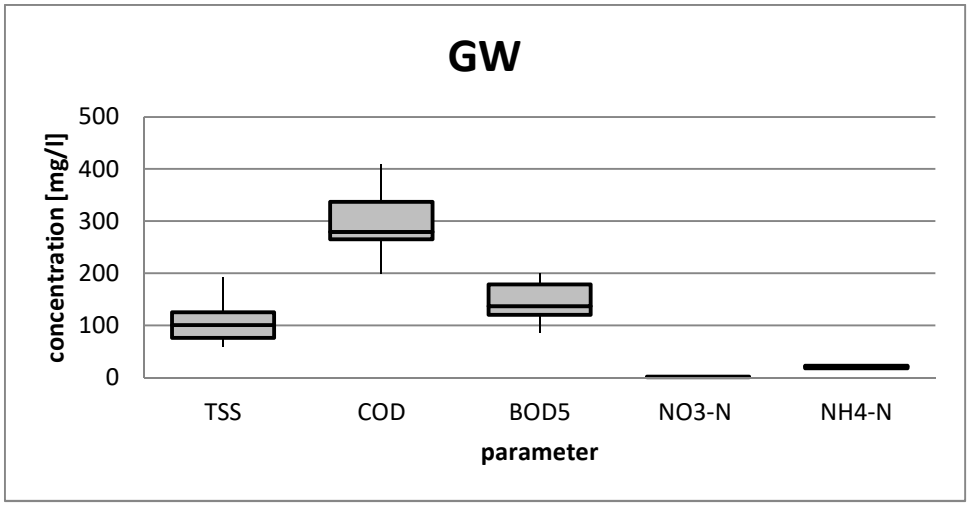
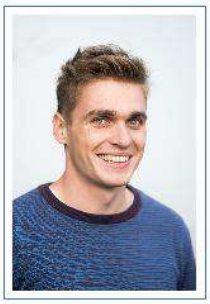


Figure 9-24: box plot of greywater of test series 5



10. Curriculum Vitae



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Education

since 2015 **University of Natural Resources and Life Sciences, Vienna**, *Master programme Civil Engineering and Water Management*, .

2011 - 2015 **University of Natural Resources and Life Sciences, Vienna**, *Bachelor programme Civil Engineering and Water Management* , *Degree: Bachelor of Science.*

2005 - 2010 **HTL Paul-Hahn-Straße**, *Mechanical Engineering*, Linz, Degree: Matura.

2001 - 2005 **Europagymnasium Auhof**, *Natural Sciences, Linz.*

Work Experience

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2017 - 2018 **Student Assistent**, INSTITUTE OF SANITARY ENGINEERING AND WATER POLLUTION CONTROL (SIG), University of Natural Resources and Life Sciences, Vienna.

2017 **Internship**, ABTEILUNG GRUND- UND TRINKWASSERWIRTSCHAFT, Land Oberösterreich.

2014 **Internship**, GEWÄSSERBEZIRK LINZ, Land Oberösterreich.

Other Competencies

Driving Licence: A, B, C, E, F

Computer Skills: AutoCAD, EPANET, EPA SWMM, cePipe, BaSYS

Languages

German: First Language

English: Fluent

Interests

- Politics
- Skiing
- Scuba Diving
- Sailing

11. Affirmation

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Vienna, 16th of May 2019, Daniel Dober