TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

WATER QUALITY BASED MONITORING AND CONTROL OF URBAN WATER SYSTEMS

LINNA VEESÜSTEEMIDE VEE KVALITEEDIPÕHINE MONITOORING JA JUHTIMINE

MASTER THESIS

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Tallinn, 2021

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THESIS TASK

Student: Álvaro Panizo Fra, 194199EABM

Study programme, EABM03/18 Evironmental Engineering and Management

Supervisor(s): Prof. Ivar Annus, Department of Civil Engineering and Architecture

Thesis Topic: Water quality based monitoring and control of urban water systems

Linna veesüsteemide vee kvaliteedipõhine monitooring ja juhtimine

Thesis main objectives:

1. Provide a review of the state of art of the water quality monitoring and control techniques of urban water systems
2. Select and design the best techniques for a real case study in Viimsi, Estonia
3. Monitor the data after the application of the techniques, in order to assess the efficiency of the proposed techniques

Thesis tasks and time schedule:

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1.	Literature review on water quality based UDS control and management	12.2020
2.	Analysis of the pilot site and water quality studies	04.2021
3.	Selection of UDS water treatment and control strategies	05.2021

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PREFACE

This topic was initially suggested by my supervisor, who provided me with the initial idea, quickly offering to be a part of the project. To him I am thankful, for this and the attention he has dedicated to me.

My profound gratitude goes to my parents, who have always supported and guided me, being comprehensive. The person I am today is mainly thanks to their unmeasurable sacrifice and dedication.

A special mention to all my friends, the old and the new ones, who have contributed to improve and love my life. They are the fuel of this engine.

This thesis aims for providing a comprehensive look at the current development of the smart urban water systems, and ultimately provides a solution to a real case study, assessing the best possible pathway to achieve a good status of the storm water.

LIST OF ABBREVIATIONS AND SYMBOLS

BOD – Biological oxygen demand

BOD_5 – 5-day biological oxygen demand

COD – Chemical oxygen demand

CWs – Constructed wetlands

CSO – Combined sewer overflow

DMPC – Distributed model predictive control

DO – Dissolved oxygen

DORA – Dynamic Overflow Risk Assessment

EC – Electrical conductivity

FLC – Fuzzy-logic control

HFCW – Horizontal flow constructed wetland

K – Potassium

MPC – Model predictive control

NBS – Nature-based solutions

NH_4 – Ammonia

PAH – Poly aromatic hydrocarbons

RTC – Real-time control

RBC – Rule-based control

SFCWs – Surface flow constructed wetlands

SSFCWs – Sub-surface flow constructed wetlands

SUDS – Sustainable urban drainage systems

TOC – Total organic carbon

TSS – Total suspended solids

UDS – Urban drainage systems

VFCW – Vertical flow constructed wetland

WWTP – Wastewater treatment plant

1. INTRODUCTION

The current society we live in is exponentially raising awareness about the ecological impact of human beings in the nature. As the number of individuals keep growing, a clear trend points towards the continuous urbanization from nearly 30% of population living in cities in 1950 to more than 50% nowadays (World Bank Group, 2016) therefore cities all over the world have been experimenting massive population growths that are often unplanned. Perhaps one of the most notorious impacts of this activity is perceived on the water bodies, as a result of the mistreatment of sanitary waters.

The urban drainage systems (UDS) have not always been able to carry on with the constant development of the cities, some of them becoming outdated or overrun (García *et al,* 2015). We can distinguish between two types of UDS: the combined systems and the separate systems. The former, more common during the development of the first big cities, conduct both storm water and sewage waters. The latter has a separate network of pipelines for storm water and sewage waters. Each of them has its own advantages and disadvantages. The combined systems occupy less space and are cheaper due to less construction materials. However, during storm events, there is a higher chance of overflow, resulting in the so called CSOs (Combined sewer overflows), where the WWTP (Wastewater treatment plant) cannot withstand the volume of water, resulting on the discharge to the closest water body (Brunsch *et al,* 2020).

Storm events are indeed, a major problem. Even in the case of separate systems, an overflow can discharge a wide range of pollutants (Borris *et al,* 2014, Gasperi *et al,* 2012). What´s more, the climate change is modifying the rainfall patterns which were used to design the UDS (Borris *et al,* 2013), resulting on a higher number of CSO events throughout the year.

In order to deal with the pollution, a new generation of solutions have been born. Among them, different innovations have been introduced, from the use of predictive models (He *et al,* 2011) to the use of real-time control (RTC) (Lowë *et al,* 2016) as well as the sustainable urban drainage systems (SUDS) (Riechel *et al,* 2020). Each alternative might be determined the most suitable, by judging different parameters such as pollutant loads, rainfall patterns, space and economics.

The implementation of new techniques to monitor and control the status of water have gained relevance in Europe, as a part of their aim towards sustainable development One of the most important water bodies is the Baltic Sea. The water status of the sea is rather fragile, due to several reasons. Its geography is an obstacle to the renewal of the water, since only a very narrow corridor connects it with the Atlantic Ocean, making the circulation of deepwater a phenomena that relies on differences of salinity and ultimately water temperature (Giesse *et al,* 2020), even though the contribution is moderate. Another important factor is the high pollutant load carried by the intensive agricultural activity in Northern and Central Europe, and its constant use as a commercial route, with vessels constantly travelling across its waters.

Concerns about the water quality were raised long ago, and it led to the creation of the Baltic Marine Environment Protection Commission or HELCOM, which includes all the countries whose shores are touched by the Baltic Sea. Ever since its creation, continuous international effort has been made in order to preserve the quality and save the water body from an ominous fate.

The case study analysed in this thesis is located nearby the city of Tallinn and might set the basis to more Baltic cities, as the rainfall patterns, water quality requirements and social standards are shared among the different countries. In addition, the thesis is a part of an ongoing Interreg CleanStormWater project currently being implemented in different cities, with several parts involved, thus encouraging cooperation and understanding among the nationalities living by this sea.

The objective of this research is to provide an overview on the state of art of the smart urban drainage systems, including a comprehensive analysis about the processes undertaken, substances that can be monitored, techniques employed on the available studies, and the results and conclusions. Further implementation in a real case will be assessed. Based on the information gathered, different alternatives will be considered in order to provide the potential best solution. Aspects analyzed will be the hydraulics, water quality, social and economic benefit. Further monitoring of the measurements will provide an output to determine the effectivity of the solutions, which may set the basis for improvements and future applications.

2. AN OVERVIEW OF THE STATE OF ART OF THE URBAN DRAINAGE SYSTEMS

As previously mentioned, new alternatives are blooming nowadays in order to deal with the environmental impacts of the uncontrolled discharges of the UDS, several of them being currently tested or implemented in some cities. Control of urban drainage systems often involves manual control carried out by an operator, passive or rule-based control, which is not optimal anymore when compared to other control techniques (García *et al,* 2015, Lund *et al,* 2018).

Real-time control (RTC) is an extended solution where the variables selected are monitored, a response is elaborated based on the monitoring, and a corrective action is executed via actuators, such as sluice gates or three-way valves (Lowë *et al*, 2016). Those systems optimize a parameter, usually the amount of water released on CSOs, adjusting to the receiving inputs from data collected.

Further look into RTC algorithms identifies different logics. Heuristic algorithms are based on the knowledge acquired during its use. The most used heuristic algorithms are the Rule-based control (RBC) and the fuzzy-logic control (FLC). The former is usually governed by "if-then" rules, stablished before operation, while the latter don´t apply the binary logic but distinguish certain degrees of membership between 0 and 1, therefore allowing a more flexible response. On the other hand optimization-based algorithms seek for an optimal control action, which is achieved by the minimization or maximization of a function which is based on the control objective chosen for the UDS (García *et al,* 2015).

Another strategy is to combine the RTC with the modelling programs. By doing so, the data gathered live is simulated using a software, getting a close-to-reality forecast, that can be implemented into the RTC, in order for it to act towards the optimization of that future scenario. This is the so-called model predictive control or MPC (Ben *et al,* 2019, Sun *et al,* 2017, García *et al,* 2015). There are different model predictive controls, main two being centralized model predictive control and decentralized model predictive control (DMPC). In the latter, no communication exists between the different controllers, which may result on each subsystem´s correcting actions perturbating other subsystem, compromising its response. On the other hand, the decentralization is the way to go for complex processes, where a centralized MPC may not reach the optimal solution on time, due to complexity of calculations. In addition, by using predictions in closed loop, the system can be stable (Venkat *et al,* 2008, Christofides *et al,* 2013, Sorcia-Vázquez *et al,* 2015).

However, reduction of CSO discharges may not be directly related with an improvement on the water status, one of the reasons being the fact that the majority of the flow is directed to the WWTP, overcrowding its capacity, thus resulting in a loss of effluent quality (Fu *et al,* 2010). Some studies have started to implement the water quality parameters to the optimization function, either by implementation on a RTC strategy (Vezzaro *et al,* 2014) or by using a multi-objective optimization approach considering water quality and the costs for wastewater treatment (Rathnayate, 2015). Among the different software used in simulation, widely used SWMM 5.0 developed by US Environmental Protection Agency is capable of introducing water quality parameters in the simulation.

Another important aspect appears when addressing the problem of water quality. Traditionally, solutions based on pipes and water retention tanks, often called gray infrastructure appear to be better, due to the noticeable reduction of CSO events, and quick conveyance of storm water. However, the nature-based solutions (NBS) are lately gaining increased popularity, due to the multiple benefits reported, not only on the overall water quality, but on aspects such as the reduction of heat island effects, carbon sequestration, or increase of recreational spaces (Alves *et al,* 2019, Yang & Zhang, 2021). These nature-based solutions try to replicate or get inspired by already existing actions in nature, and can vary on a wide range, from green roofs, permeable pavement and grass swales to rain barrels and bio-retention tanks (Mcclymont *et al,* 2020). In fact, a combined approach of both green and gray infrastructure has proven to be the optimal choice when taking into account water quantity and quality, social, economic and ecological aspects all together (Yang & Zhang, 2021).

A special mention goes to a NBS that is gaining more and more popularity during the last decades: Constructed wetlands or CWs (Vymazal, 2011, Zhang *et al,* 2021). Those artificially constructed wetlands are able to treat wastewater through physical, chemical and biological methods. They are divided into surface flow constructed wetlands (SFCWs) and sub-surface flow constructed wetlands (SSFCWs). The former replies the structure of a marshland, where water flows in the open air, and there is a high amount of vegetation, with plants submerged or floating. The latter consists of several layers of different substrates, and water flows through them, under the surface. Depending on the flow of water. SSFCWs can be divided into:

- Horizontal flow: Water continuously flows horizontally from the inlet to the outlet, interacting with the aerobic and anaerobic areas of the bed, efficiently treating organics, suspended solids and heavy metals (Vymazal, 2011).

- Vertical flow: They operate on batches, where water to be treated is fed until the bed is fully saturated. Percolated water is collected at the bottom of the bed, completely draining out and allowing the oxygen to refill the bed. On the upflow variant, water is fed from the bottom, until the bed is fully embedded and water is collected on the surface. Tidal flow systems consist on feeding water from the bottom as an upflow system, but when the bed is flooded, the water stays there in order to provide continuous contact between the substract and the bed, to be drained after a certain amount of time (Vymazal, 2011, Li *et al,* 2019).
- Hybrid wetlands: Consists of different types of integrated wetlands, such as the integrated vertical-flow constructed wetlands, which consists of two chambers, one where water goes downstream and the next where it flows upstream (Vymazal, 2011, Zhang *et al,* 2021).

As a summary, the Tables 2.1, 2.2 and 2.3 convey all the aforementioned techniques and control methods in order to provide an overall view on the existing solutions to the better management of UDS, quantity and quality wise.

Table 2.1. Different Control Techniques for UDS

Passive control			»» Already existing on the old UDS, i.e. Combined sewer spillouts
Operator-controlled			»» Manual control devices, i.e. valves, sluice gates
RTC	**»» Heuristic**	**»» Rule-based control**	»» Automatic control based on binary actions, yes-no
		»» Fuzzy-logic control	»» Automatic control based on different values between yes and no.
	»» Optimization-based		»» Optimization of an objective via control actions, i.e. minimizing CSO
MPC	**»» Centralized**		»» Optimization of an objective via predictions obtained from a simulation, with a holistic approach
	»» Decentralized		»» Optimization of an objective via predictions obtained from a simulation, each subsystem working independently

Table 2.2. Different infrastructure used in UDS management.

Combined approach	**Gray Infrastructure**	»» **Water retention tanks**	»» Decreased water load to WWTP or CSOs
		»» **Pipes and concrete channels**	»» Conveyance of wastewater and storm water
	Nature-based solutions	»» **Green roofs**	»» Pollutant and particulates infiltration »» Temperature reduction of buildings
		»» **Permeable pavement**	»» Decreased surface Runoff »» Heat Stress Reduction
		»» **Grass swales**	»» Increased water quality
		»» **Rain barrels**	»» Decreased surface Runoff »» Water availability
		»» **Bio-retention tanks**	»» Increased water quality
		»» **Constructed Wetlands**	»» Treatment of pollutants »» Tdecreased surface runoff

Table 2.3. Different types of Constructed wetlands and their main features.

Constructed wetlands	»» **Surface flow CWs**			»» Water is on the surface »» Submerged and floating vegetation
	Sub-surface flow CWs	»» **Horizontal flow**		»» Continuous flow of water underground »» Mostly anaerobic conditions
		»» **Vertical flow**	»» **Upflow**	»» Operate in batches »» Water fed from bottom, collected on surface
			»» **Tidal flow**	»» Operate in batches »» First water stays stagnant, then its drained

2.1 Monitored substances

Another important aspect of the water quality-based urban drainage systems are the monitored substances, and the equipment used on those measurements. Bibliography can provide many records from past research on the field:

A research carried in the city of Berlin (Caradot *et al,* 2011) aimed at studying the feasibility of implementing water quality sensors in both the River Spree and the CSO outlets that connected with it. The parameters taken were pH, DO, Temperature and Electrical Conductivity. Besides that, several sensors were used:

- UV-VIS spectrometer for measuring equivalents of total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD) and total organic carbon (TOC).
- Ion selective probe to provide readings on the potassium (K), ammonium (NH4) and pH measurements.
- A probe for electrical conductivity (EC) and temperature measurements.

As shown in Fig. 2.2, the sensors were placed high above the CSO channel, and the wastewater was bypassed to them via a peristaltic pump. Results proved that reliable data can be obtained through a regular maintenance of the employed devices.

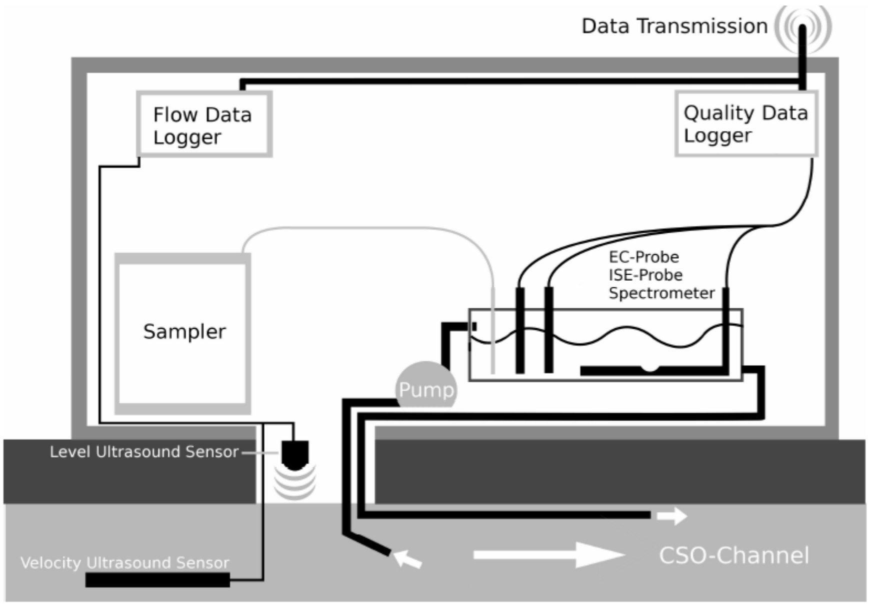

Figure 2.1. A scheme of the disposition of the devices used for measurements (Source: Caradot et al, 2011)

Another study conducted in the German Capital (Riechel *et al,* 2016) measured a major CSO outlet. Water level was monitored with an ultrasonic sensor. A continuous UV-vis spectrometer was placed on a bypass fed by a peristaltic pump. Measures of TSS, chemical oxygen demand (COD) and 5-day biological oxygen demand (BOD_5) were taken. In addition, an ion-selective electrode measured the ammonium nitrogen (NH4-N). The same parameters, in addition to total phosphorous were monitored by Barone *et al, (*2019) for their study about the impact of the CSO on the water quality of a prealpine Italian lake Iseo. Periodic samples were taken every 10 minutes by an automatic sampler, aspirating the water through a peristaltic pump.

Heavy metals do also represent a major concern on the storm water runoff. Many European cities still have metal roofs, usually made by zinc or copper. A study conducted in the city of Copenhagen focused on the identification of heavy metals, alongside with micropollutants on the urban runoff and the combined sewer system (Birch *et al,* 2011), where samples were taken at different points of the network. Another study conducted in the Danish capital (Kaas *et al,* 2016) supported the contribution of copper and zinc from roofing. In addition to the long time-already known parameters (nitrogen and phosphorous, pesticides) special attention was put on the car pollutants. These were the already banned lead from the exhaust, as well as the copper from the braking system, and the poly aromatic hydrocarbons (PAHs) originating from the tires during the accelerating and braking processes. In concordance to this, a research conducted in the Northern Sweden (Borris *et al,* 2013) also suggests road traffic as an important source of pollutants, especially heavy metals.

The results of a study conducted in Schuttgart, Germany (Launay *et al,* 2016) also manifest that pollutant load depends on the ratio of runoff to wastewater. Out of 69 selected substances, 60 were detected during the CSO discharges. When it comes to herbicides and PAHs, stormwater runoff was the main contributor, in line with the aforementioned studies. On the case of drugs, the highest concentrations were observed during the dry periods, where the contribution of stormwater runoff was non-existant. The techniques used to detect the micropollutants were liquid and gas chromatography.

A brief summary of the monitored substances on the previous research is shown on the Table 2.4. Typically, the most common parameters to be measured are the TSS, BOD, COD, nitrogen and phosphorous. One of the reasons of their popularity lies on the fact that they are considered main water quality parameters due to their impact (Rathnayake, 2015). In the case of the TSS, their modeling equations are simple enough to be integrated in the RTC and MPC of UDS (Sun *et al,* 2017). Caradot *et al,* (2011), opted for continuous measurements of COD, flow rate and O_2.

Depending on the parameters to be monitored, different sampling equipment is needed. In majority of the cases, automatic sampling is preferred (Caradot *et al,* 2011, Riechel *et al,* 2016, Barone *et al,* 2019, Launay *et al,* 2016), however sometimes grab sampling is the only way to go. Grab sampling is indeed the most inaccurate method, as the pollutant loads and parameters can dramatically change from different sites, events and times (Birch *et al,* 2011). The most representative sampling is based on taking samples every certain amount of volume has circulated through the sewer (Launay *et al,* 2016), for which a flowmeter is needed. Other techniques are the precipitation-dependent sampling, and time periodical sampling (Barone *et al,* 2019). A continuous sampling method has also proven to have high accuracy (Caradot *et al,* 2011, Riechel *et al,* 2016).

Table 2. 4. Different parameters measured, equipment and sampling methods used for the cited studies

Parameter	Studies	Equipment used	Sampling method
TSS	Caradot *et al,* 2011 Riechel et al, 2016 Barone et al, 2019	UV-VIS Spectrometer UV-VIS Spectrometer Automatic sampler ISCO 3700	Continuous Continuous Periodic
COD	Caradot *et al,* 2011 Riechel et al, 2016 Barone et al, 2019	UV-VIS Spectrometer UV-VIS Spectrometer Automatic sampler ISCO 3701	Continuous Continuous Periodic
BOD & BOD5	Caradot *et al,* 2011 Riechel et al, 2016 Barone et al, 2019	UV-VIS Spectrometer UV-VIS Spectrometer Automatic sampler ISCO 3702	Continuous Continuous Periodic
Ammonium nitrogen	Caradot *et al,* 2011 Riechel et al, 2016 Barone et al, 2019	Ion selective electrode Ion selective electrode Automatic sampler ISCO 3702	Continuous Continuous Periodic
pH	Caradot *et al,* 2011 Launay et al, 2016	Classical probe Classical probe	Continuous Periodic based on flow
DO	Caradot *et al,* 2011 Riechel et al, 2016	Classical probe DO probe	Continuous Continuous
Temperature	Caradot *et al,* 2011 Riechel et al, 2016	Classical probe Temperature probe	Continuous Periodic
Electric conductivity	Caradot *et al,* 2011 Launay et al, 2016	Conductivimeter Conductivimeter	Continuous Periodic based on flow
Phosphorous	Riechel et al, 2016 Barone et al, 2019	Grab sampling Automatic sampler ISCO 3702	Periodic Periodic
PAHs	Birch et al, 2011 Launay et al, 2016	Grab sampling Automatic sampler	Periodic Periodic based on flow

2.2. The city of Copenhagen and the DORA strategy

The city of Copenhagen is an example of a water-quality-driven UDS (Vezzaro *et al*, 2014). The system employs real time control through the Dynamic Overflow Risk Assessment (DORA) strategy, which aims to minimize the impact of the CSO events. The sewer system, as pictured in Figure 2.2, is composed by several pumping stations and retention tanks, some of them with deposits and CSO outlets to the sea. The Lynetten WWTP is where the wastewater ends up during normal conditions.

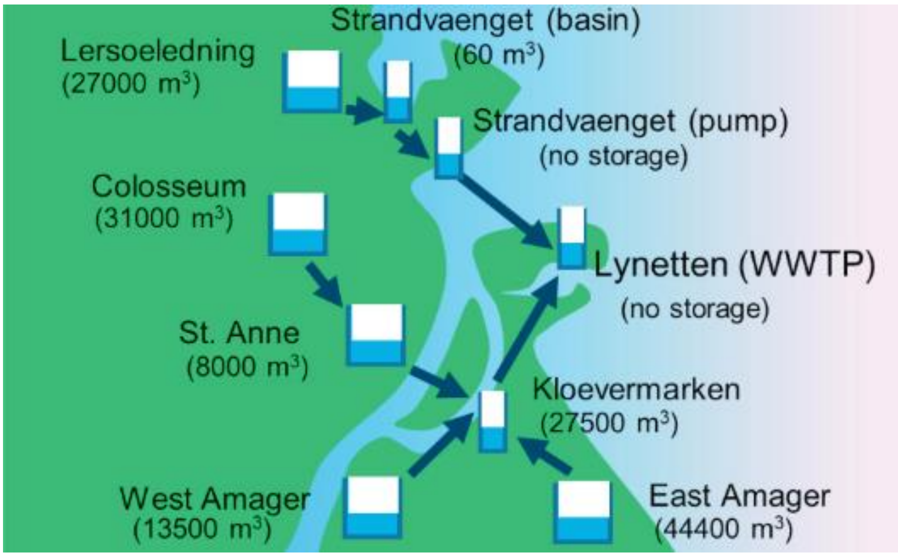

Figure 2.2. The Scheme of the Lynetten catchment area. (Source: Vezzaro et al, 2014)

The hydrological model was simulated in the software Wateraspects™, where only the total suspended solids (TSS) and the ammonia (NH4+) were analyzed. The DORA strategy aims at reducing the overflow risk of the whole system, which is calculated as the product of the overflow costs and the probability. The function considers several parameters:

- The actual volume that is used within the system´s storage tanks, seeking an optimum use of it.
- The forecast for each part of the catchment area in the upcoming hours, allowing to preventively empty those subsystems for more storage. The uncertainty of those forecasts and their runoff volumes are also considered.
- The sensitivity of the receiving water body, by assessing a cost per each m^3 of CSO poured on it, without taking into account the water quality.

In addition, the water quality can be taken into account indirectly by modifying the cost of CSO, or adopting different strategies, such as sacrificing a continuous overflow on one CSO for the benefit of keeping the rest untouched. The results proved that water quality-based control strategies can actually improve the overall performance of the UDS.

2.3 The sustainable urban drainage systems in Berlin

Sustainable urban drainage systems (SUDS) are nature-based solutions to convey and reduce the pollutant load on the storm water and wastewater. These systems are believed to have a high potential upon implementation, in addition to other benefits such as augmenting the diversity or reducing the urban heat island effect (Riechel *et al,* 2020, Alves *et al,* 2019, Yang & Zhang, 2021). On a study conducted in the quarter of Alt Schöneberg in Berlin, different SUDS were tested (Riechel *et al,* 2020). The simulation of the runoff was modelled with the program STORM, the sewer model to determine the pollutant load and transport was carried out with the software Infoworks, and the river water quality model was simulated with Hydrax-Qsim. The information about the technical parameters of the different SUDS implemented were obtained by an exhausting review of the literature.

Three different setups of the SUDS were simulated, each containing different solutions in different proportions (i.e. infiltration swales, green roofs). The results showed that surface runoff can be reduced by more than a third, and CSO activation can be cut down up to 58%.

3. TECHNICAL SOLUTIONS FOR QUALITY DRIVEN UDS MANAGEMENT

As seen in the previous chapter, there are many different solutions for UDS depending on what´s at stake such as the budget, availability of space, specific pollutant reduction goals or social benefits. The main focus of this thesis will be to apply all this knowledge to a real case study which is taking place on the municipality of Viimsi, Harju County, Estonia. Based on the monitored data obtained on this project, the main points to act will be addressed, the technical solutions will be analyzed, and the potential best solutions will be showcased.

3.1 The Viimsi case study

Viimsi is a municipality located North-East of Tallinn. With a total area of 73 km^2, the area is undergoing constant growth, passing from 5300 inhabitants on 1989 (Ovaska & Anderson, 2010) to more than 20000 nowadays (Statistics Estonia, 2020). The proximity to the capital city of Tallinn boosts its value as a residential area, with a quick connection via road.

Viimsi has become, alongside other Baltic cities such as Lieto and Turku in Finland and Lucavsala and Zakusala districts in Riga, Latvia, the objective of the Interreg Central Baltic Programme CleanStormWater project, which aims to develop and implement novel stormwater management concepts. The project has several phases, starting from taking the measurements, to gathering the data and assessing the possible solutions. The main idea is to implement nature-based solutions into already existing UDS alongside with grey infrastructure elements to reduce pollution load and stormwater runoff. An online platform will provide real time data about the UDS status, with further implementation of a control system that will allow to introduce correcting actions to minimize the pollution of the Baltic Sea.

As the project is still running the first phase, this thesis will focus on the monitoring phase and the assessment of the potential technical solutions. Latter stages, such as the design of the sensors, construction of the NBS, and validation of the results will be left as the project will continue to run in the incoming years.

3.2 Monitoring Phase

The first phase of the study consists of sampling at the various points of the stormwater network. The selected points are shown in the Figure 3.1, and later explained in the Appendix 1. The measurements were taken once per week, starting on 20th November and finishing on 17th December, with an early measurement on 30th October. More measures were taken during the month of April. The equipment for the samples consisted on 3 probes:

- LT Lutron WA-2017SD (Appendix 2): used for measurements of Temperature and total dissolved solids (TDS).
- YSI Professional Plus (Appendix 3): for measurements of pH, NO_3 and electrical conductivity.
- Global Water Flow Probe (Appendix 4): for measurements of the water velocity.

Since the water flow probe was available only during the measurements of April, during the months of November and December a bare estimation of the flow was performed by recording the surface speed of a floating object (i.e. leaves or sticks). Observations on each sampling point were added if necessary. The procedure for sampling consisted on submerging both probes for several seconds, carefully settling them on the bottom of the ditch, trying to not stir the sediments. As for the NO_3^- readings during the month of April, they weren´t trustful due to lack of calibration of the sensor. After readings were stable, the results were noted down, and the probes were slightly rinsed and covered with the protective gear. In case of any measurements out of normality, equipment was calibrated.

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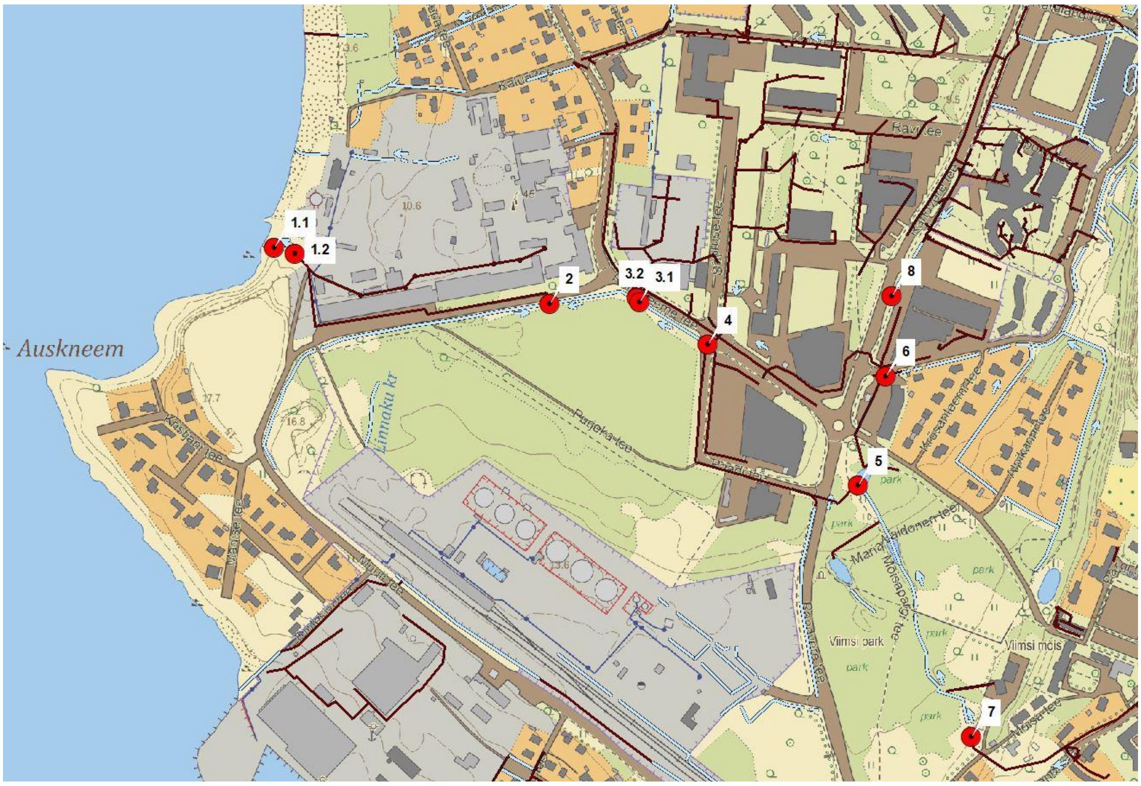

Figure 3.1. Different sampling points on the Viimsi municipality

It is worth noting that the point 8 wasn´t measured, due to its difficult access. As it was within the sewer system, opening a manhole and descending through it was necessary.

3.3 Analyzing the results

The measurements shown in the Appendix 1 are analyzed and plotted to gain some insights about the water status. Figures 3.2 - 3.5 show the readings of NO_3, pH, conductivity and TDS respectively, on the different sampling points throughout the whole measurement period. Several conclusions can be withdrawn; the readings of pH, conductivity and TDS are overall stable through the time. The same cannot be stated for the NO_3, whose concentration oscillates several times the original value. During the 4th week a peak on the NO_3 concentration can be seen in all the sampling points. This was attributed by the rainy days previous to the sampling date. In addition, peaks on conductivity and TDS are observed during the 7th week. This suggests there is a correlation between those two parameters. However, it is possible that the sensor needed to be calibrated before each sampling day, in order to reduce the uncertainty of the results.

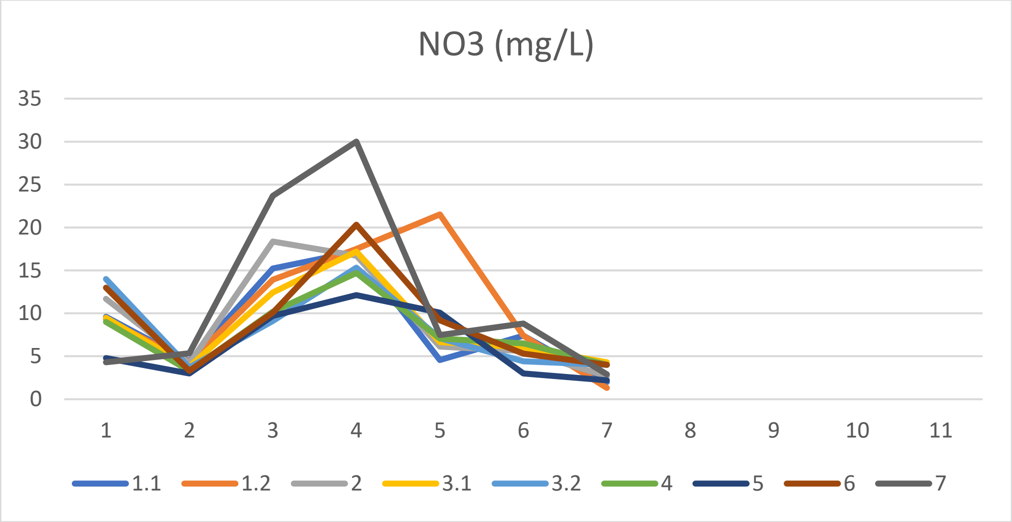

Figure 3.2. Values of NO_3 on the different sampling points throughout the length of the measurement period.

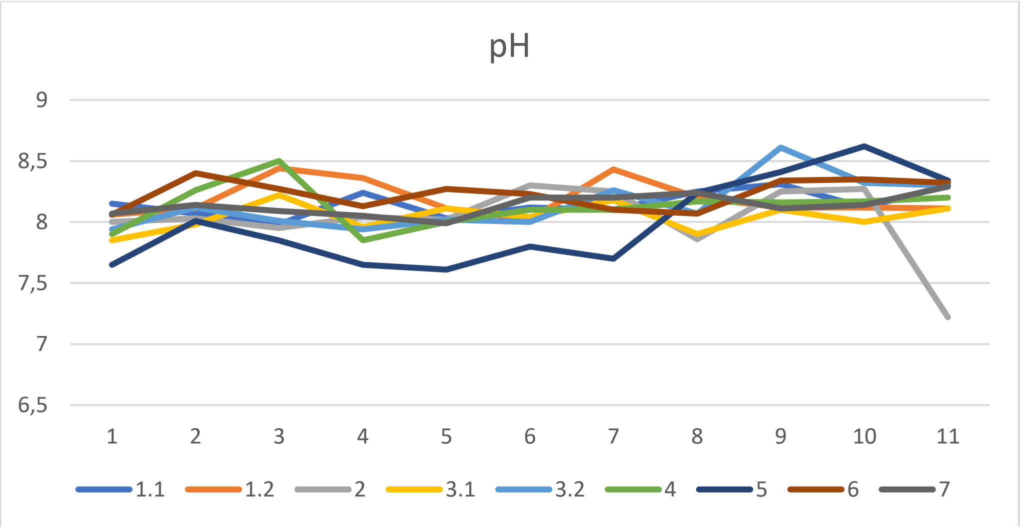

Figure 3.3. Values of pH on the different sampling points throughout the length of the measurement period.

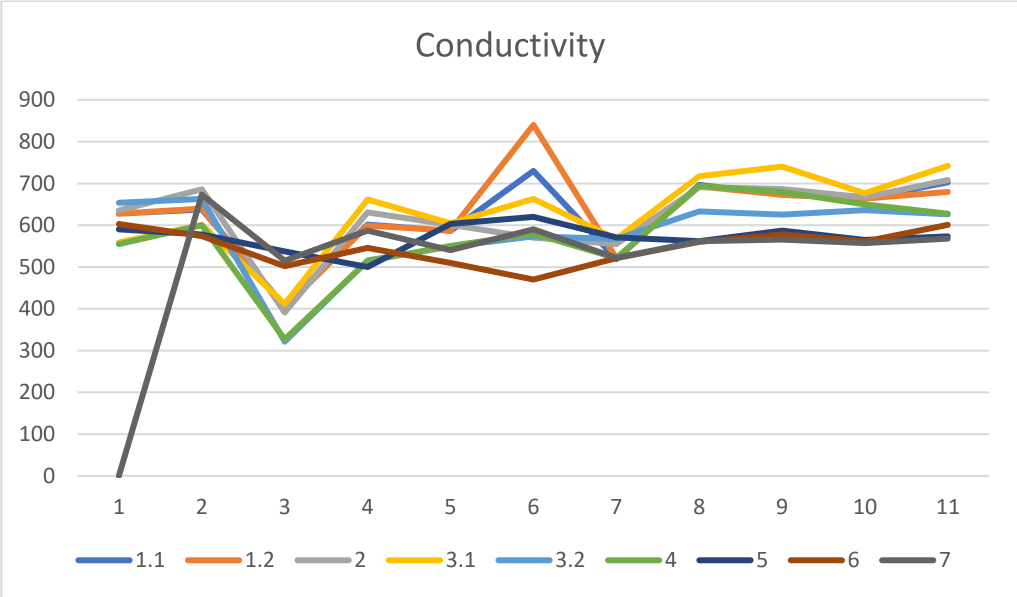

Figure 3.4. Values of Conductivity on the different sampling points throughout the length of the measurement period.

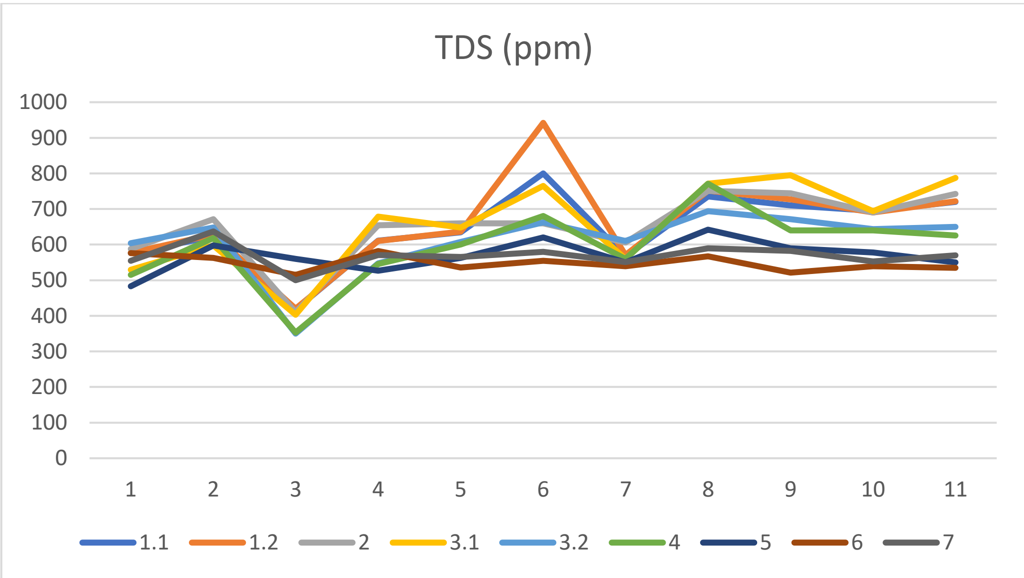

Figure 3.5. Values of Conductivity on the different sampling points throughout the length of the measurement period.

Another conclusion can be extracted by looking at the Figures 3.2-3.5. The readings of the different points for the same day are close. This is true due to the fact that all the ditches where the sampling was conducted contribute to the same outlet, as it can be seen in detail in Figure 3.6. This scheme will help determining the location of the techniques to be implemented.

3.4 A review of possible techniques

The goal of the thesis, in concordance with the project will be to improve the overall water quality of the outlet. Special effort will be put into tackling down the NO_3^-, as the Baltic Sea is particularly sensible to nutrient loads, such as Nitrogen and Phosphorous, and the monitored values suggest variable concentration of this pollutant. TDS and oil are also important parameters to reduce. The lack of substances measured also represents a problem when developing an action plan. Therefore, as a general guideline, the studies quoted on the first and second chapters will be taken into consideration, in order to shed a light on the case study.

As Viimsi is experiencing urban growth (Statistics Estonia, 2020), it is expected that the area covered by impervious surface will increase, and so the stormwater will be conveyed quicker into the pipes and ditches, and the wash-off of pollutants settled in those surfaces will increase (Borris *et al,* 2013). On the other hand, new buildings could implement some of the already mentioned nature-based solutions, like green roofs and rain barrels (McClymont *et al,* 2020). However, this is a future scenario and as such, it doesn´t provide any solution to the current one. It might, however, provide information for further additions to the case study.

In order to improve the effectiveness of the solutions, a combination of different techniques will be suggested (Yang & Zhang, 2021), mixing both nature-based solutions with gray infrastructure, all operated by an automatic control system. A more detailed scheme of the UDS with the lines and the connections is shown in Figure 3.6.

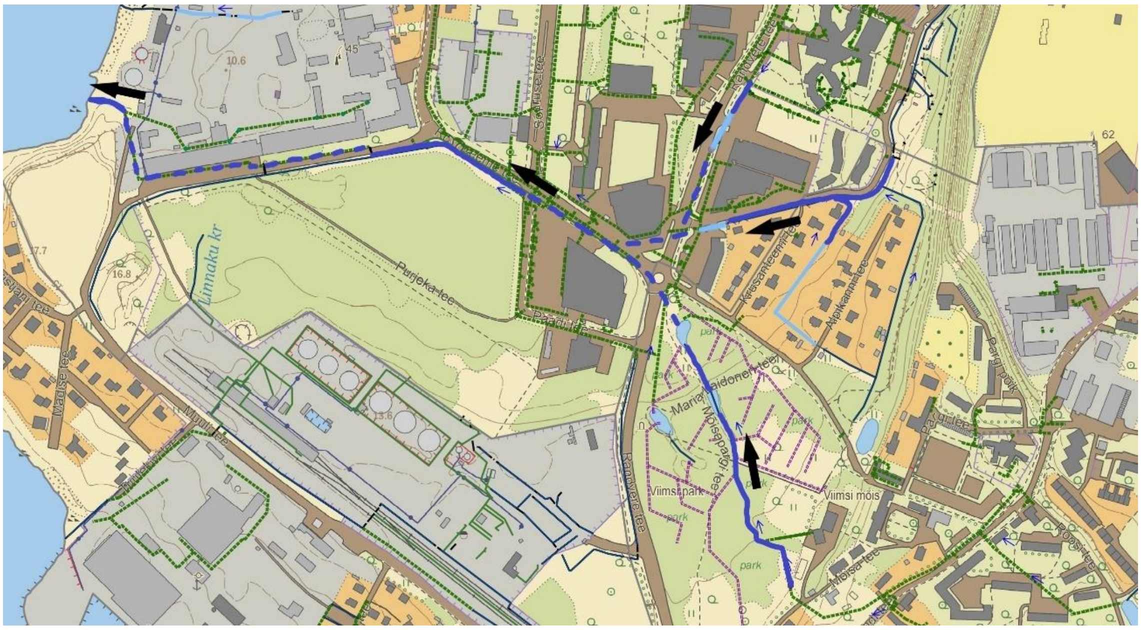

Figure 3.6. Scheme showing the flow direction on the Viimsi case Study.

The continuous lines represent the areas where the ditch is uncovered. The discontinuous lines show the pipelines or sewers that go underground. According to this, the map will be divided into 3 areas, as shown in the Figure 3.7. This will allow to focus on the best solution for different places along the extension of the UDS, and the overall best technique.

Figure 3.7. The division of the areas for the study.

3.4.1. Area 1

The Area 1 comprises a park to the south of the green area, a ditch that comes from the right side of the map, and a sewer on the upper side. The park is crossed by a ditch which carries storm water. There are two ponds in the park, the first one on the higher level, connected with the second by a pipe and a small cascade. The second pond is located close to the upper end of the park, and it has an outlet pipe that conveys the water down the road into the Area 2. The main focus will be the park, as it has a high ground water level that needs to be drained faster, and it showcases potential of implementing cost-effective solutions.

The proposal is to use both ponds as natural stormwater retention tanks. There will be sluice gate located on each pond´s outlet, ideally equipped with a remote controller that allows to manipulate it without being on site. Additionally, the lower pond´s outlet will be moved further up. This new set up will allow water to refresh, eliminating stagnation areas that may result in unpleasant odours and overgrowth of the plantation. An inclined grid will be located in the outlet of the lower pond, as well as in the entrance of the ditch into the underground system and the upper-side sewer. The grid will have an overflow in case it becomes clogged by the leaves and other floating solids. The idea is to remove any big solid present in the water so it can flow freely into the Area 2. All the conceived solutions are located in the Figure 3.8.

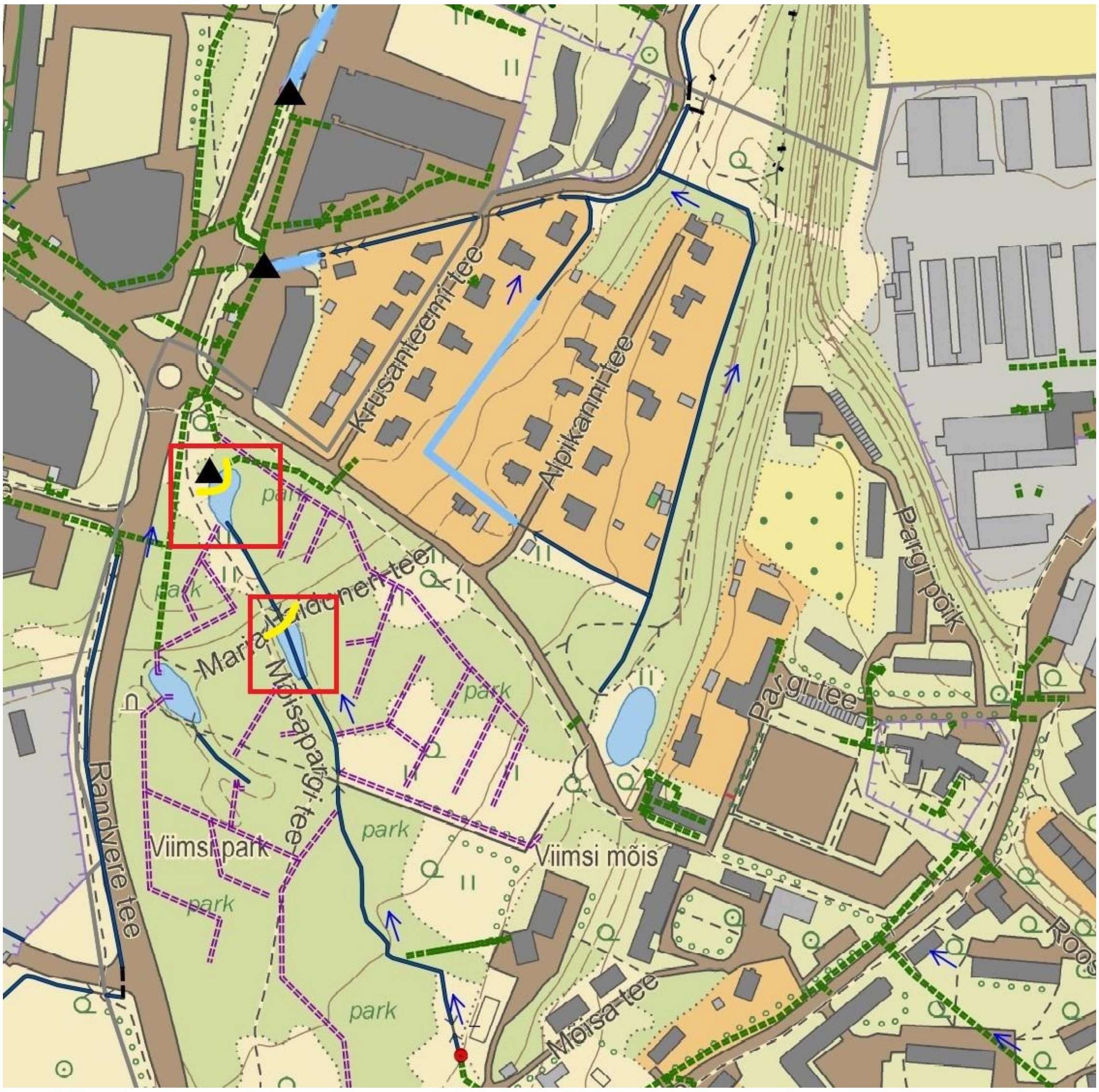

Figure 3.8. Proposal for the Area 1. The red squares are the two ponds suggested to be used as natural storage tanks. The yellow curved lines are the points where the sluice gates will be positioned. The black triangles correspond with the inclined grids.

During the monitoring period, it was noticed that the ground of the park was wet and muddy, probably as a result of a poor drainage of water. A suggestion to deal with this problem could be the installation of an impervious geotextile below the soil, with several pipes to conduct the water into the main ditch.

All the proposals are subjected to a qualitative analysis, which consists on the accomplishment of different objectives on several fields. These fields are:

- Hydraulics: This field embraces the impacts of the proposed technique on the quantity and dynamics of water.
- Water quality: Reflects the impacts of the alternatives into the water quality.

- Health, Social and Physical wellbeing: Identifies different categories related to the development of the society and the space inhabited, such as the improvement of the recreational areas, increase of safety conditions, beautification or habitability of the area.
- Ecosystem improvement: It encapsulates the improvement of space and conditions for new and old species of flora and fauna.
- Risks: The drawbacks of the alternatives, potential unwanted secondary effects.
- Cost: The costs of implementation and maintenance.

The Table 3.1 reflects all those categories, to provide a multi-objective on the technique proposed.

Table 3.1. Conclusions for the alternatives in Area 1.

	Natural Storm Water Retention tanks	**Underground drainage system**
Hydraulics	Reduction of overflows during rainy/stormy weather Storage of water for controlled release	Conveyance of water into the ditch Reduction of muddy land of the park
Water Quality	Reduction of TSS due to settling Assimilation of some of the pollution load by surrounding vegetation	N.A.
Health, Social and Physical Wellbeing	Increase of green areas Increased recreational activity Beautification of the place	Increase of recreational areas Beautification of the zone Safety
Ecosystem Improvement	Increased biodiversity	More stable soil for trees to grow
Risks	Areas where water does not refresh Lose of effective volume due to sediment settling	Draining pipe surface getting clogged by the sediments
Costs	Low implementation costs Low maintenance costs	Excavation + equipment costs Low maintenance costs

3.4.2. Area 2

The Area 2 consists of an open-air ditch where all the water from Area 1 has converged. Towards the middle of its length, another pipeline conveys stormwater into it. On the right side there is a road. On the left side there is a small forest. The ditch is dug two meters below the level of the surrounding terrain, and the average water depth is a few centimeters. This area is relevant, since the ditch has already received majority of the stormwater flows, therefore making it a suitable location for placing a nature-based solution.

The idea is to construct a wetland, taking advantage of the terrain. The size and the type of CW will vary depending on the availability of space. In addition, in order to monitor the overall performance, a flow-meter and continuous probes will be placed both at the inlet and outlet. The flow-meter will provide important data about the maximum treatment capacity of the CW, existence of leachates, and it will help determining existence of more inlets between the Area 2 and Area 3.

When it comes to the potential solutions, the different types of CWs are depicted in the Figure 3.9 & 3.10.

Figure 3.9 Technical solution consisting of a Surface Constructed Wetland (in blue). The yellow triangles represent the flow-meters and the continuous probes located both at the inlet and the outlet.

The SFCW proposed on Figure 3.9. is a reliable alternative assuming that space is not a problem. Majority of large-scale CW of China for treatment capacities higher than 100000 m^3/day are of this type, and the pollutant removal efficiency can be as high as 80% for total phosphorous, 82% for ammonia nitrogen, 80% for BOD_5 and 70% for SS (Zhang *et al,* 2021). This is possible due to the several processes that take place:

- Physical: Sedimentation, filtration or UV exposure.
- Chemical: Adsorption, chemical precipitation.
- Biological: Microbial degradation and transformation of nutrients, through both aerobic and anaerobic digestion.

As for the plant species, the most common one is the common reed or *Phragmites australis,* which can easily root on shallow and low speed waters (Zhang *et al,* 2021).

This type of CW offers little to no maintenance, besides periodically removing the sediments from its bottom. On the other hand, the implementation of this technique will include excavation works in order to create the area for its placement. And the ice formation can reduce the efficiency of some of the processes that take place on it, particularly those related with the Nitrogen (Vymazal, 2011).

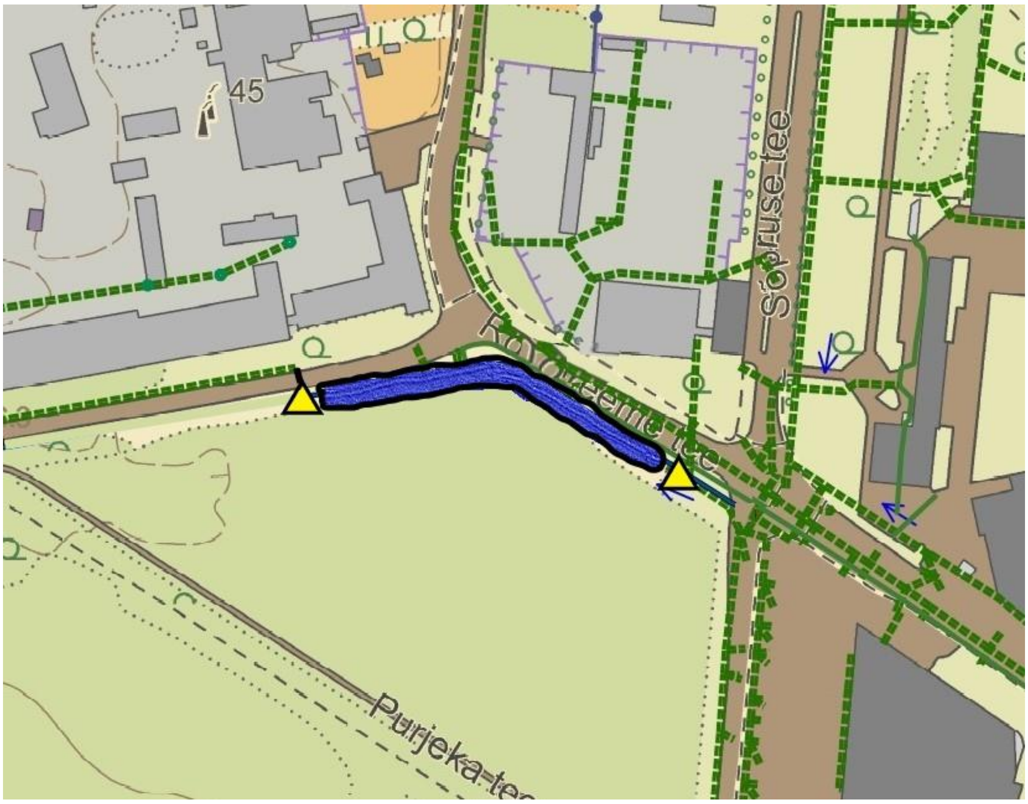

Figure 3.10 Technical solution consisting of a Sub-Surface Constructed Wetland (in blue). The yellow triangles represent the flow-meters and the continuous probes located both at the inlet and the outlet

The Figure 3.10 focuses on a Sub-Surface Constructed Wetland. Within this classification, different techniques are available, as previously mentioned (Vymazal, 2011, Zhang *et al,* 2021). A horizontal flow CW, a vertical flow CW and a hybrid CW will be proposed. The idea of an upflow vertical CW is discarded, as it implies the addition of pumps in order to flood the bed from the bottom to the surface. Same will be applied to the tidal flow. Even its higher efficiency is proven (Li *et al,* 2019), the burden of adapting a continuous system into a batch one is considered enough to close this alternative.

The Figure 3.11 shows the scheme of a horizontal flow CW. The structure is separated from the ground by an impervious barrier, which can be geotextile, in order to prevent any leachate. As the conditions are mostly anaerobic, denitrification (the process by which nitrates are converted into dinitrogen) is promoted, which results in an excellent nitrate removal (Vymazal, 2011), one of the main objectives to achieve during the case study. The operational costs are zero, since water flow is driven by gravity.

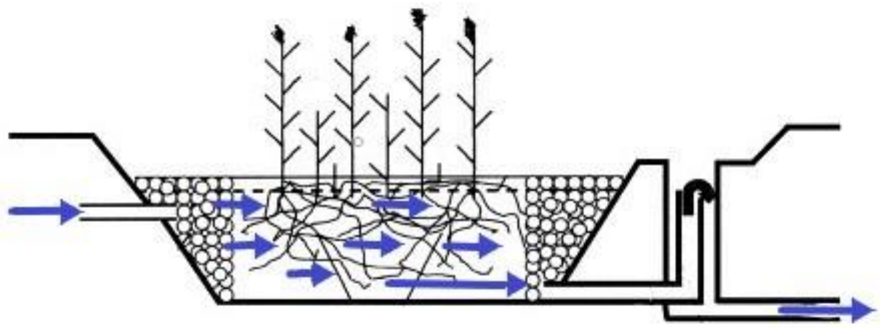

Figure 3.11. Scheme of a Horizontal Flow Constructed Wetland. Water flows across the bed, where the chemical and biological processes take place.

There are some downsides in the application of this CW. First of all, there is a potential for the bed to become clogged if the water to be treated contains a considerable amount of suspended solids (Vymazal, 2011). This can be solved however, by filtering the water prior to the entrance of the wetland, or by getting a coarse material for the bed. The second problem presented is the lack of aerobic conditions. Conversion of ammonia into nitrate is carried out in a process called nitrification, which happens under aerobic conditions. Even though ammonia wasn´t measured, evidence from studies suggest it as a mayor substance on wastewater and stormwater (Caradot *et al,* 2011, Riechel et al, 2016, Barone et al, 2019). To solve it, a solution of implementing passive aeration pipes is proposed. This might help oxygen reach the bottom part of the bed, generating aerobic conditions for the nitrification process to take place.

As an alternative to the lack of aerobic conditions, the vertical flow CWs are proposed. The structure of VFCWs is shown in Figure 3.12. The water enters from the surface, and slowly percolates by gravity, reacting with the substrate. At the bottom, there is a draining pipe, made by a permeable material, which collects all the water and conveys it to the outlet. The process is not continuous, as water needs to be drained in order to let the oxygen renew (Vymazal, 2011). Therefore, several VFCWs most be constructed in order to stablish a rotatory system that allow for aeration.

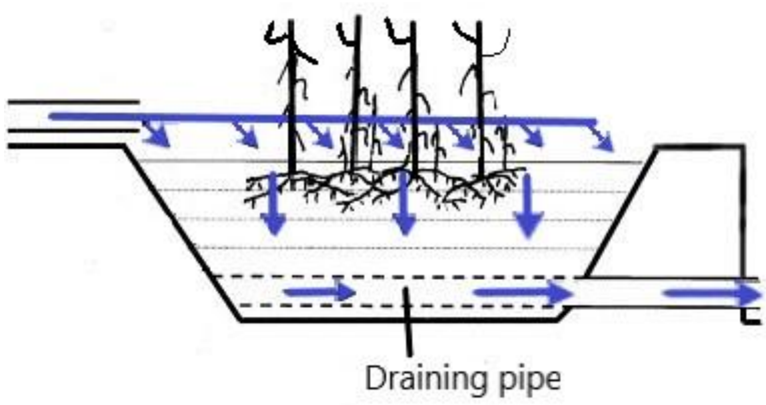

Figure 3.12. Scheme of a Vertical Flow Constructed Wetland.

An advantage that this solution present is required area, which is lower than the HFCSWs. The removal of ammonia nitrogen is high, however, as the process is run by aerobic conditions, denitrification is not achieved, leaving a high NO_3^- concentrated effluent.

By looking back into the VF and HF CWs´ pollutant removal efficiency, it seems that the weaknesses of one are the strengths of the other, and vice versa. Hybrid systems are conceived as the solution to confront this issue. They consist of various parallel VFCWs follower by a HFCW, thus achieving an efficient removal of total nitrogen. Figure 3.13 shows an example of a hybrid system.

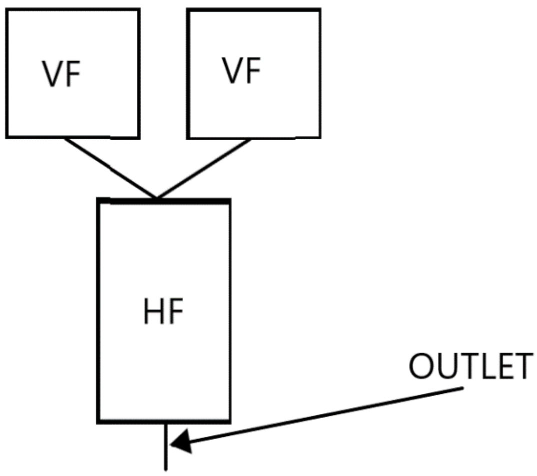

Figure 3.13. Scheme of a Hybrid system. The VFCWs establish a regular rotation in order to have a draining phase to recover, and the HFCW works continuously.

The results achieved with a hybrid system are better than those obtained with an individual system (Vymazal, 2011). Two problems are identified: first of all, the use of this method requires the installation of a small automatic device to periodically alternate between the parallel VFCWs. The other problem is the existence of a sewer that connects with the ditch halfway through its length. Water from that pipe will most likely lose the initial step of the system, therefore not obtaining an optimal pollutant removal.

As a summary, the advantages and disadvantages of the alternatives proposed for the Area 2 are exposed on the Table 3.2.

Table 3.2. Conclusions for the alternatives proposed in Area 2.

	SFCW	HFCW	VFCW	Hybrid Wetland
Hydraulics	Slight reduction of overflows during rainy/stormy weather	Minimum reduction of overflows during rainy/stormy weather	Minimum reduction of overflows during rainy/stormy weather	Low reduction of overflows during rainy/stormy weather
Water quality	Reduction of TSS due to settling Reduction of polllutant loads: TN, TP, NH4, NO3, BOD5	Excellent nitrate, heavy metal, organic compounds and suspended solids removal	Excellent Ammonia nitrogen, heavy metal, organic compounds and suspended solids removal	Excellent Ammonia nitrogen, Nitrate, heavy metal, organic compounds and suspended solids removal
Health, Social and Physical Wellbeing	Increase of green areas Increased recreational activity Beautification of the place	Increase of green areas Beautification of the place	Increase of green areas Beautification of the place	Increase of green areas Beautification of the place
Ecosystem improvement	Increased biodiversity	Increased biodiversity	Increased biodiversity	Increased biodiversity
Risks/downsides	Areas where water does not refresh Lose of effectiveness during cold weather Lose of effective volume due to sediment settling	Clogging due to accumulation of the suspended solids Low removal of phosphorous and ammonia nitrogen	Clogging due to accumulation of the suspended solids Need to stablish a rotatory system Low removal of phosphorous Lack of NO3 removal	Clogging due to accumulation of the suspended solids Need to stablish a rotatory system Low removal of phosphorous
Costs	Medium implementation costs due to construction works Low maintenance costs	Medium-Low implementation costs (already existing ditch) Low maintenance costs (depending on how quickly it clogs)	Medium-Low implementation costs (it requires a small area, but several need to be constructed for rotation) Low maintenance costs (depending how quickly it clogs)	Medium-Low implementation costs (already existing ditch) Low maintenance costs (depending on how quickly it clogs)

3.4.3. Area 3

The Area 3 covers a small extension of terrain, the last part of the water course before it flows to the Baltic Sea. The water from the main ditch is directed to an underground pipe near a small industrial area. The proposal for this area will be to construct a water retention structure, such as a storage tank. The logic behind this is to have control structure as much downstream as possible, in order to control all the water that is running through the studied ditch. In addition to the storage tank, a flowmeter and a continuous probe will be placed, in order to take measures on the flow and water quality. The water quality readings, along with the flow will help understand what happens on the underground zone between the Area 2 and the Area 3. Furthermore, they will provide information to a Real-time controller, which will operate a sluice gate in order to divert water into the storage tank. This RTC will be fed by the inputs of the flowmeters and probes from the previous areas, performing corrective actions on the sluice gates. In addition, the storage tank will have a water pump which will, in case of need, pump the water from the storage tank to the beginning of the Area 3, at the inlet of the constructed wetland. The overall scheme for the Area 3 can be observed in the Figure 3.14.

The retention tank will have an oil skimmer, in order to remove the oils and fats contained on the water. The type of skimmer selected will be a belt skimmer, because of its versatility and low operational costs.

The Table 3.3 shows the overall analysis of the alternatives proposed for Area 3.

Figure 3.14. Proposal for the Area 3. The black circle represents the storage tank and the belt oil skimmer, the yellow triangle will be the location of the flow-meter and the continuous probe, and the red line is the pipe that connects the water storage tank with the beginning of the Area 2.

Table 3.3. Analysis of the alternatives proposed for Area 3

	Concrete storage tank + pump	**Oil skimmer**
Hydraulics	Reduction of overflows during rainy/stormy weather Storage of water for controlled release	N.A.
Water quality	Slight reduction of TSS due to settling	Removal of oils from the water surface
Health, Social and Physical Wellbeing	N.A.	N.A.
Ecosystem improvement	N.A.	N.A.
Risks	Failure of the pump Cracks that may deteriorate the integrity of the structure Lost of volume due to settling of sediments	Equipment malfunction Low effectivity due to low residence time of water in the tank
Costs	High-medium implementation costs Medium maintenance costs	Low implementation costs Low maintenance costs

For clarification, the costs of the alternatives proposed in Tables 3.1-3.3 are compared among each other. As a result, the CWs are determined to have a medium-low implementation costs when compared to the other techniques proposed here, such as the storage tank and the pump, or the natural storage tank.

3.4.4. Determination of the substances to be monitored and selection of the control model

A part of the proposal of this thesis is also directed to the monitoring of data from water quality and quantity parameters. This data will in fact provide a feedback to the control system in order to operate towards the most efficient way of pollutant reduction, as well as improving the knowledge about the efficiency of the methods proposed. Therefore, the parameters to be monitored have to be carefully selected.

As the control system is fed by the data gathered on the different monitoring points, a quick availability of data is desired. Thus, where possible the data will be monitored instantly, so the control system will have a quick and effective response.

As mentioned earlier, The Baltic Sea is quite sensible to pollution, specially coming from nitrogen and phosphorus. These substances are indeed common to majority of the studies and action plans about quality of water (Caradot *et al,* 2011, Riechel *et al,* 2016, Barone *et al,* 2019). Nitrogen can be present in the water in the form of ammonia, nitrate or nitrites, and some of the alternatives proposed are only effective towards one of these forms. For the purpose of a better understanding on the quality status of water and the performance of the techniques, it is considered to measure both the nitrate and the ammonia concentration. Phosphorous is difficult to measure online, therefore it is decided to measure turbidity instead. The monitoring stations will be equipped with probes for all the parameters indicated above.

TDS and oil are parameters to be taken into account, as the national standards stablish that they need to be monitored 4 times per year. Live monitoring of those parameters will also be included in the sampling stations.

It is also worth mentioning that parameters such as pH, temperature and electrical conductivity will be available by implementing a probe and a conductivity meter (Caradot *et al,* 2011, Riechel *et al,* 2016, Launay *et al,* 2016).

COD and BOD_5 are exceptional indicators for assessment of water quality, providing a holistic approach of the performance of the techniques implemented. However, the equipment used for continuous monitoring of this parameter, a spectrometer, is an expensive device (Caradot *et al,* 2011, Riechel *et al,* 2016). As a result, only the monitoring stations located before and after the constructed wetland on Area 2, and at the end of Area 3 will be equipped for performing the measurements.

Volumetric flow is a critical parameter for the control system, and as such it will be monitored at every sampling point. Not only it will alert the system about increases in flow rate, but also will provide information about any leakages on the CW, or the existence of an unnoticed spillout in between the Areas 2 & 3.

The structure used for the sampling is similar to the one done in the Berlin study case (Caradot e*t al,* 2011). The probes will be placed in a small container, fed with the water from the ditch or sewer by a peristaltic pump. The information will be transmitted by a data logger to the controller and a server with historical records. For the volumetric flow, a Parshall flume will be used. The structure of a Parshall flume is portrayed on Figure 3.15. The device allows to calculate the flow knowing the water depth at a specific point upstream. The water depth will be determined by a sonar.

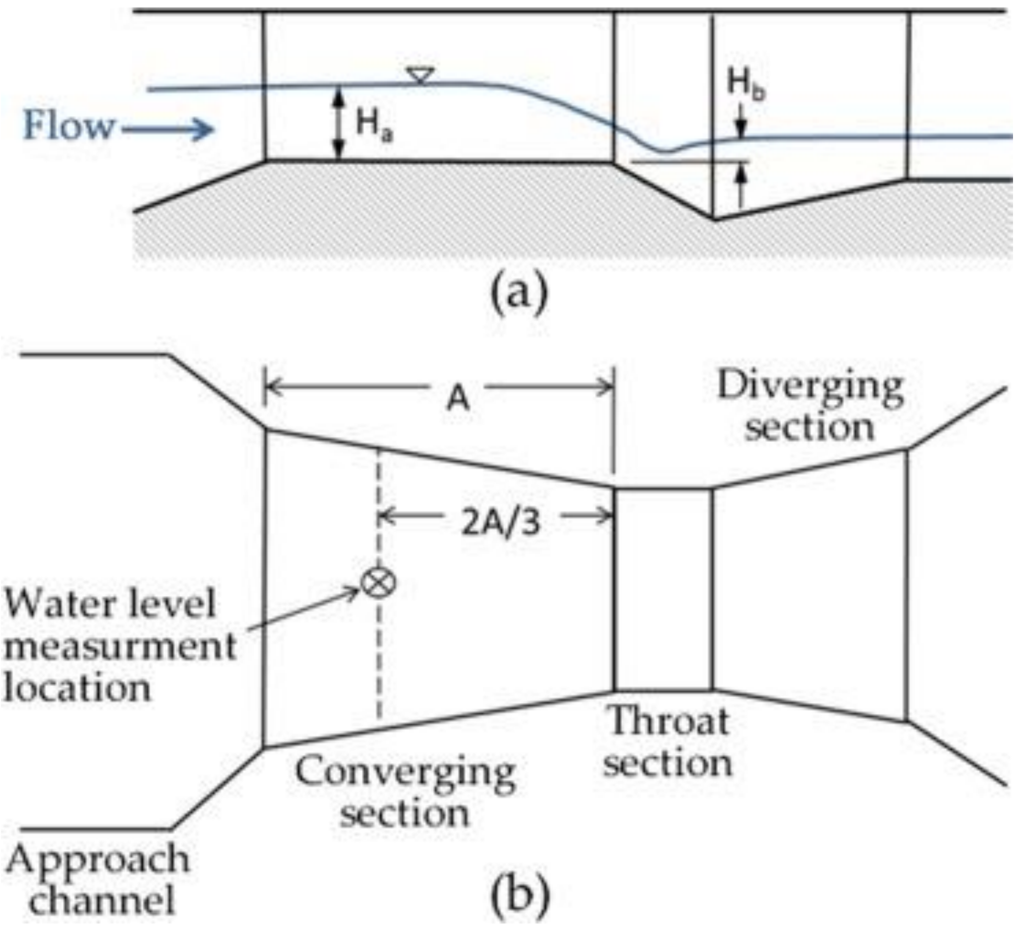

Figure 3.15. Cross-sectional (a) and aerial (b) views of a Parshall Flume (Source: Khosronejad e*t al,* 2020)

As a summary, the Table 3.4. shows all the sampling points, their locations and the parameters to be monitored.

Table 3.4. Location of the different monitoring sites, equipment used and parameters measured.

	Location	**Data collected**	**Equipment**
Monitoring site 1	At the output of the lower natural storage pond	Nitrate, ammonia, TDS, turbidity, pH, temperature, electrical conductivity, flow rate (after the sluice gate)	Sampling probes for each parameter Parshall flume
Monitoring site 2	Before the entrance of the constructed wetland	Nitrate, ammonia, TDS, turbidity, pH, temperature, electrical conductivity, COD, BOD5, flow rate	Sampling probes for each parameter Parshall flume UV-Vis spectrometer
Monitoring site 3	At the output of the constructed wetland	Nitrate, Ammonia, TDS, turbidity, pH, Temperature, Electrical Conductivity, COD, BOD5, Flow rate	Sampling probes for each parameter Parshall flume UV-Vis spectrometer
Monitoring site 4	Close to the sea outlet	Nitrate, ammonia, TDS, turbidity, pH, temperature, electrical conductivity, COD, BOD5, flow rate, oil	Sampling probes for each parameter Argus Oil-In-Water probe (Appendix 5) Parshall flume UV-Vis spectrometer

3.4.5. Selection of the constructed wetland for Area 2

Several types of CW were proposed for implementation in the Area 2. The analysis of the advantages and disadvantages of each alternative was shown in Table 3.2. As previously highlighted, availability of the surrounding land can be a problem for the SFCW. In this case, the lands located on the left side are owned by a private owner, who is planning to construct apartment buildings there. Thus, this alternative is discarded, as the price to pay for usage of these lands would be higher, in order for the owner to consider selling them.

When comparing the horizontal flow and vertical flow CWs, the main difference appears on the assimilation of different forms of nitrogen: the HFCW does not succeed on ammonia removal however it removes the NO_3^- with great efficiency, and the opposite happens to the VFCW, where the aerobic conditions favour the assimilation of ammonia into NO_3^-. Therefore, it is reasonable to go for a combined approach, placing first a series of VFCW in parallel, followed by a HFCW. The system can be repeated twice along the ditch to ensure optimal removal of all different forms of nitrogen.

The most notorious problem on this NBS is the performance under cold weather conditions. In Estonia, the freezing depth can reach to 1.8 meters below the surface on the coldest months, affecting the effectivity of nitrifying and denitrifying processes. There are two possible solutions to the problem. One could be increasing the depth of the CW´s soil, making it impossible for the cold to reach the bottom areas. The second is to try to isolate the soil by adding a layer of thick grass or wood. In any case, the impacts are not considered important, as if the weather is cold, there will be no water flow along the ditch, and precipitation will not occur in the form of rainfall but snow. Perhaps the main issue will take place after freezing season, when it might take some time and work to restore the system back to its original efficiency.

4. CONCLUSION AND RECOMENDATIONS

There are a wide range of solutions to mitigate the effects of the urbanization and climate change on the water bodies and improve the quality of the water discharged into them. From gray infrastructure to nature-based solutions, the benefits reported are diverse, with a significant reduction on the amount of pollutants on water and the number of CSO events. The combination of both green and gray infrastructure is the way to go, but the real challenge lies in designing and adapting the techniques to the given situation, according to parameters such as the social benefits, budget, hydraulics or availability of space. The monitoring of substances plays an important role in determining the overall performance of the solutions, providing a historical record and informing if the threshold values have been surpassed. Data gathering will help understand better the processes underlying the UDS, both physical and chemical, opening the gate in the future for more accurate and efficient techniques.

The research of this thesis ends with the proposal and selection of best techniques, since the implementation of those, as well as the validation of results depends on whether the proposals aforementioned are approved and executed or not, and even in the case they will be implemented, it may require some time to elaborate a conclusion. However, future developments are also proposed as a way to complement the already existing infrastructure. As mentioned in this thesis, optimal control of the UDS results on a better performance, minimizing the risks of the system. There are some parts of the UDS in Viimsi such as the sluice gates which need to be opened and closed or switched on and off in the case the pump is activated. Manual control means that an operator needs to be available, going to the place to execute the actions. It is suggested to install a real-time controller to control the whole system. Various data from the monitoring point will provide the input to the RTC, whose operating way is based on the one proposed by Vezzaro *et al* (2014). Each substance will be given a threshold value, that cannot be surpassed. Once the monitoring site 4 (located close to the sea outlet) detects a higher value, a corrective action is executed. This usually consists diverting the water into the storage tank, and depending on the oil content of it, the activation of the oil skimmer. The flow readings at the input and output of the CW will provide critical information, helping to determine if the CW is operating at its maximum capacity. Based on that, the pump located on the water storage tank will activate or not.

There is a proposal to connect the RTC with the Meteorological Agency. The idea is to receive an input on the weather forecasting and based on the intensity of the rain in the incoming days, the system will prepare to act in advance, with actions such as emptying the storage tanks to the lowest level or adjusting the flow rate at each sluice gate during the rains, so the system can absorb the overflow without releasing any out-of-standards water. The natural retention tanks can also be used as settling tanks, and the readings of the outputs will provide an idea of the ongoing situation (whether the water quality is decreasing and therefore emptying of the natural tanks should be prioritized, or the retained water is improving its quality thanks to the plants and microorganisms action).

In order to carry the desired actions in the most effective way, the corrective actions will be flexible. This means, the order should not be just fully opening of the sluice gates or fully closing of them, but all the possibilities in between. The flow rate will provide a magnitude of the degree of opening of the sluice gates, which will help the RTC understanding the procedure. As the complexity of the system is really low, it is assumed that the RTC will perform properly, allowing a quick response. The RTC, together with the new solutions implemented in the Areas 1, 2 and 3 should provide an excellent reduction of pollutants, as well as a control tool for any unwanted overflow of storm water during heavy rains, while also promoting social welfare and ecosystem sustainability.

In short, this thesis succeeds on providing an extensive review on the water quality monitoring and control techniques for urban water systems, and favorably proposes a selection of the best techniques applied to a real case study. However, data and performance results of the proposed techniques cannot be obtained, as the proposal may not be taken into consideration and in case it would more time will be needed to get some conclusions.

SUMMARY

This thesis provides an overview on the current state of art of water quality driven UDS, highlighting the improvements and benefits of implementation of new alternatives into real life scenarios. After a theoretical review, a case study is presented based on the Interreg Central Baltic Programme CleanStormWater project which is run in Viimsi, Estonia parallel to this thesis. The aim is to design and propose the best techniques to be implemented into the already existing UDS, in order to improve the water quality and provide control against storm water overflows during heavy rain periods. The choice of the new nature-based solutions and grey infrastructure is carried out after the monitoring phase, where several water parameters were measured in the urban drainage network where the project will be conducted. Aspects like hydraulics, availability of space, social benefits, risks and budget were analyzed in order to determine the best technique from the alternatives reviewed at the beginning of the thesis. The best technique is selected based on the aforementioned aspects, and its design, adaptation and implementation into the Viimsi UDS is detailed. An online monitoring system is projected within the UDS, in order to analyze its performance, and gather data for future improvements on projects of this type. Further implementation of a real-time controller is suggested as an efficient way to operate the system, seeking for optimization of the infrastructure via feedback from the different online monitoring points installed throughout the UDS, resulting on the lower environmental impact of the effluent into the Baltic Sea. The absence of results due to the fact that the proposal is neither approved nor constructed is an obstacle to the withdrawal of any final conclusion, however the forecasts about the effectivity are positive, and this is believed to be a very reliable and cost-efficient technique.

KOKKUVÕTE

Käesolev töö annab ülevaate vee kvaliteedi põhistest sademeveesüsteemide juhtimise metoodikatest ning toob esile alternatiivsete lahenduste rakendamise positiivsed mõjud reaalsetes sademeveesüsteemides. Valdkonna teoreetilise ülevaate järgselt on töös ära toodud Viimsi valla pilootalal põhinev juhtumi uuring, mis baseerub käimasolevale Interreg Kesk-Läänemere programmi projektile CleanStormWater. Töö eesmärk on välja pakkuda parimad praktikad ja planeerida sobivad lahendused, mille abil parandada vee kvaliteeti olemasolevas sademeveesüsteemis. Planeerimise esimeses etapis viidi läbi veekvaliteedi monitooring, mille käigus analüüsiti vee kvaliteedi parameetreid seitsmes erinevas punktis. Selle järel on välja pakutud looduslähedastest ja ehituslikest lahendustest kombineeritud süsteemid, mille abil parendada Viimsi piloodi sademeveesüsteemi võttes arvesse nii hüdraulikat, ruumi olemasolu, sotsiaalseid hüvesid, kaasnevaid riske ning eelarvet. Lisaks on välja pakutud reaalajas monitooringu lahendus, mis võimaldab hinnata süsteemi olekut ning analüüsida võimalike süsteemi parendusvajadusi. Reaal-aja juhtimise kontrolleri rakendamine võimaldaks efektiivselt süsteemi juhtida lähtudes mõõtmisandmetest ja süsteemi optimaalsest käitamisest, et vähendada Läänemere reostuskoormust. Kuna süsteemide välja ehitamine ja rakendamine on planeeritud pärast käesoleva töö valmimist, siis süsteemi efektiivsust on hinnatud ainult teoreetiliselt. Esmastel hinnangutel on pakutud lahendused toimivad, usaldusväärsed ning kuluefektiivsed.

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APPENDICES

Appendix 1. Table of monitoring results throughout 2020.

	Date	10/30/2020	11/13/2020	11/20/2020	11/27/2020	12/04/2020	12/11/2020	12/17/2020	08/04/2021	15/04/2021	23/04/2021	29/04/2021
Sampling point 1.1	temp	9,9	8,1	6,2	6,2	5	3,9	4	5	5,5	6,5	6,6
	TDS (Total dissolved solids)	576	623	418	611	635	800	567	735	710	695	720
	pH	8,15	8,07	7,98	8,24	8,03	8,12	8,1	8,25	8,31	8,12	8,3
	NO3	9,6	4,4	15,23	17,21	4,57	7,4	2	-			
	Cond.	628	638	406,6	602	586	730	519	697	673	664	703
	Q_estimated	w=1.2m; d=3cm	d=4 cm						0	0	0	0
	comments	outlet channel							depth 34 cm			
Sampling point 1.2	temp	10,1	8,2	6	6,1	5	3,7	4	5	5,5	6,5	6,6
	TDS	577	628	420	610	636	942	571	751	727	690	722
	pH	8,06	8,11	8,44	8,36	8,11	8,02	8,43	8,2	8,12	8,12	8,11
	NO3	9,3	4,35	13,93	17,5	21,52	7,4	1,32	-			
	Cond.	628	640	402,9	599	587	840	521	693	673	664	680
	Q_estimated	w=1.5m, d=0.3m							0,4	0,1	0,4	0,4
	comments	outflow from pipe							depth 30 cm	water didnt reach to sea		
Sampling point 2	temp	10	8,2	6,2	6,4	5,3	3	4,5	5	5,7	6,2	6,8
	TDS	588	671	410	654	660	660	606	751	744	690	742
	pH	8	8,03	7,95	8,04	8,02	8,3	8,25	7,86	8,25	8,27	7,22
	NO3	11,7	4,14	18,36	16,71	6,12	5,6	2,7	-			

	Cond.	635	686	391,2	631	601	570	555	691	687	667	708
	Q_estimated	video, d=20cm	d=20cm; w=50cm									
	comments	-							depth 17cm			
Sampling point 3.1	temp	9,15	6,8	6,6	6,9	5,9	3,6	5,2	5,5	6	6,5	7
	TDS	529	598	403	679	648	765	560	771	795	694	787
	pH	7,85	7,98	8,22	7,96	8,11	8,04	8,18	7,9	8,1	8	8,11
	NO3	9,5	3,8	12,44	17,19	6,67	6,03	4,3	-			
	Cond.	559	601	411,7	661	605	663	567	717	740	677	742
	Q_estimated		d=12cm; w=1 m						0,1	0,1	0,1	0,1
	Comments								depth 16 cm			
Sampling point 3.2	temp	10	8,4	4,9	6,9	3,7	2,7	5,2	4,8	6,2	7,2	6,7
	TDS	604	648	350	547	608	662	610	694	671	644	650
	pH	7,94	8,12	8,01	7,94	8,02	8	8,26	8,07	8,61	8,32	8,3
	NO3	14	3,7	9,12	15,32	7,09	4,4	4	-			
	Cond.	654	663	321,3	516	549	573	567	633	625	636	626
	Q_estimated	video							0,2	0,1	0,2	0,2
	Comments	from pipe outlet							depth 16 cm			
Sampling point 4	temp	9	6,9	4,5	5,4	3,8	3,1	2,5	5	9	7,7	6,8
	TDS	515	618	353	546	600	680	560	771	640	640	626
	pH	7,9	8,26	8,5	7,85	8	8,1	8,1	8,17	8,16	8,17	8,2
	NO3	9	3,3	10,19	14,7	7,05	6,5	4	-			
	Cond.	555	600	327	514	550	580	521	694	680	650	628
	Q_estimated	no flow	no flow						-			

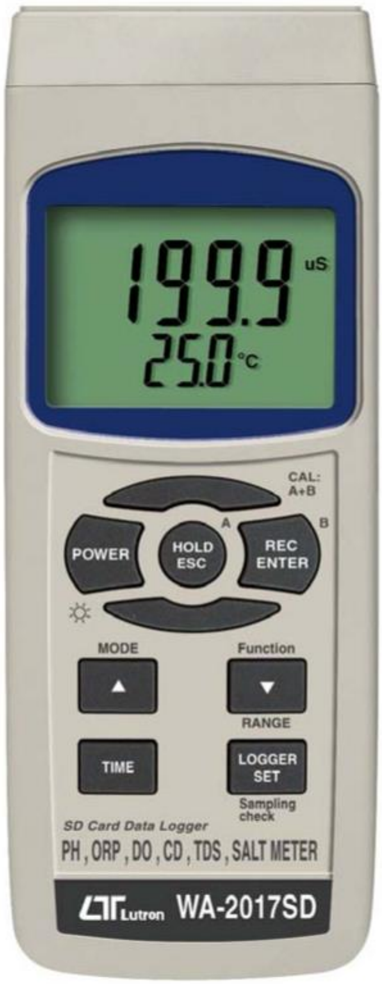
	Comments	water stinks							depth 23 cm			
Sampling point 5	temp	9,1	6	5,6	4,9	5,6	3,9	3,7	5,1	7,2	7,4	7,9
	TDS	483	598	560	527	563	620	550	642	590	578	550
	pH	7,65	8,01	7,85	7,65	7,61	7,8	7,7	8,24	8,41	8,62	8,34
	NO3	4,8	3	9,72	12,12	10,08	3	2,2	-			
	Cond.	590	578	537	500	603	620	571	562	587	565	573
	Q_estimated	0,5							0,2	0,2	0,2	0,2
	Comments								depth 10 cm			
Sampling point 6	temp	9,4	7	5,8	5,4	4,1	2	4,5	7	8,1	7,6	9,5
	TDS	576	563	515	582	536	555	539	567	521	539	535
	pH	8,06	8,4	8,27	8,13	8,27	8,23	8,1	8,07	8,34	8,35	8,32
	NO3	13	3,3	10,07	20,32	9,2	5,3	4	-			
	Cond.	603	574	502	546	510	470	521	560	578	561	601
	Q_estimated	video							0,1	0,1	0,1	0,1
	Comments	-							depth 15 cm			
Sampling point 7	temp	11,75	9,9	8,2	7,4	6,3	5,7	5,3	5,4	6,4	6,9	7,6
	TDS	555	637	500	571	565	580	551	590	582	553	570
	pH	8,07	8,14	8,09	8,05	7,99	8,2	8,2	8,24	8,11	8,14	8,29
	NO3	4,3	5,36	23,68	30	7,48	8,8	2,9				
	Cond.	-	673	515	587	540	590	522	562	566	557	568
	Q_estimated (l/s)	0,75							0,2	0,2	0,2	0,2
	Comments	-							depth 10 cm			

Appendix 2. Extract from the manual guide of Multimeter Lutron WA-2017SD

SD card real time datalogger

pH, ORP, CD, TDS, DO, SALT METER

Model : WA-2017SD



Your purchase of this pH, ORP, CD, TDS, DO, SALT METER with SD CARD DATALOGGER marks a step forward for you into the field of precision measurement. Although this DATALOGGER is a complex and delicate instrument, its durable structure will allow many years of use if proper operating techniques are developed. Please read the following instructions carefully and always keep this manual within easy reach.

OPERATION MANUAL

Appendix 3. Extract from user guide of YSI Professional Plus.

INTRODUCTION

Thank you for purchasing the YSI Professional Plus (Pro Plus), one of seven new instruments from the YSI Professional Series product family. The YSI Professional Plus features a waterproof (IP-67) case, backlit display and keypad, user-selectable cable options, USB connectivity, large memory with extensive site list capabilities, and a rugged, rubber over-molded case.

Reading the entire manual before use is recommended for an overall understanding of the instrument's features.

GETTING STARTED

INITIAL INSPECTION

Carefully unpack the instrument and accessories and inspect for damage. Compare received parts with items on the packing list. If any parts or materials are damaged, contact YSI Customer Service at 800-897-4151 (+1 937 767-7241) or the authorized YSI distributor from whom the instrument was purchased.

BATTERY INSTALLATION

This instrument requires 2 alkaline C-cell batteries. Battery life depends on parameters and usage. Under normal conditions, battery life is approximately 80 hours for continuous use at room temperature. To install or replace the batteries:

1. Turn the instrument over to view the battery cover on the back.
2. Unscrew the four captive battery cover screws.
3. Remove the battery cover and install the new batteries, ensuring correct polarity alignment on the instrument or the removed cover. (Figure 1)
4. Replace the battery cover on the back of the instrument and tighten the four screws. Do NOT over-tighten.

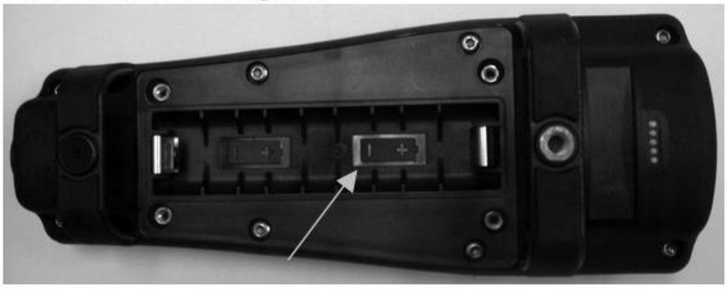
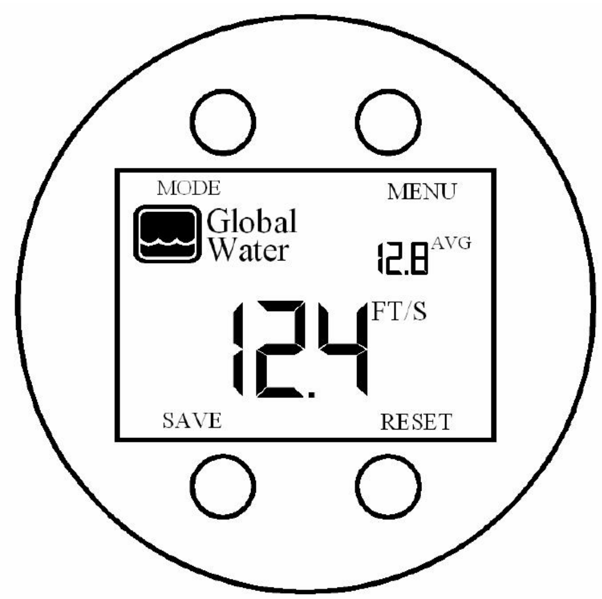


Figure 1. Pro Plus with battery cover removed. Notice battery symbols indicating polarities.

1

Appendix 4. Extract from user guide of Global Water Flow Probe.

Global Water
800-876-1172 • globalw.com



FP111-FP211-FP311 Global Water Flow Probe User's Manual

Global Water
151 Graham Road
P.O. Box 9010
College Station, TX 77842-9010
T: (800) 876-1172
Int'l: (979) 690-5560, F: (979) 690-0440
E-mail: global@globalw.com

01-994
Publication Number 38330112

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Appendix 5. Extract from product data sheet of Oil-In-Water Probe.

MEASUREMENT

Measurement principle
Laser Induced fluorescence (LIF)

Sensor probe configuration
In-line

Number of measuring points per control unit
1 – 4

Number of measuring points per cabinet
1 – 12

Measurement range oil in water
0 –3000 mg/l Note 1

Measurement repeatability oil in water < ± 1 % Note 2

Measurement range
Turbidity: 0 – 1000 FNU
TSS: 0 – 100 mg/l

Sampling frequency
1 reading per second

OPERATIONAL CONDITIONS

Process temperature
-29 – 149 °C

Ambient temperature
-20 – 65 °C Note 3

Design / operating pressure
0 – 100 barg Note 4

Pipe dimension
≥ 2”

Flow velocity
< 10 m/s

MAIN COMPONENTS

1. Control unit
   (electronics and communication)
2. In-line measurement probe
3. Retraction tool for safe probe extraction under operation

PROCESS CONNECTION

2” 150/300/600# RF/RTJ flange

Connection flange orientation
0 - 360°

Probe insertion length
Recommended 1/3 of pipe ID

Standard material, probe and retraction tool wetted parts
22Cr Duplex (UNS S31803),
titanium gr.5 Note 5

Weight, probe and retraction tool
typical 17-35 kg

CERTIFICATION

2014/68/EU Pressure Equipment Directive
2014/34/EU ATEX Directive
2014/35/EU Low Voltage Directive
2014/30/EU EMC Directive

POWER SUPPLY

Supply voltage Control unit
110 – 240 VAC, 50/60 Hz, 16A

Power consumption
200-300 W (average)

INSTRUMENT INTERFACE

Ethernet
Ethernet hard wire (standard)
Ethernet 10/100 Mbps,
hard wire (standard)
2.4 GHz WIFI, 3G/4G/5G service (optional)
Modbus TCP/IP (standard)

Serial
Modbus RS 485 RTU (optional)

Analogue
4 - 20 mA, HART (optional)

Self-cleaning technology (Patented)
Ultrasonic cleaning

Cleaning intervals
Configurable

NOTES

1. Measurement range above 3000 mg/l on request. Possible measurement range depends on oil composition and API
2. Repeatability measured on a stable fluorescent object for example Argus check
3. Ambient temperature over 40°C requires cooling
4. Higher pressure available on request
5. Other materials are available on request