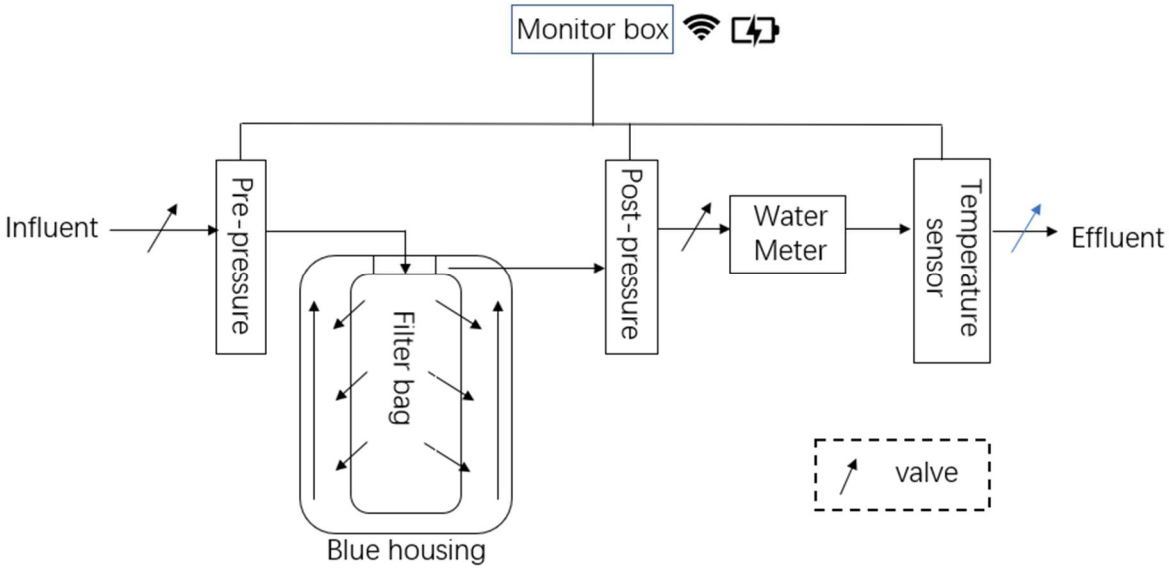
Smart Water Meters in Full-scale Drinking Water Distribution Networks (DWDNs)



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By

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Yingfei Zhang

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Abstract

For drinking water companies in Netherlands, the current conventional treatment technique may not be fully capable to cope with potential future problems resulted from climate change, salinization and social developments, such as population growth. Innovative technologies like reverse osmosis and more strict drinking water standards are expected to be applied to provide better water quality to customers.

In Oasen drinking water company, reverse osmosis has been applied in Lekkerkerk drinking water treatment station since 2016 to prepare for the future challenges, while potential transition effects like biofilms detachment and resuspension of loose deposits in the drinking water distribution systems might occur under irregular changes caused by supply water switch. A setup named Smart Water Meter was developed and used with integrated functions, such as seizing particles inside distribution networks and monitoring several parameters, to investigate this phenomenon. Although slight and temporary transition effects were captured with the help of this device, the amount of retained materials were not sufficient for transition effects study. According to the company, new treatment stations are being planned where background information is required to be collected and still potential transition effects might occur.

The main objective of this research was to optimize the Smart Water Meter for future transition effects study by re-selecting the pore size of the filter bag to make it more sensitive and install the upgraded setups in four different locations under different water quality to have a better understanding on its performance and characteristics. Before being applied into the fields, a stagnation (water retained inside the setup for a long time) test was conducted as well to figure out the feasibility of experiments simplification where water is kept flowing through the setup instead of intermittent mode and possible deterioration of the water quality.

10 microns filter bag is selected in this research after three stages tests. Results reveal that the optimized filter bag with new pore size is able to intercept more particles without arousing sudden pressure drop under normal conditions. However, if this setup could set an early alarm, like a sudden pressure drop, when serious transition effects occur remains to be checked in the future. According to the stagnation test, chemical elements concentration and biological activity increased inside the filter bag, meaning that the water quality was indeed deteriorated when it was stagnated inside the filter bag for 23 hours while the quality could go back to normal after opening both influent and effluent valves on the setup for a while. This also indicates that the simplification of experiments is acceptable.

Pore size of the filter bag may require to be reconsidered when the influent pressure in households is not sufficient, otherwise great pressure loss is inevitable. For different water quality in four locations provided by three drinking water companies, the performance of the setup is relatively reliable with a stable 100% removal rate of the particles larger than 29 microns inside the water while for the five elements, little relationship could be found. Besides, the filter bag could remove part of the living cells inside it when water keeps flowing through it. Observation of the filter bag inner surface could provide a general idea of the filtrates composition and by making chemical and biological analysis of them, possible origins of the distribution network harbored materials are conjectured. In this research, most of the distribution network harbored materials might come from detached biofilms as calcium is crucial for biofilm formation while part of the retained materials may also originate from loose deposits due to As and Aeromonas existence in some locations.

With the optimized setups and a deeper understanding of its performance under different water quality, the setup could be better applied in the future study of transition effects and early warning systems.

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List of Abbreviations

DN	Distribution network
DWDS	Drinking water distribution system
DNHM	Distribution network harbored material
DWTP	Drinking water treatment plant
RO	Reverse osmosis
ATP	Adenosine triphosphate
TCC	Total cell counting
Ca	Calcium
Fe	Iron
Al	Aluminum
Mn	Manganese
As	Arsenic
ICP-MS	Inductively couples plasma mass spectrometry
TMP	Transmembrane pressure
HNAC	High nucleic acid
LNAC	Low nucleic acid

1 Introduction

1.1 Motive

According to the National Water Plan 2016-2021, the water quality has been improved substantially in the past few years as stated by the monitoring results while meeting higher targets set by the Water Framework Directive is still a major challenge. For Dutch drinking water companies, conventional treatment technique may not be fully capable to cope with potential future problems resulting from climate change and social developments, such as groundwater salinization and population growth. Optimizing present drinking water treatment processes, applying advanced technologies and tightening relative regulations could be the main ways to guarantee water with higher quality to customers.

Oasen is a Dutch drinking water company, providing around 750,000 people and 7200 companies with safe and reliable water in the western part of Netherlands. With the sea level keeps rising and more salted water moves further into the mainland, less fresh groundwater water, which is the main source of the Oasen drinking water, will be available in the future. To provide and guarantee customers with higher water quality, advanced treatment process is required.

Membrane filtration is a pressure-driven separation process (Badu, 2016) which is increasingly becoming popular as an advanced treatment process for drinking water treatment. As one of the membrane filtration methods, reverse osmosis (RO) could retain almost all dissolved particles inside solution while let only water molecules pass through, and this characteristic can be applied to desalination. Although RO is not widely used in Dutch drinking water treatment process as the best source is always preferred for drinking water production and relatively sufficient freshwater at present, previous research conducted by Oasen revealed that RO application in Lekkerkerk area greatly reduced the nutrient load for bacteria and improved biological stability (Dusseldorp, 2013).

Meanwhile, sudden modification of supply water treatment and dramatic change of drinking water quality will in turn arouse inevitable destabilization/restabilization of drinking water distribution systems (DWDS) ecology (Jiaxing, 2017), where biofilms detachment and loose deposits resuspension might occur, leading to the deterioration of the water quality at end users and water meter clogging problem. With the purpose of a better understanding of this phenomenon and prevent it as early as possible, a special setup named Smart Water Meter was innovated by the company with integrated functions to capture and further study these

changes, such as seizing particles inside distribution networks, monitoring and automatically recording pressure, temperature and flow rate all the time.

1.2 Relevance of the project

In 2013, a RO installation pilot was constructed in Lekkerkerk to study the influence of RO on biological stability in the full-scale treatment process, which refers that the bacteria regrowth will be limited within a certain range (Oasen, 2016). In addition, several biofilm monitors were developed to investigate the effect of the switched water on biofilms growth. According to the research completed by Dusseldorp, high level of biological stability could be achieved after RO applied to the treatment plant.

With the successful pilot test, a project named 'Oasen West' was launched in Oasen supply area – ZS Lekkerkerk drinking water treatment station to officially apply RO into the field. The main project objective is to build a new treatment station in Krimpen aan de Lek with new purification technology based on RO to provide customers with better water quality in the future, along with a pipeline beneath the Lek river to transport water from the southern part to Schuwacht treatment plant.

After RO application in Lekkerkerk area and supply water switch, another research was conducted in mid-2016 by installing Smart Water Meters mentioned above in several households at the beginning of the premise plumbing to seize and investigate possible transition effects, which is defined as the physicochemical and microbiological water quality problems resulted from the destabilization and mobilization of distribution network harbored materials (DNHMs) and their release into the bulk water caused by the breakup of forces balance (Gang et al., 2017), as the Smart Water Meter was verified to be a suitable method to monitor water quality and fouling issues during the distribution process according to Zewei's study. As reported in Jaxing's research, results reviewed that transition effects did occur and was observed with the help of setups, but gradually settled down without triggering serious problems.

1.3 Objectives of the project

To capture the detached biofilms and resuspended solids inside the distribution network under transition effects, one filter bag is put inside the setup. Although setups applied in Lekkerkerk area successfully captured transition effects, according the results of the previous test conducted by Jiaxing, very few amounts of particles could be retained by the filter bag due to the large pore size when it was collected every two months. This means that this setup was

not sensitive enough to provide sufficient data for the field study. Besides, it remains uncertainty if the Smart Water Meter could set an alarm when real irregular changes caused by supply water switch occur, meaning that further optimizations are needed.

The initial plan was to keep running the improved setups in mentioned four households to continue studying potential transition effects in DWDN after supply water switch from a long term. However, according to the company's feedback, the drinking water in Lekkerkerk area is with high water quality thus no further research was needed.

Based on setups' reliable operation in four tested households, Oasen decided to apply it in more customers' houses as the drinking water treatment process in several treatment stations will be optimized and new stations are expected to be built as well in the next coming years, where potential transition effects still might take place. In the consideration that the setup was developed not a long time ago and its characteristics are remains to be discovered, a deeper understanding of the setup performance is essential and necessary to make the best use of it. For treatment stations which are about to be upgraded, this setup could also collect early water quality information used for comparisons after advanced process applied.

Therefore, the main objectives of this research are to optimize the setup firstly to provide more data for future potential transition effects study and then install it in different area with separate water quality to have a clearer grasp of the setup characteristics.

1.4 Research questions

This research is divided into two parts in all. The first part is to optimize the present setup for that the original version did not live up to our expectations. Considering that more setups will be put into more households for transition effects study in different area after treatment stations have been upgraded, the second part is to further test the improved setup under different water quality to get more knowledge of its characteristics for future applications.

1.4.1 Primary research question

The main primary research question is about optimization:

- *How to optimize the setup to make it more sensitive?*

Sub-questions need to be investigated to answer this primary question:

- *What is the proper pore size for the filter bag in the setup?*

- *Will the filter bag with the new pore size clog when discoloration caused by transition effects occurs?*

1.4.2 Secondary research questions

Limited by the time, distance and traffic conditions, it is not realistic to simulate exact the same circumstances in households. To simplify the experiments, water will keep flowing through setups within several hours instead of intermittence operation in real daily life. One problem is that the water inside the filter bag will remain stagnated for a long time after tested hours and such a stable environment with higher temperature might induce the biological regrowth and deteriorate the water quality of the tap water as the setup was installed at the beginning point of the premise plumbing, which also applied to that in daily households especially in the evening or during vacation. Therefore, stagnation should be simulated to make sure that its influence could be ignored or acceptable for further tests and application.

The main secondary research questions are more focused on the setup performance:

- *Will the long hydraulic retention time of the filter bag(stagnation) influence the water quality at the tap water?*
- *How do setups perform under different water quality (setup characteristics)?*

Materials retained by the filter bag may have different origins like detached biofilms or loose deposits. By making certain chemical and microbial analysis, possible conclusions could be deduced for a better understanding of changes inside the distribution network.

Sub-questions need to be investigated to answer this secondary question:

- *Can the retained materials inside the setup indicate their origins?*

2 Background

Background information of three drinking water companies where setups are installed, as well as the drinking water treatment process is presented. Most part of it is written according to their official websites. Drinking water delivery pathways where potential transition effects and stagnation problems might occur are also discussed. Significance and necessity of the measured indicators are introduced as well.

2.1 Drinking water company

Three drinking water companies Oasen, Dunea and Evides are mentioned in this research for that these three companies provide water with distinct water quality for setups test. Different water sources and treatment process are the main reasons contributed to it, and will be introduced in details below.

2.1.1 Oasen Drinkwater

2.1.1.1 'Oasen-West' project

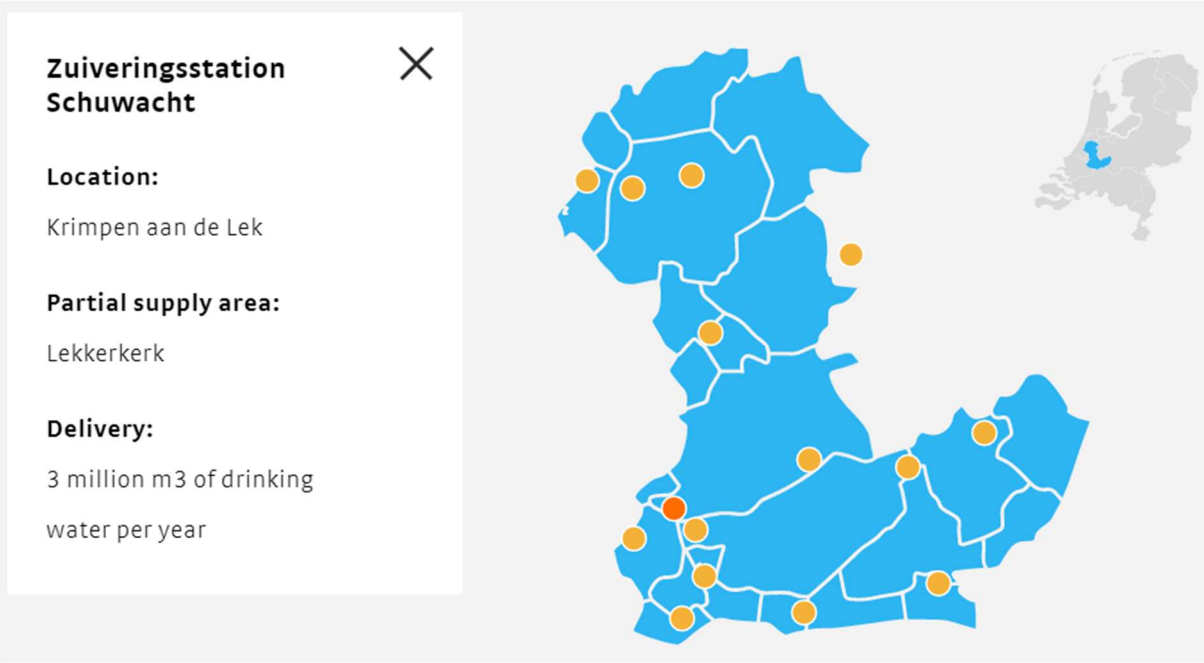


Figure 2-1 Oasen supply area and pumping stations map.

It can be seen from the Figure 2-1 a number of drinking water sources of Oasen are located in the western part of Netherlands. Although salinization currently is not a direct problem for Oasen as bank filtrated groundwater is used in the supply area, a rising sea level and gradually decreased river water levels due to climate change, such as global warming, are expected in the future. The saltwater would move further into the land and the groundwater would get saltier than the regulated as stated by the drinking water standards, as a result of which the conventional treatment technology could not cope with. Therefore, the 'Oasen-West' project was launched to take a step ahead of future challenges by improving the drinking water quality and security, where a new treatment station Schuwacht in Krimpen aan de Lek (orange point in Figure 2-1 with new purification technology based on the reverse osmosis was built. Reverse osmosis is the finest membrane filtration method avaible by now (Dahlberg, 2019,). It is chosen not only for the salination, but also to remove micro organic pollutants such like pesticides.

2.1.1.2 Treatment process

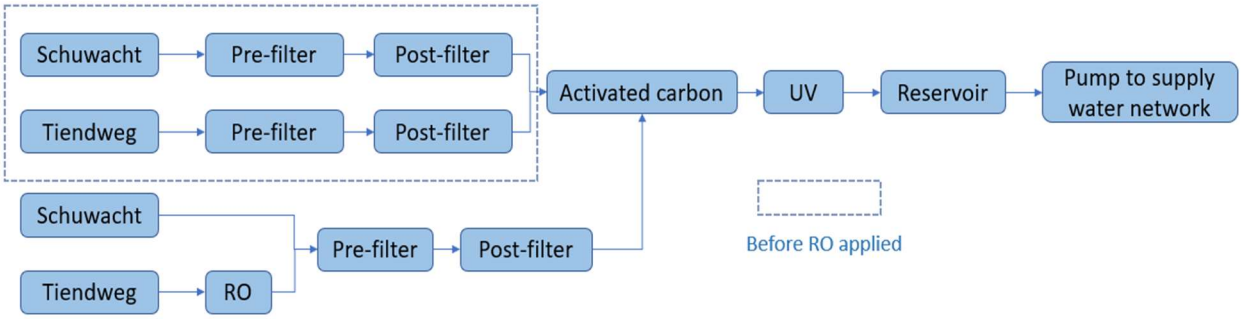


Figure 2-2 Configuration of the treatment process at ZK Lekkerkerk (before and after RO applied).

Figure 2-2 gives an overview of the treatment process in ZS Lekkerkerk in two periods. Before RO applied to the purification, groundwater extracted from well Schuwacht and Tiendweg was mixed (50/50) before pre-filtration. Since June 2016, 50% of the raw water taken from Tiendweg first went through the RO system and then combine with another 50% of the raw water extracted from Schuwacht, followed by the previous treatment steps.

The bank filtrated deep groundwater is extracted and aerated by using sprinklers to oxidize dissolved metals ($Fe^{2+} \rightarrow Fe^{3+}$, $Mn^{2+} \rightarrow MnO_2$) and volatile organic chemicals, as well as remove dissolved gases such as hydrogen sulfide, carbon dioxide and methane. A two-step filtration is followed where the pre-filter is a double layer consisted of sand and anthracite and the post-filter is a large container with fine sand. After that, filtered water goes through the activated carbon to adsorb organic matters, taste and odor. UV disinfection is the last safety precaution to kill any remaining bacteria in the effluent.

2.1.2 Dunea Duin & Water

Delftgauw, who consumes water supplied by Dunea, is selected as one of the test locations as it is close to the TU Delft. Dunea supplies around 73 billion litres of drinking water to 1.3 million people every year. The drinking water provided by Dunea comes from the dune water, part of which is the pre-purified Dammed Maas river.

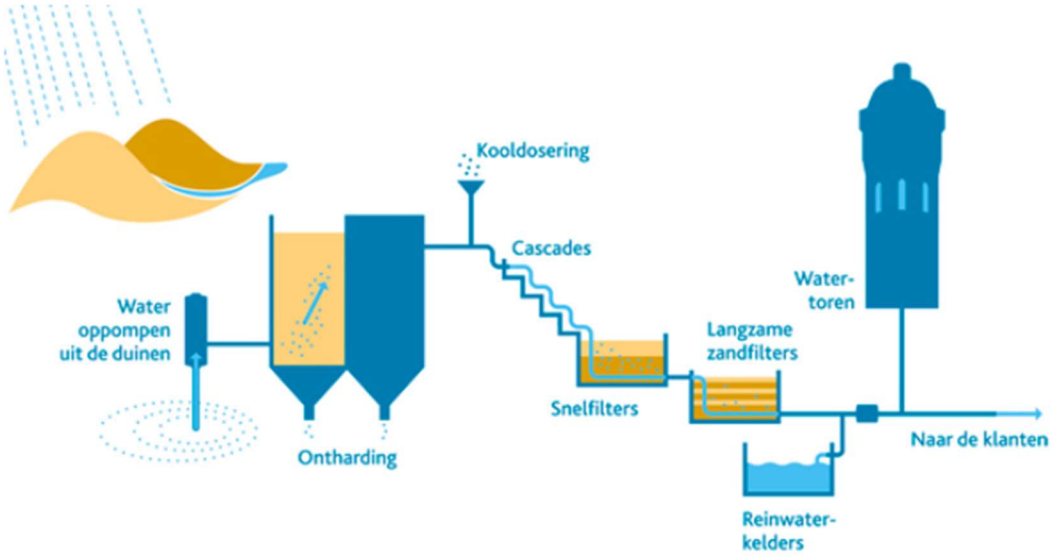


Figure 2-3 Configuration of Dunea drinking water treatment process (Dunea, 2019).

The Afgedamde Maas is a branch of the river Maas and has a low current, making it a large reservoir with long residence time for self-purification where pollutants are decomposed with the help of physical, chemical and biological processes. Before collecting and pumping the river water to the dune area which functions like a filtration tank to bring down the harmful bacteria and viruses, it is pre-treated by dosing iron sulphate and oxygen to reduce the phosphate concentration. After slowly flowing to the bottom of the dune, the water will be mixed with the fallen precipitation and together be pumped to the treatment plant for normal production progress.

As shown in Figure 2-3, the recovered water first goes through the sand pellet reactor to lower the hardness by adding caustic, and activated carbon is also dosed into the water to improve its taste. After that, the water is pumped via cascade aeration and rapid and slow sand filters to oxidize the iron and manganese ions and remove the activated carbon particles. The purified water will be stored in reservoirs for consumption.

2.1.3 Evides Waterbedrijf

Evides receives water from three different sources: surface water, infiltrated dune water and groundwater, each of which corresponds to different production process. For each household, its water source can be checked on Evides website by entering the postcode. The post code of the TU Delft Waterlab is 2628 CN, thus the drinking water comes from the production locations Beernplaat and Kralingen (two different DWTPs), whose raw water source is Biesbosch basin water.

The configuration of Evides drinking water treatment process is presented in Figure 2-4. After taking surface water from the river Maas, it first passes through three large reservoirs in the Brabant Biesbosch where water quality could be improved due to strong self-cleaning capacity under long residence time and then be pumped to the drinking water treatment plants. Micro sieves and double-layer filters, along with the added floccutants, follow after the pre-treatment to remove both coarse and fine particles inside the water. Ultraviolet light is used for disinfection to kill the bacteria. Activated carbon filters ensure the acceptable taste, colors and odor.

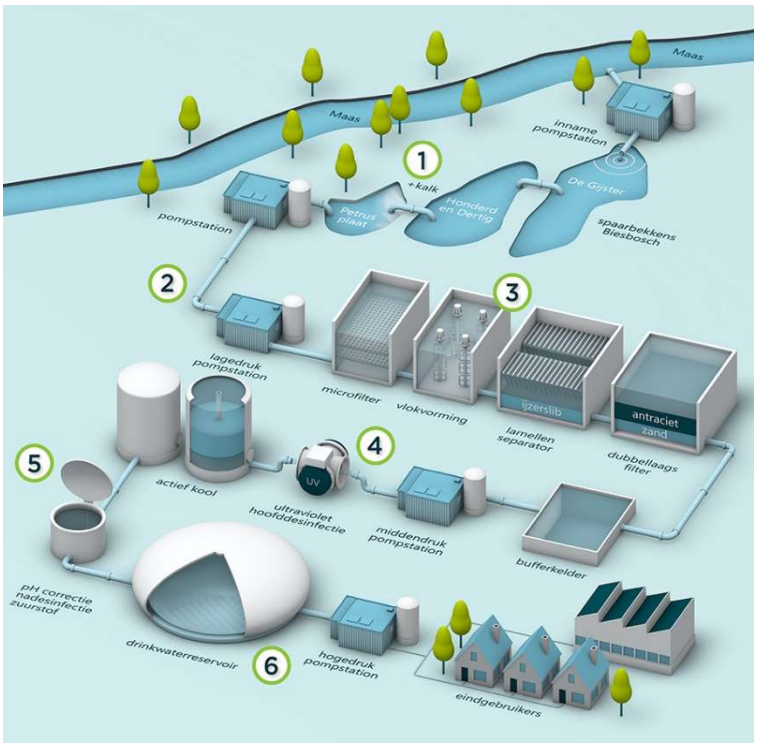


Figure 2-4 Configuration of Evides drinking water treatment process (Evides, 2019).

2.2 Drinking water distribution networks

The tap water quality is impacted by a series of factors like raw water source, treatment process, and one of the most important – drinking water distribution networks (DWDNs) which is regarding to the pipe material, age, length, hydraulic retention time and other factors (Reynolds, 2007). The treated drinking water stored in reservoirs of drinking water treatment plants is pumped to DWDS with physical loads (particles), microbial loads (cells) and nutrient loads (organic and inorganic nutrients), and enters end users through premises plumbing (Liu et al., 2017). These two parts (DWDS and premises plumbing) consist of the pressurized drinking water distribution networks (DNs) (Mays,1999; Ainsworth, 2013). The premises plumbing is defined as the pipes along with other appurtenances within buildings to distribute water to the point of use (NRC, 2006) In Netherlands, unchlorinated drinking water with sufficient water quality is guaranteed mainly by limiting biodegradable organic carbon concentrations and restricting microbial growth materials (Learbuch et al., 2019). However, deterioration of the water quality is inevitable due to complicated physicochemical and microbiological processes inside distribution networks.

For tracing back the origins of retained materials by the filter bag, four phases in the drinking water distribution system with different characteristics are defined and summarized as bulk water (flow through the distribution pipelines), suspended solids (particulate matter transported throughout the network), pipe wall biofilms (formed and attached on the inner-pipe surface), and loose deposits (substances accumulated / sedimented on the pipe bottom) (Gang et al., 2013; Gang et al., 2014). Bulk water is the most intuitive element reflecting the real-time water quality while the other three phases require accumulation. Organic matter and bacterial biomass are the main components in recent reports of the deposits in potable water systems (Echeverria et al., 2008).

2.3 Water quality stability and transition effects

One of the driving forces of upgrading the treatment process is to guarantee the water quality stability consisted of three parts - physical, chemical and biological stability. The standards included: re-suspension potential measurement (RPM, turbidity < 0.8NTU,) for physical stability; a saturation index (SI, -0.2 to 0.3) for chemical stability; and assimilable organic carbon limite (AOC, < 10 ug C/l) for unchlorinated water. (Gang et al., 2013; Vreeburg et al., 2008; Verberk et al., 2009; Van der Kooij, 1992).

It is widely acknowledged that materials contained inside DWDNs accumulate, develop and reach to a dynamic equilibrium with acceptable variation under historical environmental

conditions after a long time (Gang et al., 2017; Jiaxing, 2017). The transition effect is defined as the physicochemical and microbiological water quality problems resulted from the destabilization and mobilization of distribution network harbored materials (DNHMs) and its release into the bulk water phase caused by the breakup of forces balance (Gang et al., 2017). It can be attributed by irregular changes resulted from any external disturbance such as supply water switch, disinfectant replacement and optimization of the treatment techniques. Negative impacts of the transition impacts include but not limited to the clogging of water meters, certain water pressure drop at end users and releases of DNHMs. The release of DNHMs could lead to series problems like discoloration, one of the main reasons for customers to complain to water companies (Vreeburg et al., 2008). Therefore, it is significant to make effective evaluation for underlying transition effects and set early alarming to prevent further harms. Changes like seasonal source water quality variation and adjustment of treatment procedure can be seen regular and acceptable which will reach to a dynamic equilibrium after certain time. Transition effects may not be detected or observed until after a longer period of time of supply-water switch when it is dominated by microbiological destabilization (Gang et al., 2017).

2.4 Stagnation

Due to privacy and other reasons, drinking water companies have limited access to monitor the portable water quality inside households in most European countries (Lautenschlager et al., 2010). Premises plumbing has a longer retention time, higher temperature and smaller pipe diameters compared to the public distribution networks, inducing the regrowth of the organisms and posing a threat to the water quality. It has been realized that temperature is the fundamental factor controlling the rate of microbe's development (Rotkowsky et al., 1982). According to the existing thermal environmental conditions standards for human occupancies, the operative room temperature should be 20-23.5 degrees in winter and 23-26 degrees in summer (ANSI, 1992).

According to the available data in the previous research, water consumption is focused mainly in daytime, resulting in a long hydraulic residence time at night for the water inside the filter bag when the setup is not used, which is defined as stagnation, therefore biological regrowth is expected when it comes to the long residence time. Especially for customers not using water for a long time like during summer vacation, it is suggested by drinking water companies to open taps to flush for a while before use it.

Besides, limited by inconvenient conditions like traffic and research time, it is not possible to simulate exact the same water consumption mode in normal households, where water is

consumed for many times within a day with certain intervals especially the long time in the evening. In this research, water is kept flowing through the setup for hours without stop for experiments simplification. Therefore, whether stagnation influence can be ignored or acceptable in terms of chemical accumulation and biological growth is with great significance to test for the following experiments,

2.5 Water quality indicators

One of the most important functions of the setup is to seize DNHMs by using filter bags. Further analysis on chemical and biological parameters of these particles are required for understanding their compositions, characteristics and tracing back possible origins, which directly reflect the water quality of water samples. Besides, 'Oasen West' project is a long-term last project. To make all related researches consistent, complete and easier for comparisons before and after treatment process upgrades in different supply area, water quality indicators could provide essential information.

2.5.1 Chemical parameters

Iron (Fe), manganese (Mn), calcium (Ca), aluminum (Al) and arsenic (As) are measured in this research. According to the new research (Cook and Boxall, 2011), inorganic elements like iron, manganese and aluminum are usually the main metal elements in the flushed water samples under discoloration and deposits, regardless of pipe material, diameter or age of the pipe. Besides, calcium takes up a certain part in sediments (Zacheus el al., 2001). In plastic pipes, inorganic elements like Al, Ca, Fe, Mn, Mg and As are found in biofilm matrix developed and accumulated in DNs (Gang et al., 2013). Heavy metals, such as chromium (Cr), lead (Pb), copper (Cu), and arsenic (As), can accumulate in DWDS loose deposits (Lytle, Sorg, & Frietch, 2004).

2.5.2 Biological parameters

Biomass quantification is the most direct way to evaluate the microbial regrowth in the filter bag. Total cell counts (TCC) is an accurate, rapid and quantitative method to detect both cultivable and uncultivable microorganisms and are easy to perform by using flow cytometry.

As a general indicator for the presence of microorganism in drinking water, adenosine tri-phosphate (ATP) can be measured in a very sensitive and rapid way to determine the total microbial activity (Ochromowica and Hoekstra, 2005).

By combining the results of TCC and ATP, not only number of cells and the activity of the cells be studied, but the physiological state of the cell can also be assessed (Berney et al., 2008; Hammes et al., 2010). Heterotrophic plate count (HPC) method is not used in this test by the fact that only a small fraction (less than 1%) of the microorganism in drinking water can be detected (Liu, 2013). Besides, the colonies cultivated from the pipe biofilms were rarely detected in the previous research.

As one of the most ubiquitous organisms in dutch drinking water, Aeromonas is commonly analyzed as an indicator for bacterial regrowth in distribution networks (E. I. Prest et al., 2016). Furthermore, possible origins of DNHMs could be deducted for that loose deposit niches are the only accumulation site for Aeromonas (Liu et al., 2017). Not all experiments conducted in this research will measure this parameter. Limited by the lab device, Aeromonas will only be analyzed by Vitens lab.

In-depth cultivation-independent methods have been developed such as using 16S rRNA gene-based approaches to identify bacterial species and study the bacterial community richness and diversity (Henne et al., 2012; Prest et al., 2016b). In addition, bacteria which are potentially harmful like Legionella, mycobacteria and Naegleria can be observed. However, the cost is expensive thus this analysis will be done once a year. Specific analysis time is determined by the company depending on the progress of all researches arranged within that year. DNA extraction is conducted for 16S rRNA gene analysis. Harvest biomass is stored at -70 degrees until further analysis (Henne et al., 2012).

3 Materials and methods

This chapter lists the materials and methods used in this research. A general introduction of the Smart Water Meter setup and working principle is shown below. Indicators used in the tests as well as their measurements are presented. Three experiments designed for answering two main research questions are described in detail.

3.1 Experiment set-up

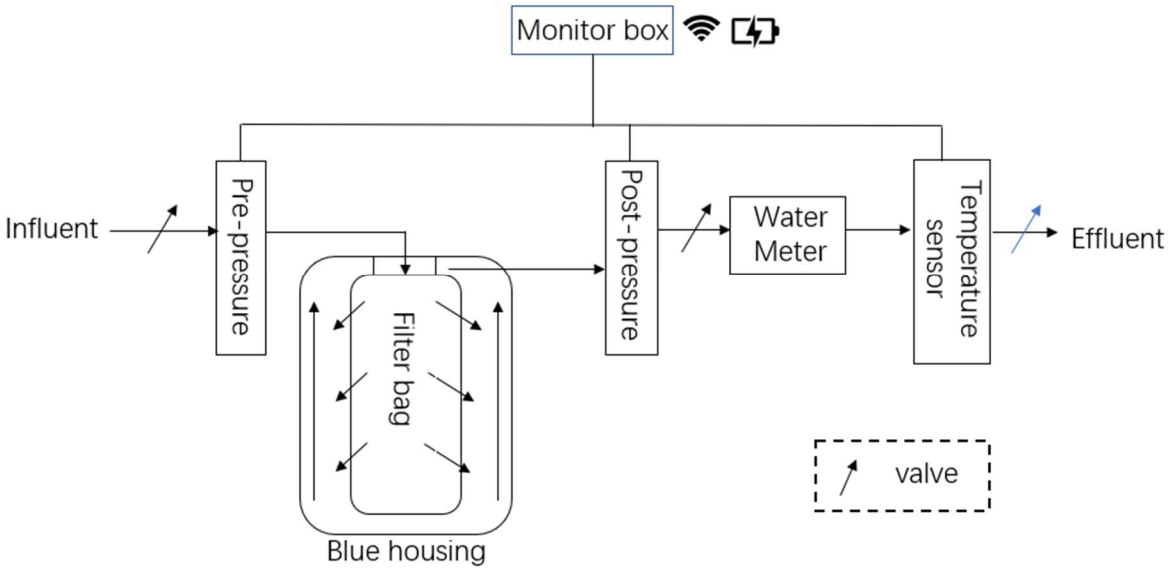
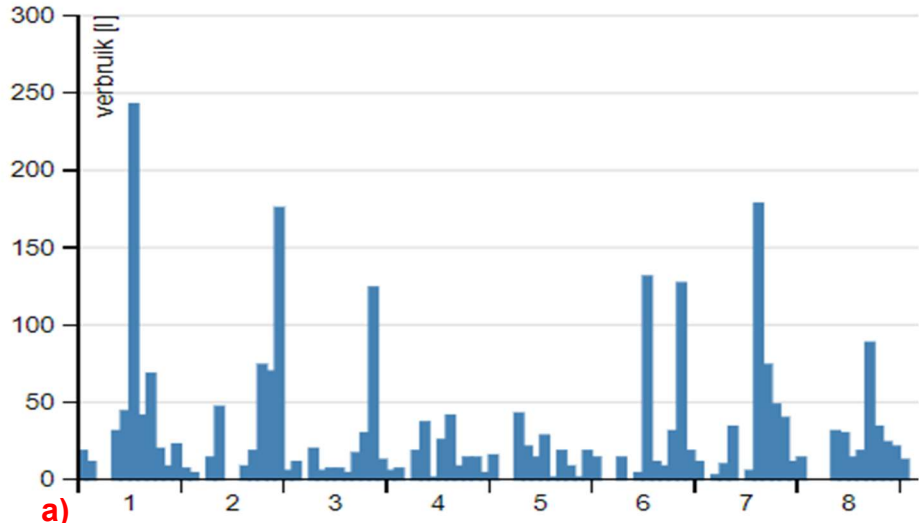


Figure 3-1 Smart Water Meter schematic diagram.

As indicated in Figure 3-1, the setup is called Smart Water Meter which comprises two pressure sensors, one temperature sensor for measuring water temperature, one blue filter housing containing a filter bag, one normal water meter, one monitor box and three valves for operation and repair. Two pressure sensors are installed before and after the filter bag respectively for pressure difference check as pressure drop will increase when transition effects occur. The body of the blue housing can be taken off for the filter bag installation with the valves closed. The monitor box needs to be connected to a WiFi network and power plug for normal operation. Two methods are suitable for network connection. One is to enter the WiFi account and password into the corresponding software but reset is required when a new WiFi applies. Connecting to the network interface by using a cable is always an alternative when the first one fails. All the logged data is available on the website https://oasen-monitor.nl/,

of which only company researchers and users who achieved privacy agreement have the access.



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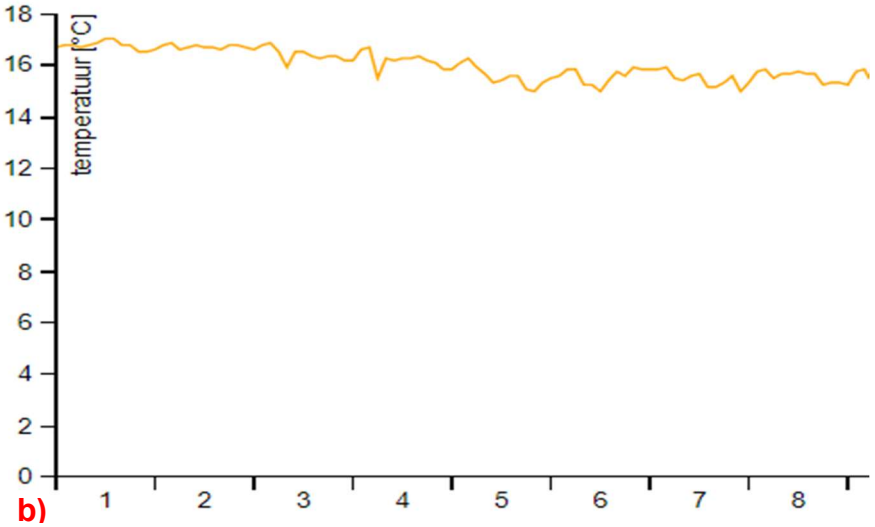

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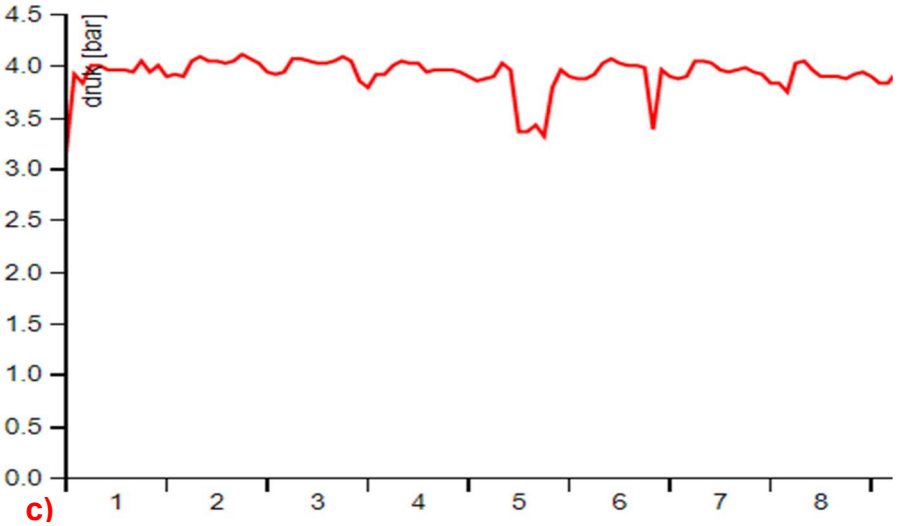

c)

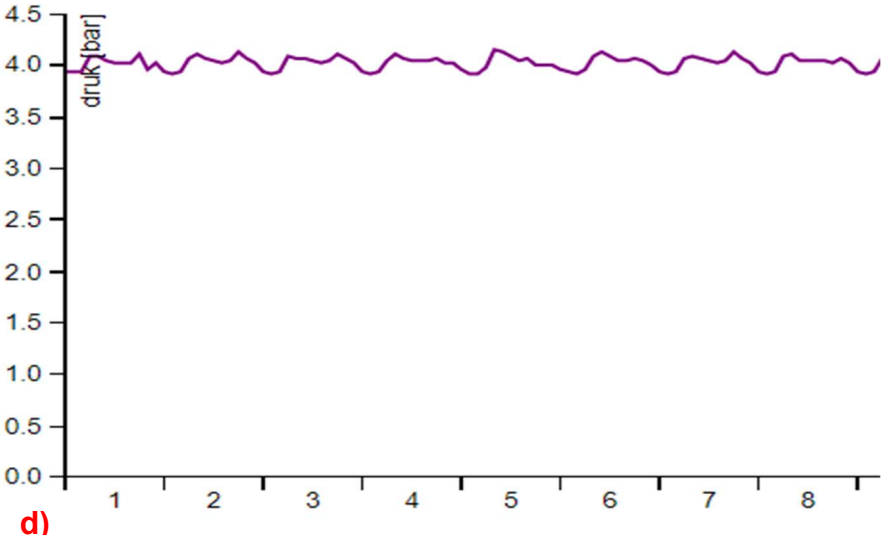

Figure 3-2 Examples of online data monitoring in the first ten days in September after filter bag replacement: a) flow rate; b) temperature; c) effluent pressure; d) influent pressure.

The Smart Water Meter is used as an incorporated on-line monitor in this research to record the water consumption, temperature along with the pressure and upload these data to the cloud through the monitor box every eight seconds as shown in Figure 3-2. Besides, it could also intercept materials whose particle size are larger than the filter bag pore size inside the drinking water distribution networks.

3.2 Indicators measurements

3.2.1 Pressure resistance

As more particles flow through the filter bag, its filtration performance decreases with lower flow flux and increased transmembrane pressure (TMP). This could be defined as membrane fouling, which refers to the blockage of membrane pores during filtration by the combination of sieving and adsorption of particles on the membrane surface or within membrane pores (Abdelrasoul, Doan & Lohi, 2013). With two pressure sensors installed before and after the filter bag separately on the Smart Water Meter, both influent and effluent pressure can be recorded and read all the time with the help of online data monitoring system. Pressure drop (difference between the influent and effluent pressure) is of great importance for indicating membrane fouling. Under normal conditions, the pressure drop will remain steady with little fluctuation and gradually increase with filtration time while when transition effects caused by abnormal changes occur, more particles consisted of detached biofilms or resuspended solids resulted from the balance breakup inside distribution networks will block the pore within certain

time and then a cake layer on the membrane surface forms, leading to the sudden jump of the pressure drop.

However, only pressure drop cannot represent membrane fouling state as the influent hydraulic condition, especially the water pressure and flux, keeps changing all the time. Therefore, an alternative parameter should be found to indicate the potential fouling issues. Considering that water flow in porous media is traditionally described by Darcy's law and by the conversion of it, pressure resistance can be calculated by using the formula shown below (Zewei, 2016).

$$R = \frac{TMP}{J \cdot \mu}$$

where,
R – filter resistance (m^{-1})
TMP – transmembrane pressure, difference between influent and effluent pressure (bar)
J – permeate flux ($m^3/m^2/s$), which is flow rate over the surface area
μ – dynamic viscosity of the water (mPa · s)

Note: *The real surface area is estimated to be 634.3 cm^2 according to the company but this number is not for sure. Considering that the permeate flux in this part is only for comparison of two filter bags with the same surface area, it is assumed to be 1 m^2 to simplify the calculation.*

Viscosity need to be corrected as temperature keeps changing all the time. According to the Vogel Equation, constant A, B, C depend on the liquid type. For drinking water, parameters are listed below.

Table 3-1 Vogel Equation (DDBST GmbH, 2019)

Vogel Equation Parameters (Viscosity in mPa*s, T in K)

No.	A	B	C	T_{min}	T_{max}
(1)	-3.7188	578.919	-137.546	273	373

$$\eta = e^{A+\frac{B}{C+T}}$$

Another alternative way is to correct the flux, where viscosity is regarded as a constant under 20 degrees.

$$J' = J \times e^{-0.0239 \times (T-20)}$$

3.2.2 Particle size distribution

The selection of filter bag pore size depends on the particle size distribution of its influent water. Too large pore size will result in capturing little particles while too small pore size can lead to frequent clogging issues, which is not desirable and convenient for both the company and customers. Moreover, water from three drinking water companies is expected to flow through the Smart Water Meter to inspect its performance under different water quality. The particle size distribution is the most direct and intuitive index to reflect the distinction between these three types although they are treated by independent treatment process, and the delivering pipes are of different materials and length. In this research, all distribution networks in three drinking companies have been existed for a long time and no external change was observed. Therefore, the particle size distribution of water samples are considered to be under normal conditions.

PAMAS OLS4031 online particle counter with 32 size channels (Figure 3-3 a) along with the software PAMAS PMA (Figure 3-3 b) is used for the particle size distribution measuring and analysis. 50 mL water sample is needed each time. The cumulative and differential particle counts results are the average value of 10 times measurements which are readable on the software page as shown in the right figure below.

Figure 3-3 a) Pamas particle ananlyzer b) Software PAMAS PMA.

3.2.3 Total cell counting

Total cell counting is conducted by a flow cytometry and BD AccuriTMC6 software (Figure 3-4) in TU Delft applied science laboratory. As an easy and fast method, flow cytometry is

extremely sensitive, avoiding the need for culturing or enrichment procedures, and can be both qualitative and quantitative (Gunasekera, Attfield and Veal, 2000).

According to Hammes et al., 10 µL mL^{-1} SYBR® Green I dye (1:100dilution in DMSO; Molecular Probes) is used for staining bacteria in samples due to its intensity, ease of use and reproducibility. Samples with the dye inside needs to be incubated in the dark for at least 15 minutes before measurement. To make the results more accurate and reliable, dilution is required when necessary to make sure that the concentration of total cells is always smaller than 2×10^5 cells mL-^{1}. 50 µL of each sample was taken at medium speed using an FL1-H acquisition threshold of 800. The standard instrument error of flow cytometry measurements is always below 5%.

DNA free water sample was taken and analyzed to get the background area. Samples without adding dye was able to show also part of the microorganisms as some of them were still detectable by the machine, but the final results were based on the samples with dye. By drawing the region of the dark area shown in the software, total cell numbers could be read.

Figure 3-4 BD Accuri C6 flow cytometer.

3.2.4 ATP measuring

ATP is a rapid and interference-free indicator of total living biomass (Ricordel, Darchen and Hadjiev, 2010). 2nd Generation ATP test kits (Figure 3-5) from Aqua-tools are used to conduct the ATP measurements including tATP, cATP and dATP. The Total ATP (tATP) measures

ATP from both living and dead cells. The Dissolved ATP (dATP) evaluates ATP from only dead cells while the Cellular ATP (cATP) stands for the ATP contained inside the living cells.

According to the guidebook of the 2nd Generation ATP test kits, the working principle can be explained as shown below. By adding the sample into a solution with enzyme Luciferase, light will be produced and detected in a Luminometer with the unit of Relative Light Units (RLU), which is based on the firefly luciferase.

$$ATP + O_2 + luciferin \xrightarrow{Mg^+ + luciferase} AMP + PPi + oxyluciferin + light$$

For drinking and sanitary water, the measured samples volume is suggested between 50 and 100 mL. In this measurement, 60 mL per sample was selected for cATP. According to the Test Kit Instructions, samples should be analyzed within two hours of collection whenever possible, otherwise be stored refrigerated (2 to 8 degrees) and test within 24 hours of collection.

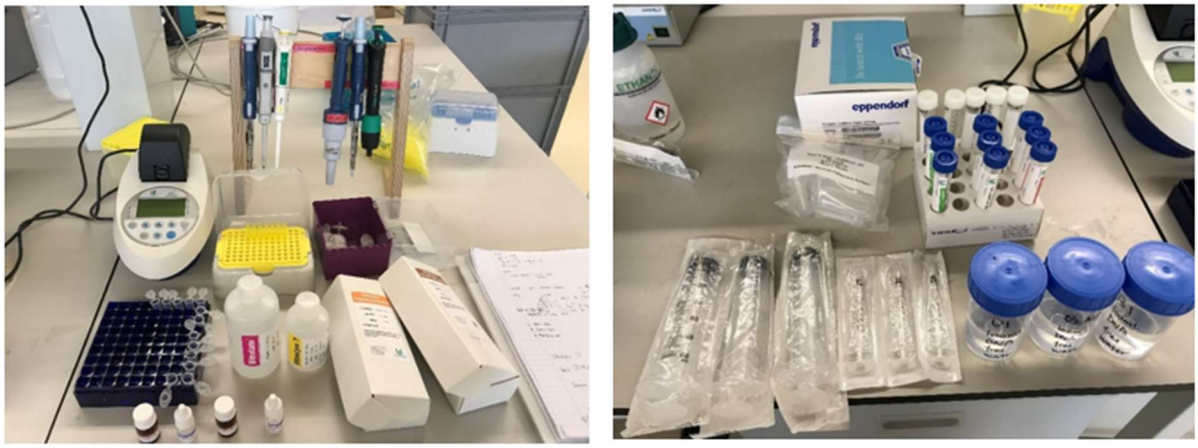

Figure 3-5 ATP test kit.

Detailed test procedures were performed as described in Table 3-2:

Step 1 – Calibration

Add 100 µL Luminase and 2 drops of UltraCheck 1 into the assay tube, record RLUATP1. Add 100 µL LuminaseW and 2 drops of UltraCheck 1 into the assay tube, record RLUUC1.

Step 2 – ATP Analysis

Table 3-2 ATP test instructions.

tATP	dATP	cATP
1. Add 1 mL sample to a GQ21W Extraction Tube, wait 1 minute for incubation. 2. Pour the QG21W Extraction Tue contents into a QG21W Dilution Tube. Cap and invert twice. 3. Add 100 µL of the QG21W Dilution Tube contents and 300 µL of Luminase^{W} to an assay tube, swirl gently for several times and put into the Luminometer. Record RLU_{tATP} for later calculation.	1. Add 1 mL sample to a GQ21W LumiSolve Tube, wait 1 minute for incubation. 2. Add 100 µL of the QG21W LumiSolve Tube contents and 300 µL of Luminase^{W} to an assay tube, swirl gently for several times and put into the Luminometer. Record RLU_{dATP} for later calculation.	1. Add 60 mL into the syringe and push through the 0.22 µm filter. 2. Add 1mL UltraLyse 7 in a new 1 mL syringe and push slowly through the filter used above. 3. Add 100 µL of the filtered UltraLyse 7 and 0.9 mL UltraLute into the tube. 4. Add 100 µL of the UltraLute Tube contents and 100 µL of Luminase to an assay tube, swirl gently for several times and put into the Luminometer. Record RLU_{cATP} for later calculation.

Step 3 – Calculation

$$\text{tATP (ng ATP/mL)} = \frac{RLU_{tATP}}{RLU_{UC1}} \times 11(\text{ng ATP/mL})$$

$$\text{dATP (ng ATP/mL)} = \frac{RLU_{dATP}}{RLU_{UC1}} \times 11(\text{ng ATP/mL})$$

$$\text{cATP (pg ATP/mL)} = \frac{RLU_{cATP}}{RLU_{ATP1}} \times \frac{10000\ (\rho g\ ATP)}{V_{sample}(mL)}$$

3.2.5 Elemental analysis

Fe, Al, Ca, Mn and As were measured in this test by inductively coupled plasma mass spectrometry (ICP-MS) as shown in Figure 3-6 by the lab technician in TU Delft Waterlab. One of the most impressive advantages of the ICP-MS is that it offers extremely low detection limits for trace elements (ppn level = µg/l) and ultratrace elements (ppt level = ng/l) (Rao and Talluri, 2007), which is suitable for detecting elements in the drinking water.

Figure 3-6 Inductively coupled plasma mass spectrometry (ICP-MS).

Add 9.9 mL sample and 100 µL nitric acid into a new assay tube for elemental analysis and multi-elements could be detected at the same time. The concentration of samples should not exceed 7 mg/L, otherwise dilution is needed.

3.2.6 Filtrate detachment

Filtrated materials need to be detached from the filter bag for sample analysis. A 40 kHz low-energy ultrasonication water bath (Figure 3-7) is chosen to efficiently shake off filtrates and avoid shattering cells. Suspensions can be obtained by running the machine for three times and two minutes each. The cut pieces from the filter bag were taken out from bottles after ultrasonication to maintain a constant concentration as filtrates may keep dissolving into the water.

Figure 3-7 Bransonic 521 ultrasonic bath.

3.3 Smart Water Meter optimization

3.3.1 Filter bag pore size selection

A previous research was conducted to study the transition effect right after the supply-water switch. The pore size of filter bags was selected to be 50 microns which failed to capture enough particles for analysis. In order to better study the transition effects in the drinking water distribution network in the long term, new filter bag with smaller pore size is needed to seize effective and sufficient substances.

According to M-Filter company, the available pore sizes smaller than 50 microns are 25 and 10 microns. These two types of filter bags are all the same except for the pore size. The surface area of the filter bag is 634.3 cm^2 ($\pm$5% variation). Considering the needed amount in the experiment and long delivery time, 16 filter bags were ordered for each size.

In principle, this experiment is supposed to be conducted in Oasen's water supply area. However, it is not convenient and realistic to shuttle back and forth between Delft and Oasen for sample collection and analysis. Nevertheless, according to the particle size distribution from Figure 3-8 a) and b), it can be seen that the water in the lab shares almost similar particle size distribution as Oasen water where small particles ranging from 0 to 10 microns takes up the most. Besides, filter bag will not be clogged when it is not clogged in TU Delft as more particles are contained in the water sample collected from the Waterlab. Thus, the chosen pore size of the filter bag is supposed to be applied to the Oasen area.

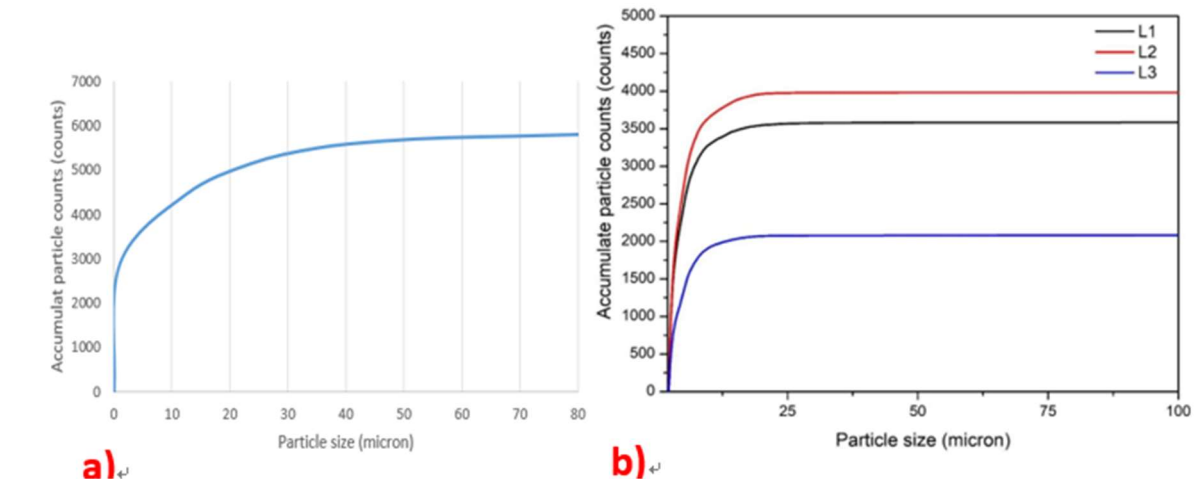

Figure 3-8 a) Average particle size distribution in TU Delft Water lab; b) Particle size distribution in water samples from 3 locations in Lekkerkerk area (Jiaxing, 2017).

The main purpose of the filter bag is to seize more particles without clogging under regular circumstances where no transition effects occur. Theoretically, smaller pores can intercept more particles, meaning that these two sizes can all be taken in consideration. However, pressure drop is ought to be observed as well to check the potential clogging.

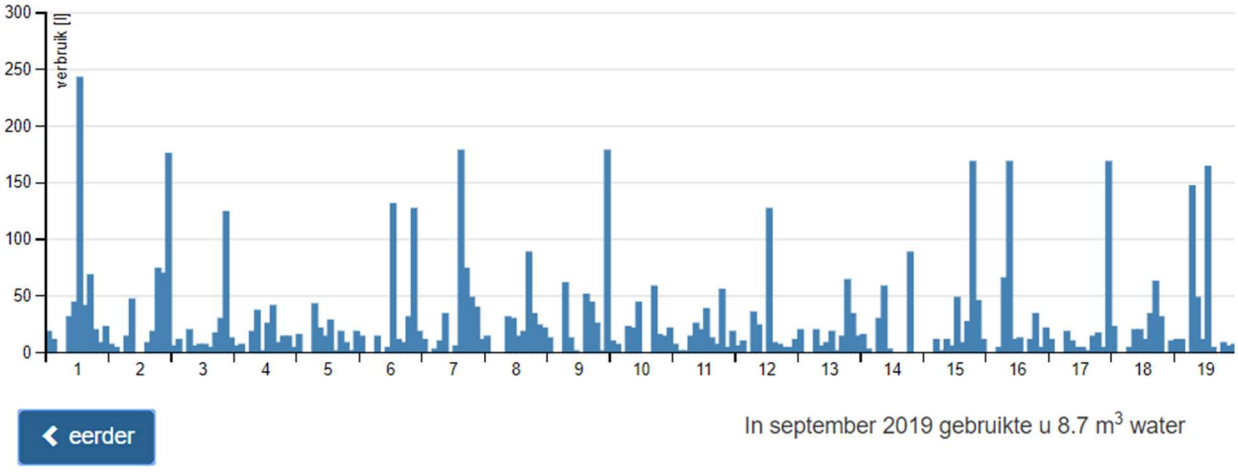

Figure 3-9 Example of the water consumption in Schuwacht in September 2019.

In this research, it is scheduled that filter bags will be replaced per month for a better track of the potential transition effects. Water usage is the most important parameter as following measurements are all based on it. Influenced by seasons, number of family members, habits and other reasons, water usage varies each month even in one household. By checking the water consumption monitored by the Smart Water Meter in four households in Lekkerkerk area, it ranges from 5 to 18 m^3 per month (example is presented in Figure 3-9).

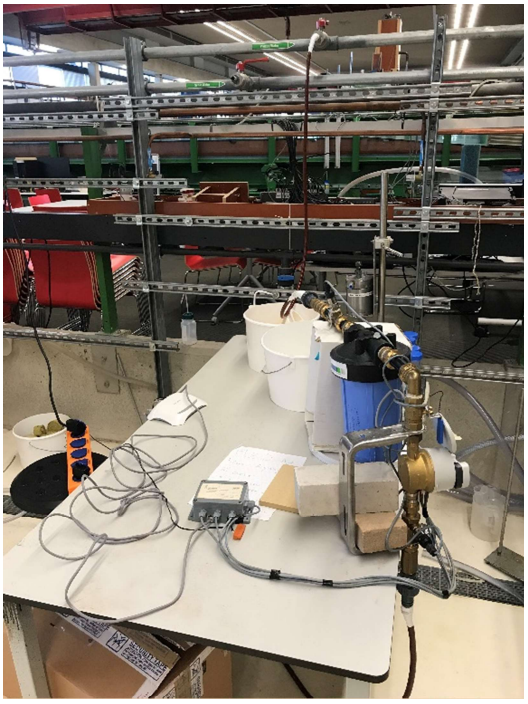

Figure 3-10 Smart Water Meter set-up in TU Delft.

Since these four households use the same filter bag pore size, 12 m^3 is selected for the lab test. By simulating the discharge of the system tap water, required operation time can be calculated.

This lab test is divided into three stages with single trial as only one set-up was available in TU Delft (Figure 3-10). Other setups were still in households. All the parameters were measured also in TU Delft Waterlab with the help of the lab technician.

Only one stage was planned for the filter bag selection at the begining. However, due to unexpected results and short of understanding in filter bag's performance, the second stage was scheduled to figure them out. After that, the final selection was made in the third stage based on the results got from previous stages.

3.3.1.1 First stage

The initial aim of the first stage was to make the filter bag selection by comparing the physical performance of both 25 and 10 microns filter bags when running the system for one month's water consumption (12 m^3). Ran the system for one hour to find that the tap water discharge in the lab was around 0.546 m^3 per hour. Therefore, 22 hours were needed for 25 and 10 microns filter bags separately in the first test for simulating one month's water usage. Tests of both filter bags would be conducted from 10 a.m. to 8 a.m. in the next day without stop. Therefore, only water samples within first 11 hours (10 a.m. to 9 p.m.) could be collected and

recorded with the exception of the parameters monitored by the monitor box because waterlab in TU Delft is not accessible during the evening.

Theoretically, the pressure resistance was supposed to increase along the operation time due to the accumulation of filtrates which would gradually clog the pore size. However, opposite results showed in the first stage where the pressure resistance gradually decreased, requiring extra two stages to be added to have a better understanding of the filter bag.

3.3.1.2 Second stage

In the second stage, the system was operated for a longer time (177 hours) to investigate the performance of the filter bag. Not only physical aspects, but also chemical and biological analysis were conducted.

3.3.1.3 Third stage

In the third stage, the running time was shortened to be 76 hours, and both chemical and biological analysis were still applied during the operation. More details were inspected to make the final selection of a proper pore size.

Considering the uneven distribution inside the filter bag due to the flow direction (from top to bottom) and relative high concentration of filtrates, three 1x1 cm^2 pieces of the filter bag were cut from upper, middle and bottom part and ultrasonicated for chemical and biological analysis. Filtration might be needed for elements and TCC analysis when the suspension is of great turbidity. Cut pieces were put in plastic bottles filled with 140 ml DNA free water (ultrapure water+autoclaved+0.22 μm filter) separately. Microscope was not used as the filter bags were opaque due to great number of particles retained on the inner surface.

3.3.2 Clogging test

In the previous research, transition effects aroused by the supply water switch was captured. However, significant pressure drop was not observed within that research period. This could be explained that the cake layer had not formed on the membrane surface although pores were getting blocked for that the particle size of DNHMs very small and with little amount according to the observation of the filter bag. The pressure resistance increased while it still took a long time for the pressure drop jump. Slight transition effects leading to pore blockage of the filter bag could be seized by analyzing the DNHMs retained by the filter bag.

However, the Smart Water Meter is also expected to be performed as an early warning setup

to prevent households from bad influence. For serious transition effects like discoloration caused by irregular changes, the newly selected filter bag is ought to be tested to make sure that it will suffer heavy clog and sudden pressure drop of the setup occurs under this situation as great number of particles whose size are much larger than the filter bag pore size will present according to the company.

However, considering that the present water quality is quite stable, only flushed water could be used for simulation as suggested by Oasen. The company provides one photo in Figure 3-11 to give an indication of the water with flushed loose deposits that is suitable for the influent of the test.

Figure 3-11 Flushed water sample.

By pumping certain volume of the water through the Smart Water Meter, clogging could be checked to see if the new pore size is appropriate. The schematic diagram is drawn in Figure 3-12 to give an idea of the recirculation process.

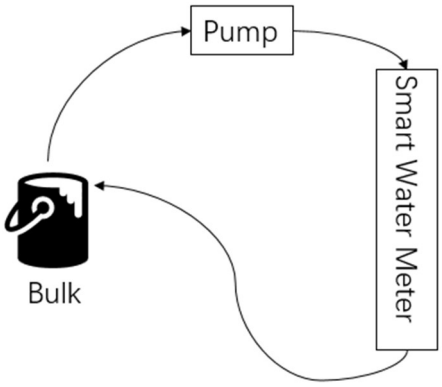

Figure 3-12 Recirculation schematic diagram.

The pump is selected according to the discharge and head while the required volume can be

calculated based on the flushing data (turbidity change along the time). However, since there is no suitable pump available both in lab and company, this test is not accomplished.

3.4 Stagnation

This part was conducted to simulate the water consumption in households for one month. On one hand, the experiments will be simplified with continuous flow instead of intermittent in real daily life mode. On the other hand, in the consideration that the filter bag was installed at the beginning of the premises plumbing, where the microorganisms in the filtrates might regrow inside the filter bag and thus deteriorate the water inside the filter bag, effluent of the filter bag after the valve installed on it opened needs to be sampled and analyzed for chemical and biological analysis to check if potential harm would be aroused when the water is retained inside the filter bag for a long time like overnight stagnation or during summer vacation. Both the temperature and hydraulic retention time, even the pipe material could affect the bacterial growth inside the filter bag.

This experiment was taken place in TU Delft for convenient daily water samples collection. Influent pipe was connected to the tap of the process water in the waterlab and the effluent of the setup would be charged to the sewer pipe. Influent water samples could be collected from another tap just next to the connected tap and the effluent was able to be taken directly from the effluent pipe.

For chemical analysis, Al, Ca, Mn, Fe and As were measured for both the influent and effluent of the setup. For biological analysis, rapid and accurate assessing methods like total cell counts and ATP were used to have a general microbial activity of the filter bag's effluent. The tap connecting to the setup was opened at 10 o'clock in the morning every day for one hour. Water samples was taken before the tap had opened, right after tap opened and then at an interval of ten minutes for three times. Flow cytometry (BactoSense) provided by the company was used to measure total cell counts which separated into two cluster by using SYBR Green fluorescent dyes, high (HNA) and low nucleic acid (LNA) bacterial cells. Generally speaking, high-nucleic acid bacteria are usually regarded as the active part of the microbial metabolic group, whereas LNA bacteria are considered inactive or even dead (Lebaron et al., 2001; Lebaron et al., 2002; Servais et al., 2003; Tadonleke et al., 2005).

In this experiment, 90 water samples were collected and analyzed for 18 days with the average flow rate of 0.35 m^3/h to simulate the water consumption situation in the households.

3.5 Smart Water Meter under different water quality

The Smart Water Meter is expected to be tested in four locations supplied by three drinking water companies (Table 3-3) to investigate how it performs under different water quality. It is of great importance to have a deeper understanding of the Smart Water Meter itself as more setups will be brought into fields according to Oasen's schedule and suggestions are prospected to be given for optimizations.

Table 3-3 Water in four locations provided by three drinking water companies.

Drinking water company	Location	Raw water source
Oasen	Schuwacht (with RO)	groundwater
	Kamerik	bank filtrated water
Dunea	Delftgauw	filtrated surface water
Evides	TU Delft waterlab	surface water

These four water types in four locations provided by three water companies are of great difference mainly due to distinct raw water source, drinking water treatment process, delivery distance from DWTP to end users, pipe materials and so on. Groundwater contains lower hardness and pollutants compared with the surface water. After being treated with RO, water in Schuwacht could be estimated to be with great water quality. Although the drinking water leaving treatment plants meets regulated standards, it still could be deteriorated during transportation along distribution networks. Combinations of different treatment steps are expected to provide water with complicated characteristics which is hard to predict.

3.5.1 Sampling locations

In Oasen, RO installation has been applied in the Schuwacht purification station in Krimpen aan de Lek since 2016. Four households in Schuwacht, Commandeur, Hobbemalaan and Lavendel were installed with Smart Water Meters to study the potential transition effects resulted from the supply water switch from June to September in 2016 by one master student from TU Delft. According to the research results, slight transition effects occurred after water purification while gradually settled down. Afterwards, water is proved to be with super good quality as very few particles could be seized when the pore size of the filter bag is selected to be 50 microns and little reports were received from the customers.

In July 3rd, three of the setups in Commandeur, Hobbemalaan and Lavendel were removed from households by the arrangement department of the company and installed at new locations, while the rest one remains to be in Schuwacht for this research.

Figure 3-13 Kamerik treatment station.

One of the removed three Smart Water Meters is installed in Kamerik treatment station (Figure 3-13) in Oasen supply area with conventional treatment procedures. To prepare for the future challenges as the same in Lekkerkerk, Oasen is planning to build a new treatment station in De Hooge Boom in Kamerik to purify the river bank filtrated water with membranes. The current stage comes to the designing of the building layout and installations. It is expected to start tendering at the beginning of 2020 and run the new station at the end of 2021 or the beginning of 2022. A background information collection is necessary as the preliminary preparation to gather samples in the drinking water distribution network before supply water switch. Besides, potential transition effects resulted from the supply water switch could also be well-captured by the Smart Water Meter. Therefore one removed setup was installed inside the station by the technician man in the end of July as shown in Figure 3-14 with the influent flow rate of 2.4 m^3/h.

Figure 3-14 Smart Water Meter in Kamerik treatment station.

The rest two locations are selected in Delftgauw (Figure 3-15) and TU Delft Waterlab with the flow rate of 0.78 and 0.4 m^3/h separately, where the water is supplied by Dunea and Evides drinking water companies respectively, for that it would be relatively convenient for the setup installation and sample collections. Different flow rate resulting from different DNs might have influence on the setup performance. Although it could be adjusted by controlling valves on the setup, no action was taken as this experiment only focused on the total water volume passing through the setup. For both these two locations, setups were connected directly to the tap.

Figure 3-15 Smart Water Meter in Delftgauw.

3.5.2 Influent particle size distribution

Influent particle size distribution of four setups in different locations should be sampled and analyzed for the performance test.

3.5.3 Sampling schedule

Unlike the filter bag selection in TU Delft Waterlab, the analysis of all samples collected from four locations was conducted by Vitens Lab for more professional and accurate results.

The initial plan was to run setups in four locations for both short and long simulation periods, meaning that only two times sapling were needed. However, as a result of the separate setup arrangements at these four locations, such as the schedule of Kamerik's technician man, re-order of the pipe due to insufficient length in Delftgauw, the vacation plan of the household in Schuwacht, installation failed to be completed at the same time. Besids, July and August are summer holiday months, as a consequence of that the filter bag analysis takes quite some time, not all days could be possible for Vitens lab. According to the Vitens vacation schedule, the available dates for analysis were only 24th July, 7th and 28th August. To achieve the initial plan and collect samples as much as possible for better understanding the filter bag, the whole sampling process was divided into three times with corresponding simulated water consumptions as shown in Table 3-4.

Table 3-4 Sampling schedule and simulated water consumption

Location \ Date	6.29-7.24 (26 days)	7.29-8.7 (10 days)	8.7-8.28 (22 days)
TU Delft Waterlab	1st (one month)	2nd (one month)	3rd (six months)
Delftgauw	installation	2nd (one month)	3rd (one month)
Schuwacht	no water, on vacation	3rd (one month)	
Kamerik	installation	2nd (one month)	3rd (six months)

Note: one month and six months refer to the simulated water consumption, which were 12 and 72 m^3 respectively.

Not all bags could be collected for each sampling. Considering that the setup installed in Schuwacht was one of our customer's house, it is impossible to narrow the operation time and too frequent visit might disturb our customer. Therefore, only one sample with one month's water consumption was collected in Schuwacht. In the third sampling period, setup in Delftgauw was supposed to be operated for six months' water consumption. However, only one month's usage was simulated due to broken and leaking problems.

For the rest two setups, Smart Water Meters in TU Delft and Kamerik were operated for a longer time to simulate six months' water usage in normal households to find out how it would perform under different water quality due to the setup internet connection fault by comparing filter bags' analysis results.

Besides, limited by the complicated operation conditions, water samples of both influent and effluent of setups in four locations were taken every 10 minutes in the first operation hour to check the removal rate of Smart Water Meters (six times in total).

Filter bags inside the setup would be changed on the sampling date. The replaced bags were sent to De Meern and put in the refrigerator right after collection before five o'clock. After that, Vitens would arrange a sample delivery car to send samples from De Meern to Leeuwarden where the laboratory is located, and the analysis was conducted on the next day as the same procedure in the previous research.

According to Vitens description, filter bags were cut into 2×1 cm^2 pieces from top, middle, bottom in duplicate. For microbial test, cut pieces were filled with 90 ml DNA free water individually for ultrasonication. After that, the suspension was used as 20 ul for ATP, 5 ml for TCC and 10 ml for Aeromonas. For chemical analysis, cut pieces were filled with 50 ml DNA free water for ultrasonication and then mixed with nitric acid for five elements analysis by ICP-MS.

4 Results and discussions

In this chapter, all the results are presented and discussed to answer the three main research questions, along with several sub-questions listed above. The chapter is divided into three parts which is corresponding to the three experiments designed for three main questions and explained one by one.

4.1 Filter bag selection

All the experiments introduced in this part were conducted only once without repeat due to time limitation.

4.1.1 First stage

4.1.1.1 Observation

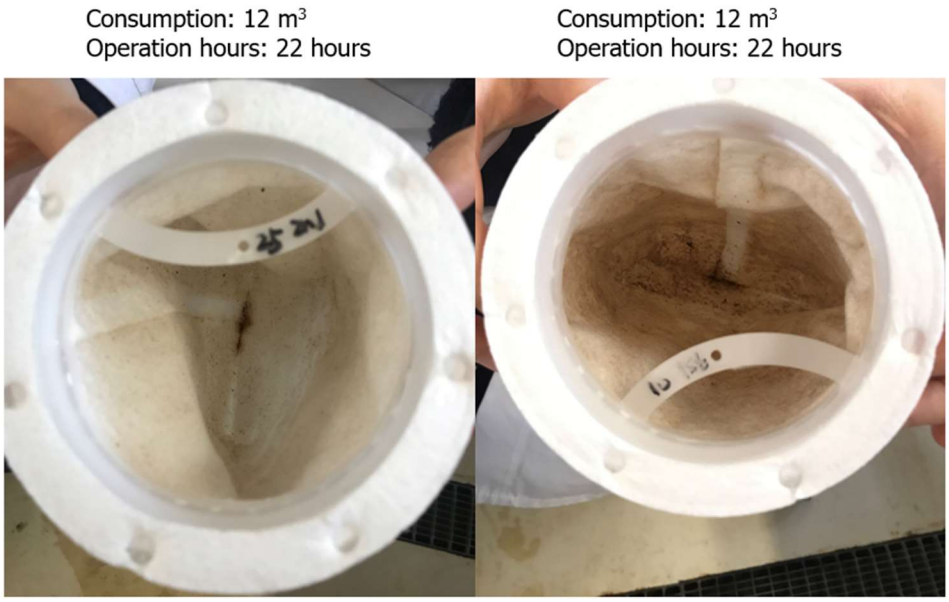

Figure 4-1 25 and 10 microns filter bag after one month's water consumption.

As is shown in Figure 4-1, more solids are present at the bottom of both filter bags as the water flows from top to the bottom. 10 microns filter bag has a deeper brown color of the inner surface than the 25 microns' after running 22 hours, which is reasonable as smaller pore size can seize more particles.

4.1.1.2 Particle size distribution

The influent process water and effluent of both 25 and 10 microns were analyzed by the PAMAS particle analyzer. The diameter ranging from 1 to 80 microns is auto-divided by the PAMAS PMA software.

Table 4-1 Average particle size distribution of the influent process water.

Diameter (micron)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
Percentage	98.03%	1.60%	0.26%	0.08%	0.03%	0.01%	0.00%	0.00%

Table 4-1 indicates that the diameters of most particles (over 98%) in the influent process water are below 1 micron, and almost no particles are larger than 34.86 microns.

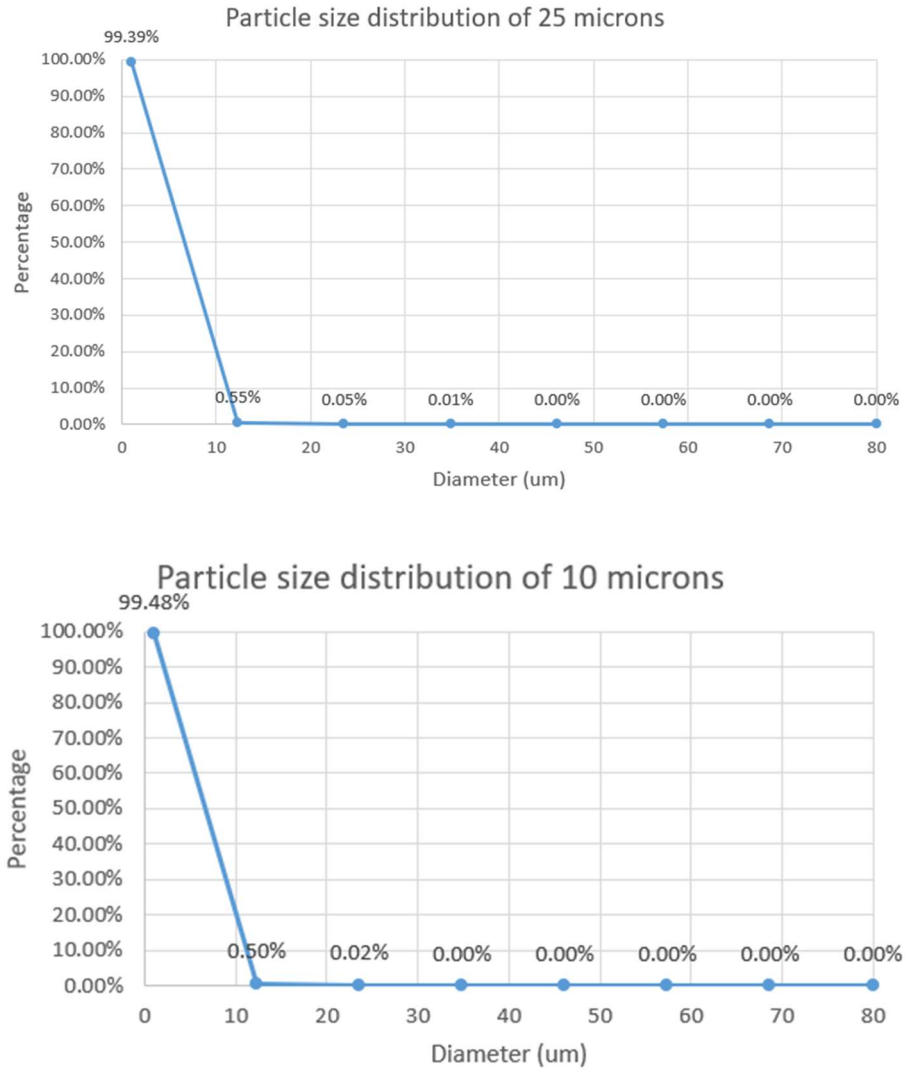

Figure 4-2 Average Particle size distribution of the effluent in 25 and 10 microns filter bags after operating 22 hours.

From Figure 4-2 it can be seen that the average particle size distribution of the effluent of 25 and 10 microns filter bags are not significantly different. Over 99% of the particles are smaller than 1 micron.

4.1.1.3 Removal rate

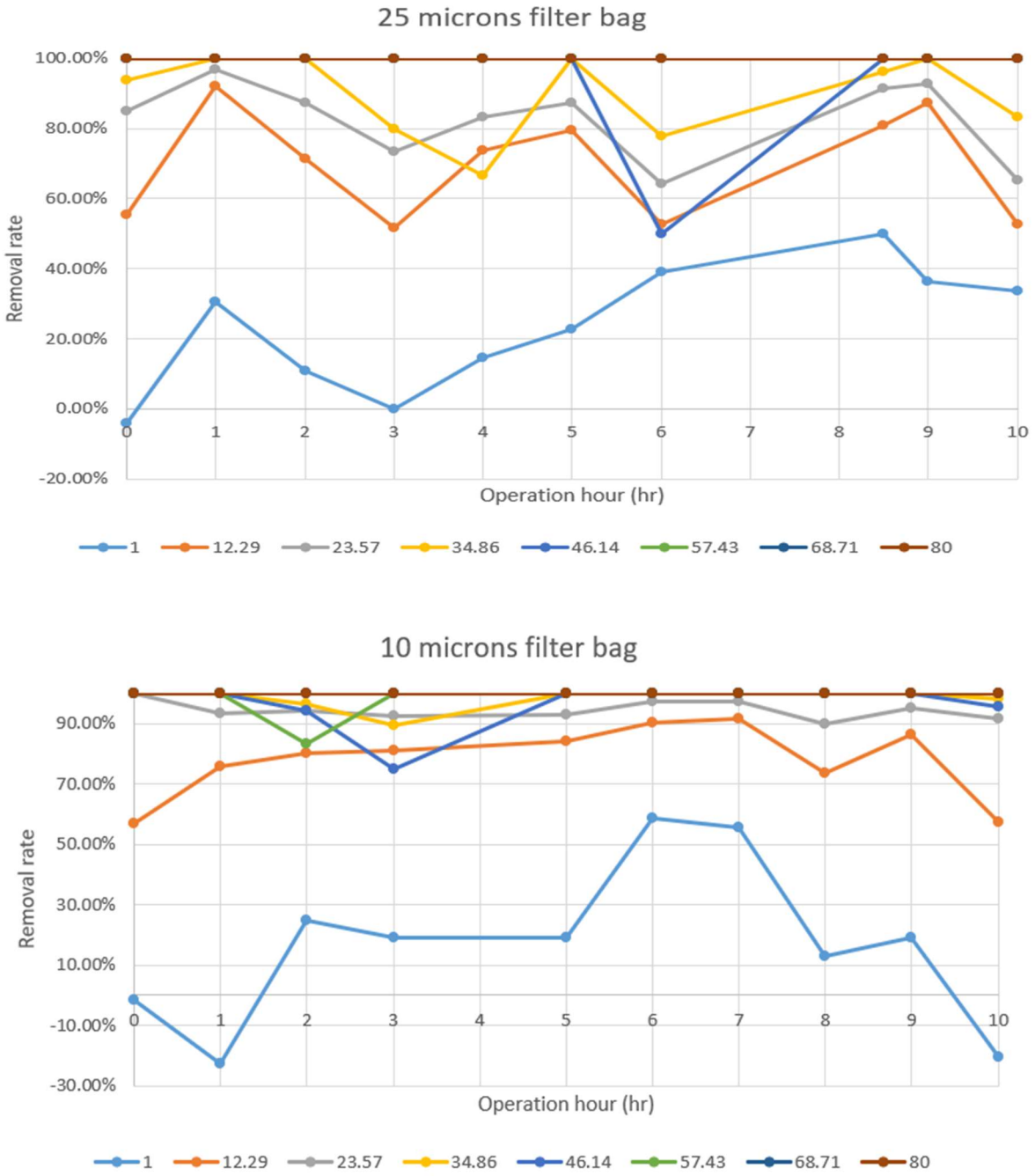

Figure 4-3 Removal rate along the operation time of 25 and 10 microns filter bags.

Figure 4-3 depicts that 10 microns filter bag has a more stable and stronger removal ability compared to 25 microns' for particles exceeding 12.29 microns although the difference is subtle. Particles larger than 57.43 microns are almost totally retained in both 25 and 10 microns filter bags. Besides, certain percent of particles smaller than 1 micron can still be removed. This could be explained that both 25 and 10 microns are the average pore size of filter bags while actual pores are uneven due to different shape. For the particle size measurement, most particles are of irregular shape like oval or line thus how they go through channels of the analyzer would greatly affect their defined particle size. In addition, very small particles could be sieved or adsorbed on the membrane surface during filtration.

Negative removal rate in the first few hours indicates that the filter bag itself may not be clean and requires the pre-wash before use.

4.1.1.4 Pressure resistance

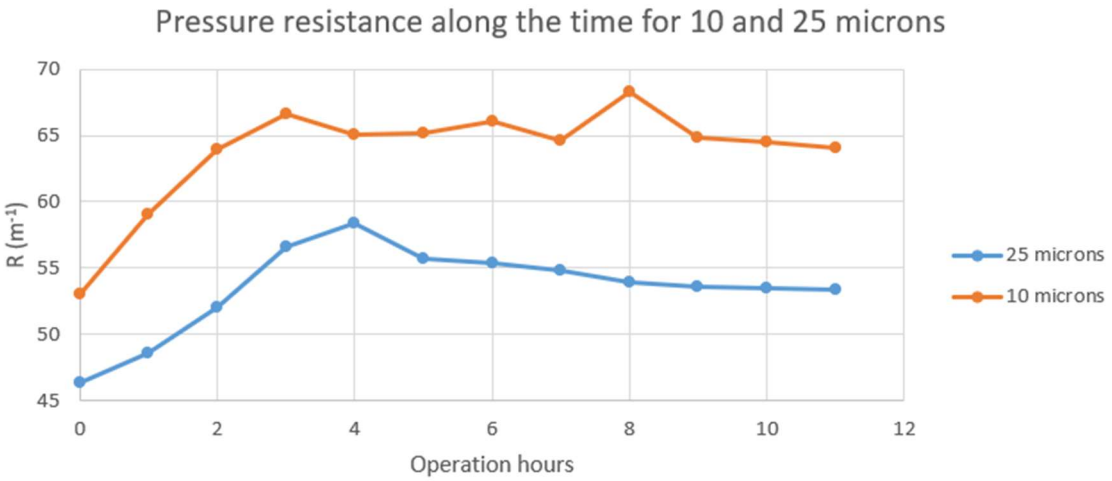

Figure 4-4 Pressure resistance along the time for two filter bags.

For two filter bags, the pressure resistance fluctuates along the time but slightly increases on the whole. According to the pressure resistance formula, it corresponds to the pressure drop, temperature and flow rate. Based on the online monitor data of two filter bags, pressure drop and temperature are nearly constant, therefore the increase flux is the main contribution to the resistance change. In principle, the pressure resistance is ought to increase along the time as filtrates can accumulate gradually on the membrane surface due to pore blockage. However, it can be noticed in Figure 4-4 that, the resistance of two pore sizes decreases after running 11 hours, which is different from the initial hypothesis. Therefore, assumption was made that the operation time was insufficient and the pressure resistance change could be aroused by its material characteristics.

4.1.2 Second stage

In the first stage, pressure resistance rose to a peak first and then revealed a trend of gradual decrease. This might be caused by the filter bag material, short operation time, fluctuating influent flux and low influent pressure. Considering that pure polypropylene membrane filters are very resistant to wetting with water and takes time to be softed, the filter bag was soaked into the DNA free water overnight before using for pre-wash and wetting.

The setup was operated for a longer time (177 hours) to inspect the performance of the filter bag and try to find out when pressure drop jump caused by serious clogging will occur. Besides, chemical and biological analysis would be added to have a better understanding of the system function.

Considering that the second stage was to check the performance of the filter bag and smaller pore size would capture more particles which requires multiple dilution for sample analysis, 10 microns filter bag was not tested in this stage for convenience. Only 25 microns filter bag was tested in this part and it was soaked into the DNA free water for 24 hours before using to avoid negative removal rate.

4.1.2.1 Observation

Figure 4-5 25 microns filter bag after running 177 hours.

Figure 4-5 shows that the inner surface of the 25 microns filter bag is rather dirty compared to the one in the first stage (Figure 4-1) after running for a much longer time. Intercepted materials not only lie on the inner surface, but also penetrates and expands to the outside literally.

4.1.2.2 Removal rate

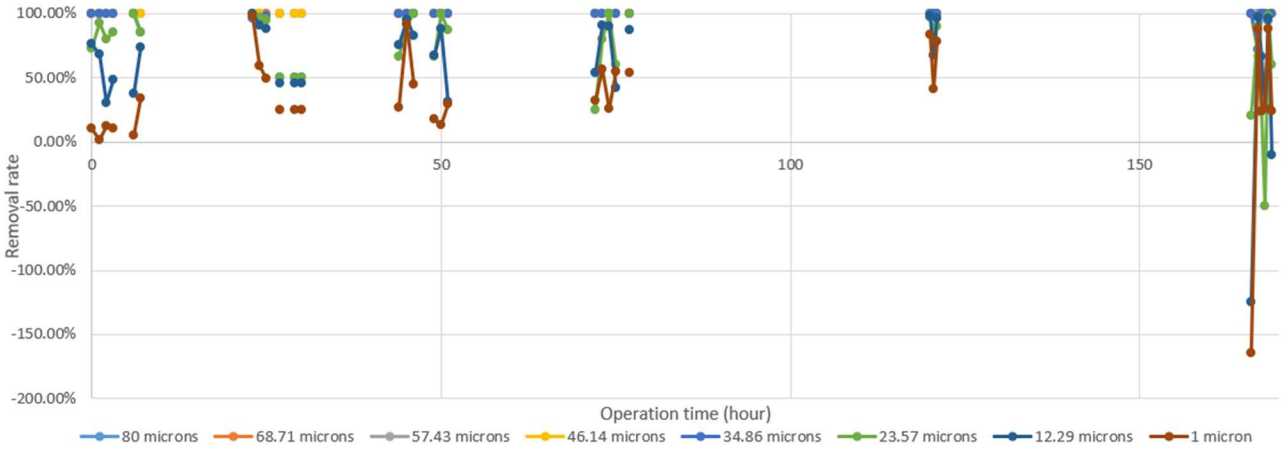

Figure 4-6 Removal rate of 25 microns filter bag along the time.

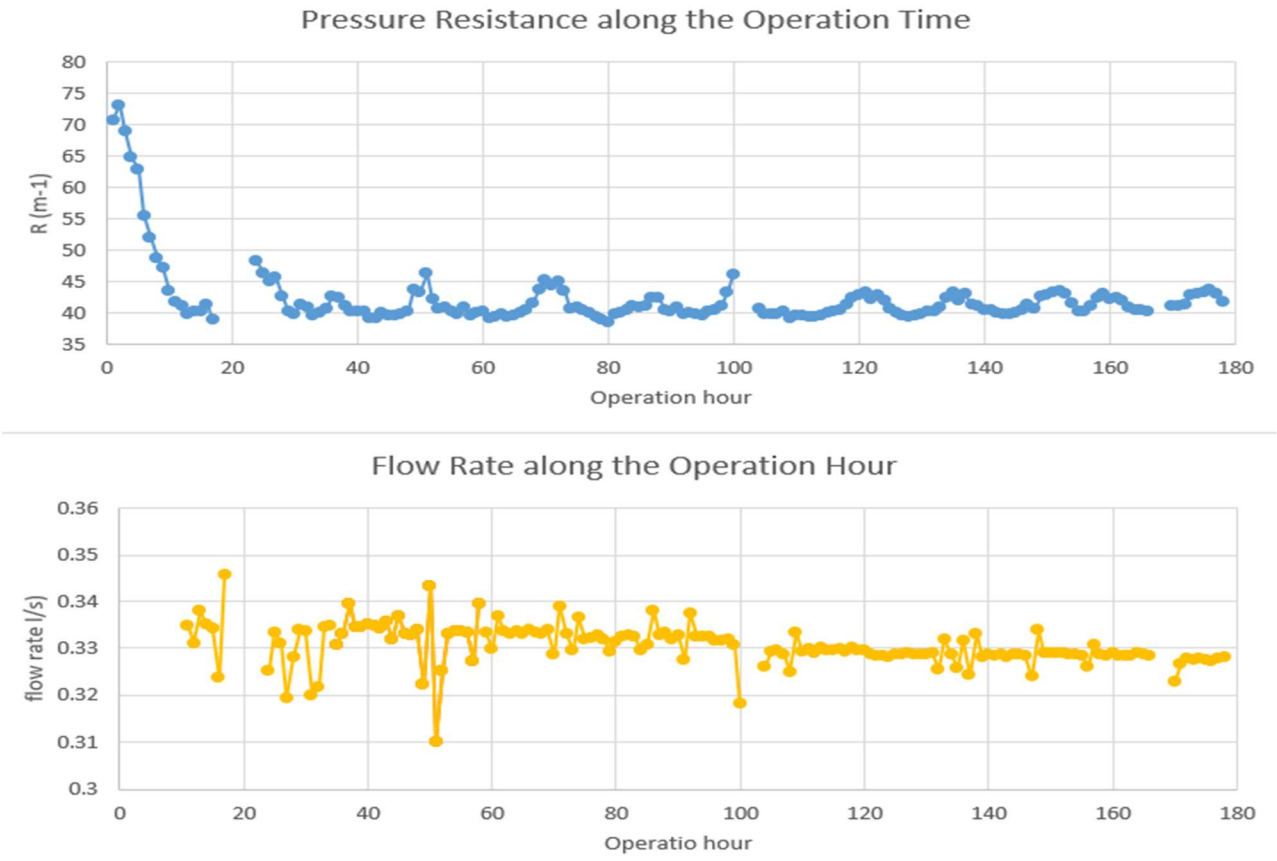

Figure 4-7 Pressure resistance and flow rate of 25 microns filter bag along the time.

Particle size distribution of both influent and effluent were also analyzed for removal rate calculation. Due to the lab limitation, samples could not be taken all the time and most of them were conducted in the afternoon, leading to the inconsistency of the removal rate graph.

Several conclusions can be obtained based on Figure 4-6. Removal rate of the particles whose pore sizes are larger than 25 microns is almost 100% while smaller ones fluctuates all the time resulted mainly from the influent water quality change. Another point needs to be noticed is that there is always a lowest point for 1 micron particles within a certain period meaning that filtrates are flushed out from the filter bag. This can be explained in the next part when combined with the pressure resistance.

4.1.2.3 Pressure resistance

Figure 4-8 illustrates that it takes shorter time for pressure resistance to reach the peak while the soaking hours may not be sufficient as a sharp decrease still exists at the beginning of the operation. After soaking into the water for a long time, material particles can be compacted and thus the pore size can be larger, leading to the decrease of pressure resistance. After that, the resistance represents a periodic change at an interval of 20 hours which was effected by the influent flow rate.

According to the pressure resistance calculation formula, resistance is in inverse proportion to the flow rate when pressure drop, and viscosity remain unchanged and this relationship can be proved in Figure 4-7. The periodic flow rate change might be related to the pump operation mode in the building. Combine Figure 4-6 and 4-7, it can be found that the lowest point of 1 micron particles' removal rate is right after the peak of pressure resistance, meaning that part of the 1 micron particles were flushed out from the filter bag after the pressure resistance decreased as compact biofilms have not yet formed inside the filter bag.

Although the filter bag inside is dirty, no pressure drop was observed during operation, indicating that the cake layer was not formed on the surface of the membrane. Pressure resistance kept increasing when the flow rate remains relatively stable, this could be explained as the gradual pores blockage. Based on the pressure drop and pressure resistance data, conclusion can be given as serious clogging did not occur in 177 hours.

4.1.2.4 Element analysis

Table 4-2 Elements concentration inside the filter bag.

	Mg24(mg/m2)	Al27(ug/m2)	Ca44 (mg/m2)	Fe56 (ug/m2)	As75 (ug/m2)
Upper	0.062	27.905	0.708	43.985	0.020
Middle	0.063	26.959	0.579	49.661	0.006
Bottom	0.047	19.864	0.554	27.274	0.002
Average	**0.058**	**24.909**	**0.614**	**40.307**	**0.009**

Samples were diluted for 100 times as the original concentration is above the upper limitation. Table 4-2 illustrates that all the elements are not well evenly distributed on the inner surface of the filter bag. Calcium, magnesium and iron are the main mental elements in the filtrates.

4.1.4.5 ATP measurement

Table 4-3 cATP results for three parts inside the filter bag.

	Upper	Middle	Bottom	Average
cATP (pg ATP/m2)	**62241.8**	**102443.6**	**433328.1**	**199334.7**

Only cATP was measured in the second stage to grasp a general knowledge of the biological activity. From Table 4-3, it can be seen that living cells are not well evenly distributed in the filter bag inner surface and the bottom part has the highest value mainly due to the gravity. The average ATP level in the distribution network and tap water is 1.8 ± 1 pg/mL (Lautenschlager et al., 2013) while the value inside the filter bag is much larger than that. Besides, samples may need dilution for total cell counting as these three values are much higher than those in the drinking water.

4.1.4.6 Total cell counting

To have a better overview of the distinct ‘fingerprint’ of the microbial populations, a DNA free water with dye is also added for analysis.

According to the guide of absolute cell counting, three samples were diluted by 10, 20 and 200 times separately based on cATP results as the higher concentration might result in inaccurate counting due to system saturation (the volume measurements on the BD Accuri

C6 are of the most accuracy with cell concentration between 1000 and 5×10^6 cells/mL). However, dark parts were not obvious due to the low concentrations of cells, which brings very subjective and inaccurate counting, total cell counting analysis was not conducted in the third stage

$$\text{Total cells counting} = \frac{Count_{sample+dye} - Count_{sample}}{Volume} \times Dilution\ factor$$

Table 4-4 TCC results for three parts inside the filter bag.

	M+dye	M	U+dye	U	B+dye	B
Count	1033	594	2167	1499	6520	3443

	U (x10)	M (x100)	B (x20)
Cells (cells/cm2)	6.146×10^7	1.870×10^7	4.309×10^7

Note: M, U and B stand for middle, upper and bottom respectively. Number in the parenthesis refers to the dilution factor of samples.

Table 4-4 shows that cells are not well evenly distributed in the filter bag inner surface and the middle part holds relatively higher concentration of cells.

4.1.3 Third stage

With the deeper understanding of the filter bag that serious clogging did not occur when running for a long time, both 25 and 10 microns filter bags were tested and operated for a shorter time in this part to select a proper pore size for the field scale combined with the information collected in previous two stages.

4.1.3.1 Observation

Figure 4-8 25 and 10 microns filter bag inner surface after running 76 hours.

After running the same time of 76 hours, it can be seen clearly from Figure 4-8 that the 10 microns filter bag has a darker inside compared to 25 microns one.

4.1.3.2 Particle counting

Particle size distribution of both influent and effluent were still analyzed in this stage while more focus was put on calculating the particles whose size ranging from 10 to 25 microns.

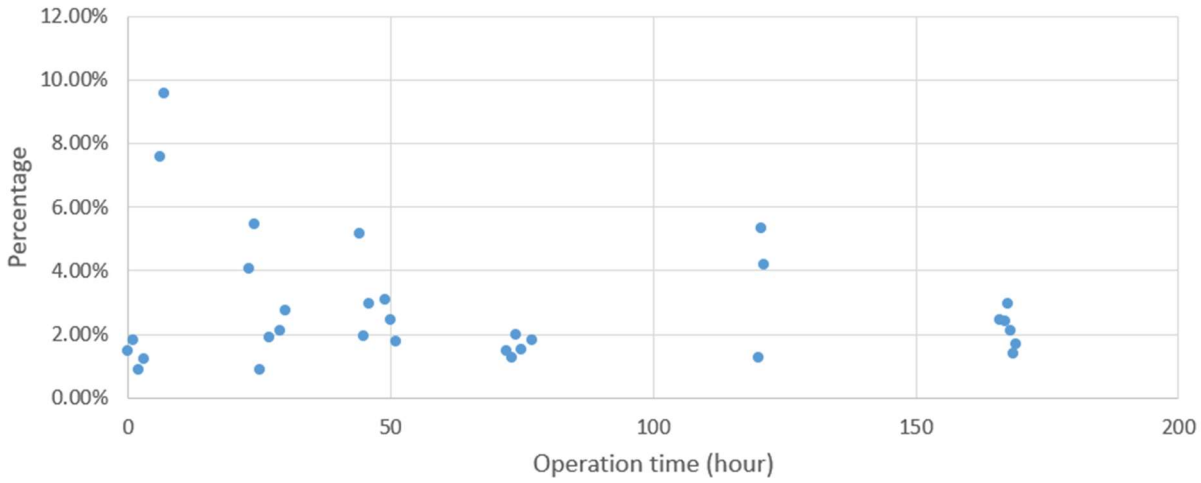

Figure 4-9 Particle percentage of the sizes lie between 10 and 25 microns in the influent.

In general, the percentage (10-25 microns particles / total particles) lies between 1% and 10% as illustrated in Figure 4-9, which is of very small fraction. With the conclusions obtained in the first stage, influent particles size distribution and amount in the water are greatly affected by the water quality, which also applies for this percentage. By checking the daily particle size distribution results where also total particle numbers are available, it could be concluded that the more particles in the influent, the larger the percentage will be.

4.1.3.3 Pressure resistance

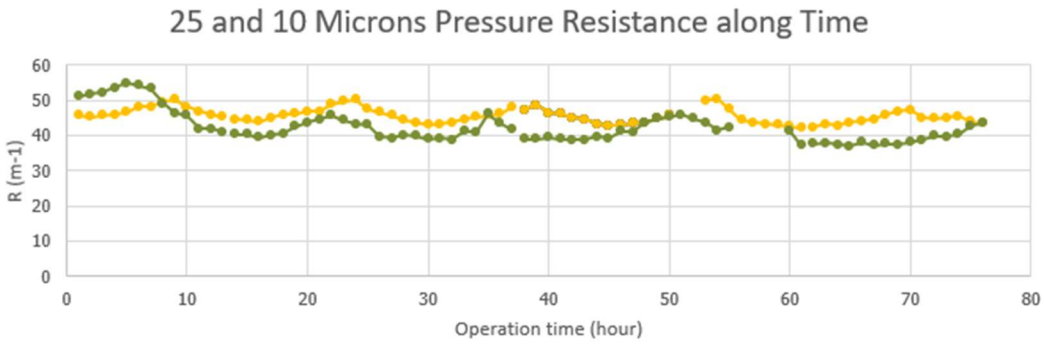

Figure 4-10 Pressure resistance of 25 and 10 microns filter bags along the time (yellow – 10 microns; green – 25 microns).

In the second stage, soaking was supposed to be set as 24 hours but the setup was knocked down accidentally. Only near 8 hours was taken actually and according to results as shown in Figure 4-7, sharp peak of the pressure resistance still existed. In the third stage, soaking in the DNA free water for 24 hours before use can effectively lower the peak according to Figure 4-10 as the filter bag material particles had been compacted.

10 microns filter bag has a relatively larger pressure resistance compared with 25 microns one as smaller pore size can seize more particles while the difference is not significant. Serious clogging issues were not happened within 76 hours as no significant pressure drop was observed

.

4.1.3.4 Element analysis

Mn was added in this due to accidently by the lab technician, but it was not removed from the element analysis to have a better grasp of the composition of filtrates.

Table 4-5 Elements concentration inside 25 and 10 microns filter bags.

25	Al27(ug/m2)	Ca44(mg/m2)	Mn55(ug/m2)	Fe56(ug/m2)	As75(ug/m2)
Upper	6.94	0.53	BL	16.61	BL
Middle	5.08	0.57	BL	37.61	BL
Bottom	6.90	0.60	BL	14.92	BL
Average	6.31	0.57	/	23.05	/
10	Al27(ug/m2)	Ca44(mg/m2)	Mn55(ug/m2)	Fe56(ug/m2)	As75(ug/m2)
Upper	17.15	0.55	BL	12.00	BL
Middle	21.92	0.54	BL	18.72	BL
Bottom	19.84	0.90	BL	9.31	BL
Average	19.64	0.66	/	13.34	/

Note: BL stands for 'below detect limitation'.

Table 4-5 presents the five elements concentration inside 25 and 10 microns filter bags. Elements are not well evenly distributed inside both filter bags. Calcium concentration is of the highest among these five elements while manganese and arsenic are all below detect limitation. 10 microns filter bag contains more Al and Ca but less Fe when running for the same time. In view of the fact that the process water was delivered by iron pipes in TU Delft Waterlab and tests for 25 and 10 microns filter bags were not conducted at the same time, it could be conjectured that few iron was detached from pipes when it came to the 10 microns filter bag test.

4.1.3.5 ATP measurement

Table 4-6 ATP results of 10 and 25 microns filter bags.

10	Upper	Middle	Bottom	Average
tATP (ng ATP/m2)	264.86	302.69	331.07	**302.69**
dATP (ng ATP/m2)	198.64	359.45	425.67	**331.07**
cATP (pg ATP/m2)	26192.6	29607.4	17442.8	**24414.3**

25	Upper	Middle	Bottom	Average
tATP (ng ATP/m2)	175.94	171.21	275.26	**207.16**
dATP (ng ATP/m2)	99.32	71.89	93.65	**87.97**
cATP (pg ATP/m2)	17641.5	7245.8	7964.7	**10953.8**

In principle, cATP = tATP – dATP while in Table 4-6, tested cATP is much lower than the theoretical caculated values as living cells kept dying all the time. Total cells including living cells are still not well-evenly distributed but also no specific relationship could be found

between concentration and the place of the cut part. To sum up, concentration of living cells is one to three times higher in 10 microns filter bag compared to the one in 25 microns'.

4.2 Stagnation study

4.2.1 Temperature

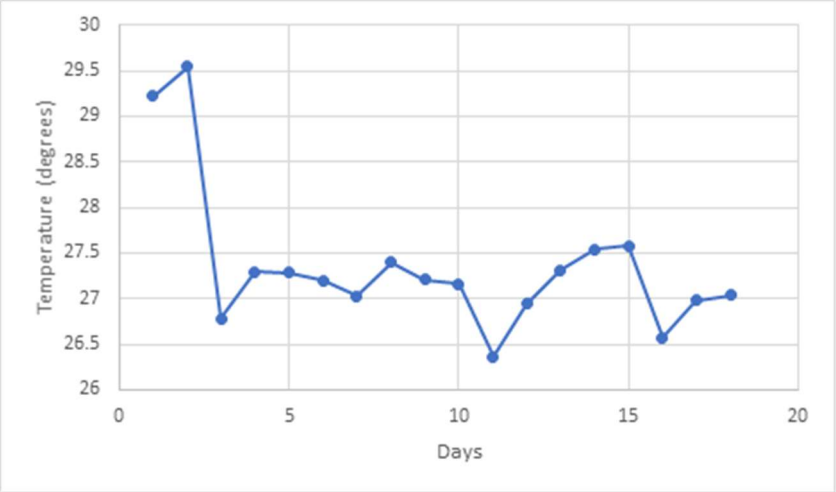

Figure 4-11 Average temperature from 10-11 a.m. within 18 days.

With the help of temperature sensor, temperature can be recorded all the time. Statistics on Figure 4-11 shows that the average temperature of the water passing through the setup from 10 to 11 a.m. ranges from 26 to 30 degrees with the average value of 27.36 degrees. Slight variation is observed within 18 days as the setup is installed indoor during summertime.

4.2.2 ATP measurement

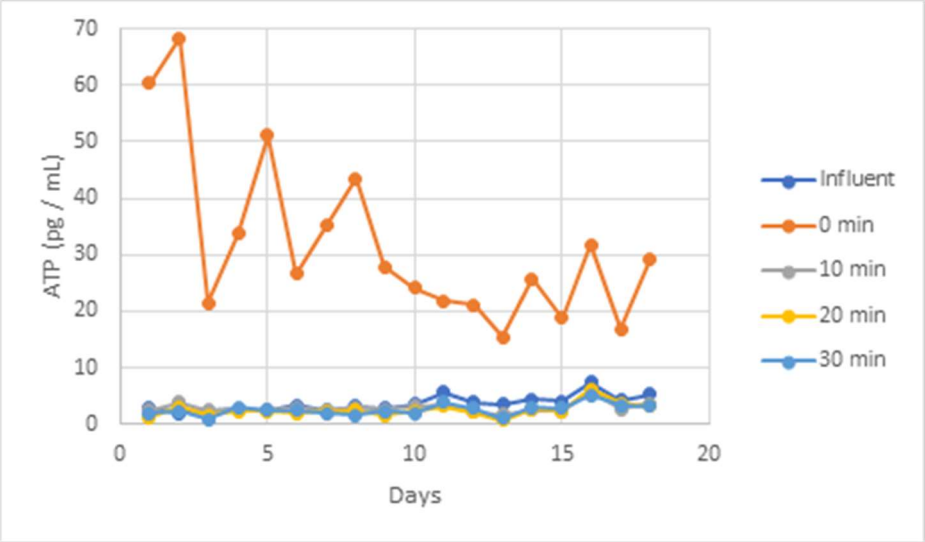

Figure 4-12 ATP along the time within 18 days.

Figure 4-12 shows the ATP values change over time within 18 days. A dramatic fluctuation is observed in the samples taken right after three valves on the setup opens (0 min), which could be two to ten times larger than other values. The curves are relatively steady for the rest four types, where almost no difference exits between each other, revealing that the effluent water quality in terms of microbial activity is fairly stable and stagnation for 23 hours would not affect the microbial activity after flushing more than 10 minutes.

4.2.3 Total cell counts

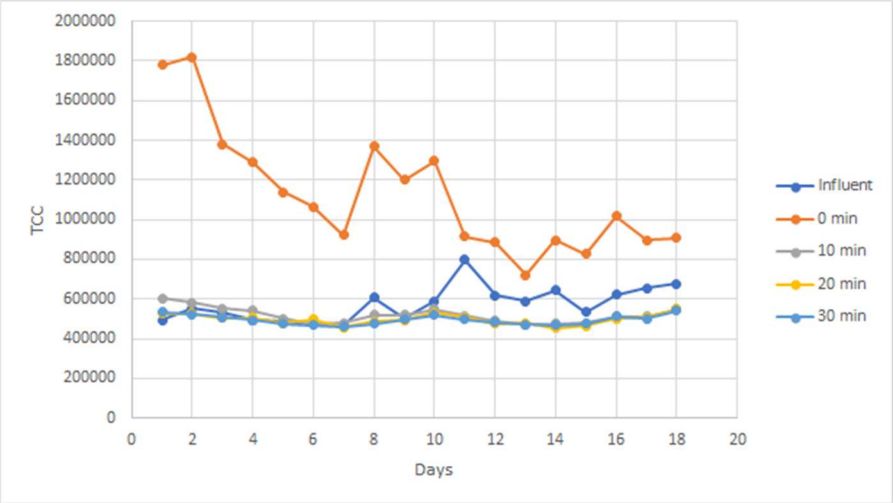

Figure 4-13 Total cell counts in the effluent of the filter bag along the time.

Figure 4-13 records the changes of total cell count in the effluent of the filter bag along the time from June 29th to July 23th. Although the TCC in the influent slightly fluctuates, it remains relatively stable in the effluent after running for 10 minutes, indicating that the rejection ability of the filter bag is steady. However, the TCC value of the samples taken after stagnated (0 min) for 23 hours is much higher than the one in the influent. Little difference can be found between operating for 10, 20 and 30 minutes after opening the valve installed on the blue housing, demonstrating that the number of total cells inside the filter bag tends to stabilize after flushing for a certain time. Besides, it could be seen that the effluent of the setup after flushing contains fewer total cells than the one in the influent, showing that part of the total cells were intercepted by the filter bag. No direct correlation between temperature and total cell counts was found due to steady room temperature.

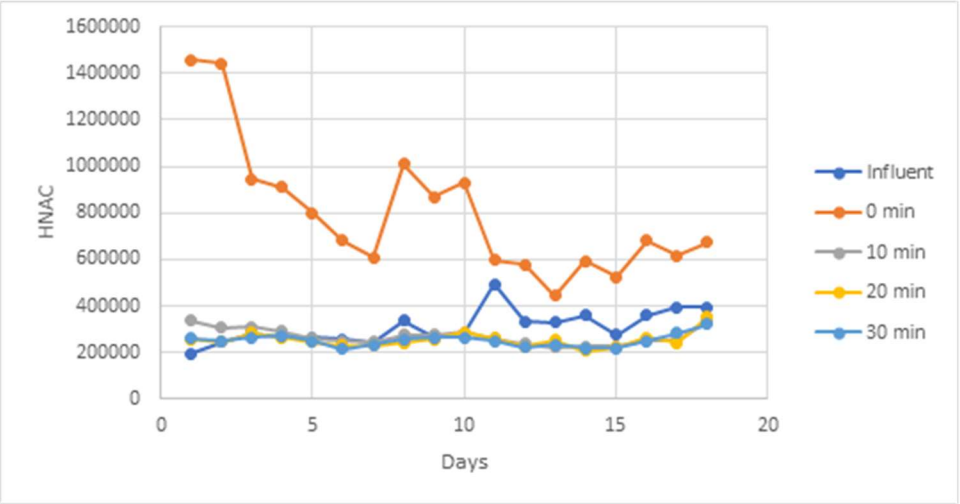

Figure 4-14 HNAC values along the time within18 days.

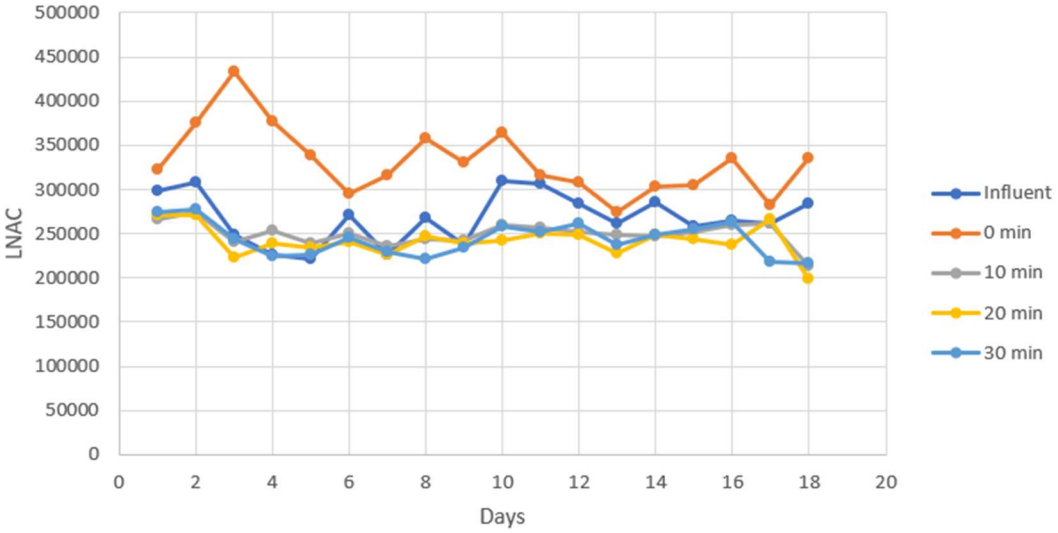

Figure 4-15 LNAC values along the time within 18 days.

Figure 4-14 and 4-15 show the change of high nucleic acids (HNAC) and low nucleic acids (LNAC) measured after three valves on the setup opened for 30 minutes within 18 days respectively. For the HNAC, although its value in influent samples slightly varies, it remains relatively stable and almost no changes occur after the setup operated for 10 minutes, while sharp increase and dramatic changes can be observed right after three valves opened (0 min). In Figure 4-16, both HNAC and LNAC is lowered after filtration.

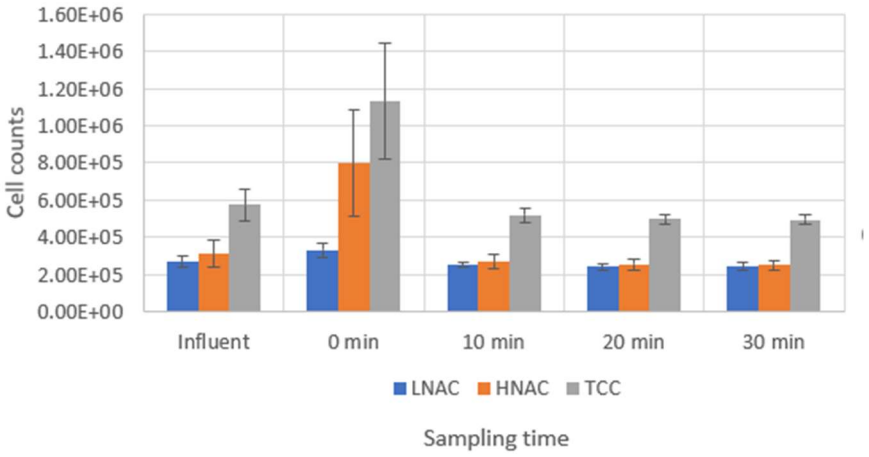

Figure 4-16 TCC, LNAC and HNAC comparison along the time within 18 days.

To make it more intuitive, Figure 4-16 is presented for comparison. It can be observed that HNAC and LNAC almost share the similar percentage in the samples collected from the influent and effluent after running 10 minutes when TCC decreases.

By combining TCC and ATP results, it can be concluded that the microbial activity inside the filter bag did increase after stagnated for 23 hours, where longer retention time provides a relative stable environment for microorganisms to make used of the nutrition in the water to regrow. However, longer stagnation time may not always lead to a further increase in cell concentrations due to the substrate limitation (Lautenschlarger et al., 2010).

The initial worry was that the increasing microbial activity might pose a bacteria threat to the households who are equipped with setups. However, according to the experiment results, microbial activity could return to the initial value in the influent after flushing over 10 minutes. This could be explained that part of the cells was flushed out since the size of the bacteria is much smaller than the pore size of the filter bag, Meanwhile, it is not realistic for households to always open the tap and let it run for few minutes before using after long time stagnation. Limited by the unknow harmful bacteria concentration inside the filter bag, it is difficult to conclude if customers will suffer risks without flushing. Related researches are expected to be conducted in the future.

4.2.4 Elemental analysis

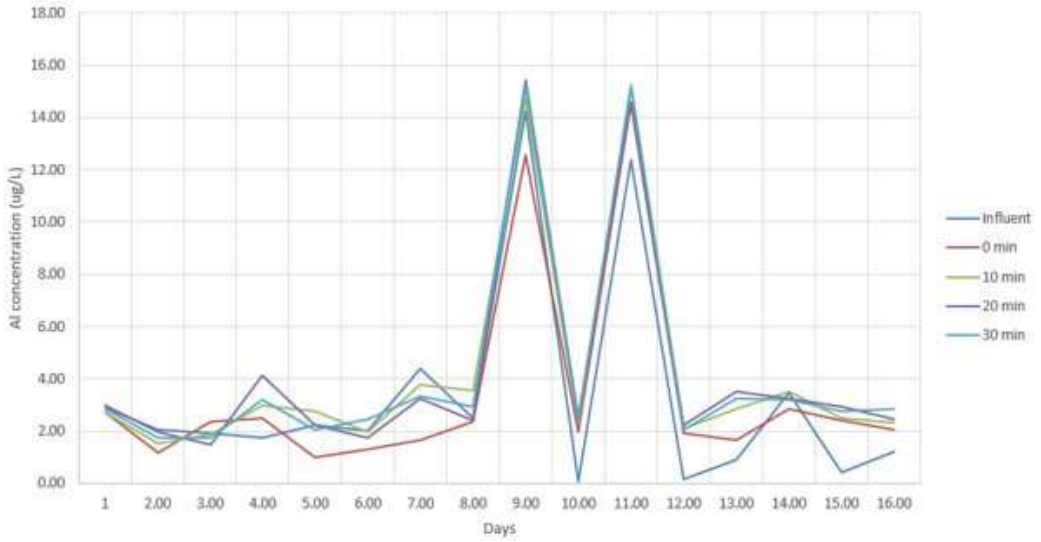

Figure 4-17 Al concentration in water samples along the time within 18 days.

The concentration of aluminum in the influent fluctuates in Figure 4-17, which directly affects the one in the stagnated and flushed samples. However, no specific relationship can be found between these samples. Al is not completely removed mainly because flocculant like aluminum sulphate is added in treatment process in Evides who provides water to Delft. It can occur in a number of different forms and according to the results, it could accumulate inside the filter bag under stagnation while it took some time to be flushed out as the concentration in 0-min samples is lower than that in the influent.

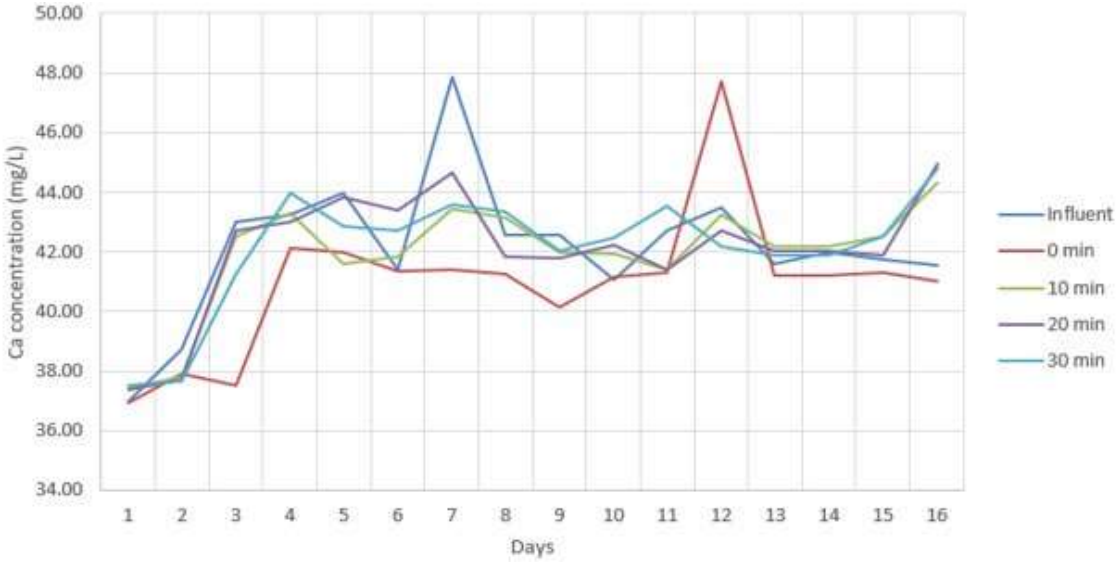

Figure 4-18 Ca concentration in water samples along the time within 18 days.

As stated in Figure 4-18, calcium concentration in the samples taken right after the tap opened (0 min) is lower than that in the influent most of the time, meaning that part of the calcium might be attached to the filter bag during stagnation and take time to be flushed out. However, it would be gradually flushed out after water flowing over 10 minutes. The unusual peak of 0-min sample on the 12th day is hard to explain as no stronger influent pressure or higher Ca concentration was observed at that time. It might be described as a release after the gradual accumulation for few days or an unexpected measurement error.

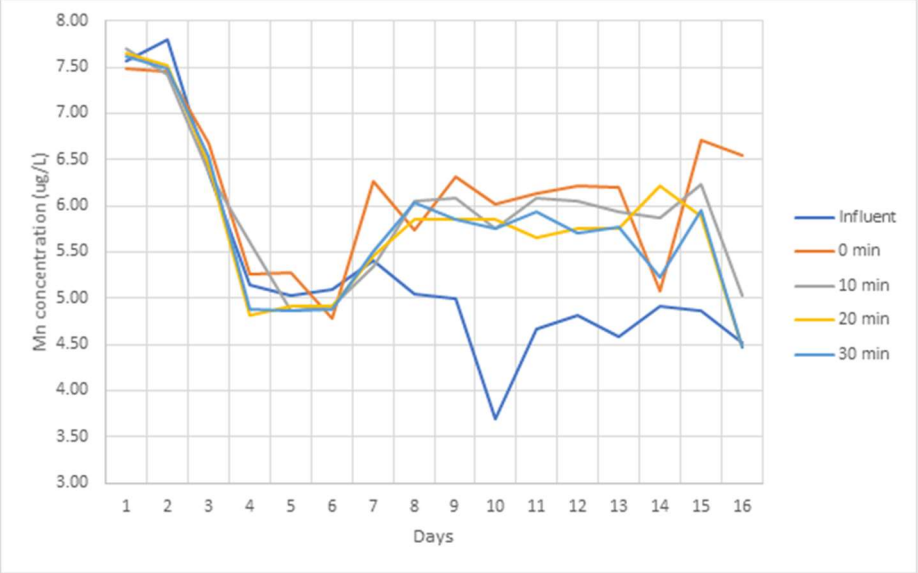

Figure 4-19 Mn concentration in water samples along the time within 18 days.

Compared with the other elements measured in this research, the manganese concentration in five samples varies in a small range from 3.6 to 7.6 ug/L according to Figure 4-19. Although the water quality of the influent changes along the time, the Mn concentration in the effluent of the setup remains to be above 4.7 ug/L. For the first seven days, five types' Mn concentration is almost the same, no specific relationship could be discovered. While a few days later, it could be seen that Mn accumulated inside the filter bag under stagnation and could be flushed out easily. Concentration of the 30-min effluent water sample is still higher than that in the influent, implying that great amount of Mn was retained during hydraulic retention time.

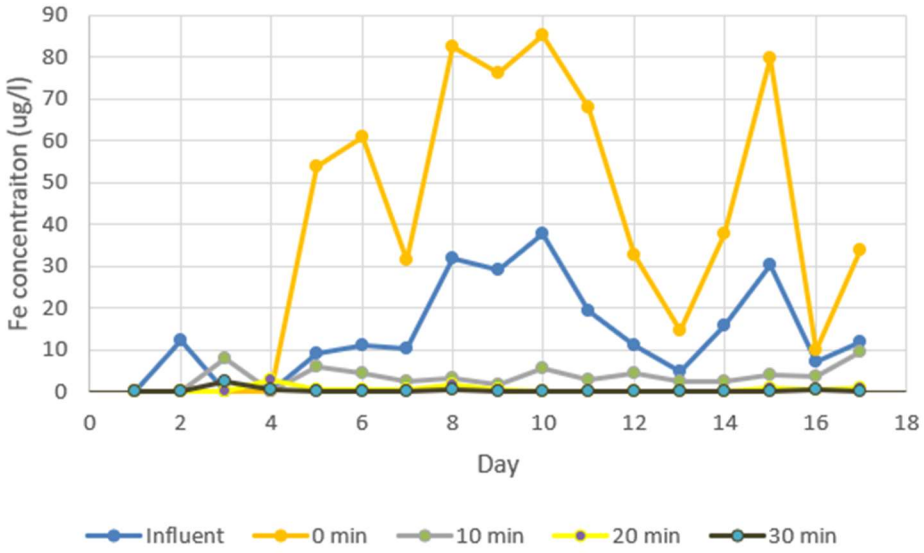

Figure 4-20 Fe concentration in water samples along the time within 18 days.

Figure 4-20 provides the data of Fe concentration in the influent along the time within 18 days. In the real results, several samples were below the limitation (see Appendix B-4.4). To be more intuitive, value of these samples is set as 0.01 ug/l. The influent iron concentration is higher than the average value in drinking water samples measured by Evides due to iron pipes in the lab for process water. Iron concentration of 0 min's water sample is in positive relationship with the one in the influent. Besides, iron accumulates, and the concentration is enlarged two to five times under stagnation. However, after flushing for 10 minutes later, the concentration is greatly lowered and remains to be blow 1 ug/L after operating for half an hour. Some of which is even below detection, meaning that the filter bag has great removal ability of iron compounds.

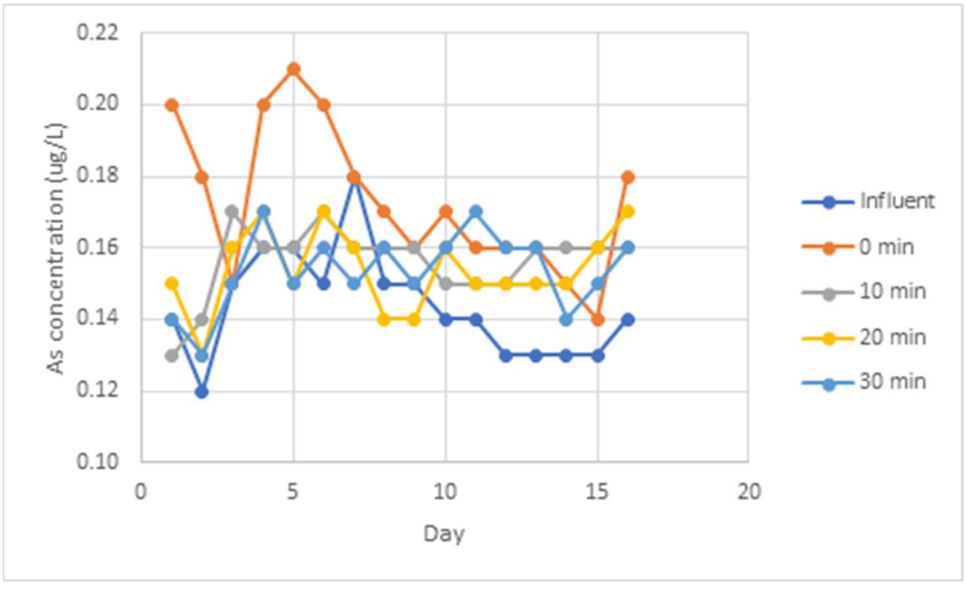

Figure 4-21 As concentration in water samples along the time within 18 days.

The arsenic concentration in the five kinds of samples is relatively steady as shown in Figure 4-23, ranging from 0.12 to 0.21 ug/L. As accumulated inside the filter bag and is easily to be flushed out due to certain increase after the valves opened. However, As concentration in 30-min water samples are still higher than the one in the influent, indicating that great amount of As is retained inside the filter bag under stagnation.

4.3 Smart Water Meter under different water quality

According to the results obtained in the second experiment, simulation of the Smart Water Meter operation mode in households could be simplified to let water pass through it without stop.

4.3.1 Pressure loss

It is worried that the pressure loss (difference between influent and effluent water pressure) would be enlarged as 10 microns pore size is much smaller than 50 microns, leading to the insufficient pressure to households. Considering that the influent tap water pressure of the setup in TU Delft is rather low and the online system of the setup in Kamerik had not been completed yet where pressure failed to be read, more attention is paid on the other two households. By checking the online data collected by the monitor box, almost no pressure loss was observed with the influent pressure of 4.5 bar in Schuwacht (Oasen) while in Delftgauw (Dunea), it took up a quarter of the influent pressure whose value was 1.2 bar. Explanation could be that there were more particles inside the drinking water in Delftgauw than that in Schuwacht, which could also be supported in the next part. More particles retained by the fiter bag leads to a higher pressure loss of the influent pressure. Furtheromre, influent pressure influence may not be ignored neither as higher pressure could provide larger force, pushing more particles passing through pores. To confirm it, an experiment was suggested to be further conducted to discover the relationship between influent pressure and pressure loss of the filter bag.

4.3.2 Particle size distribution

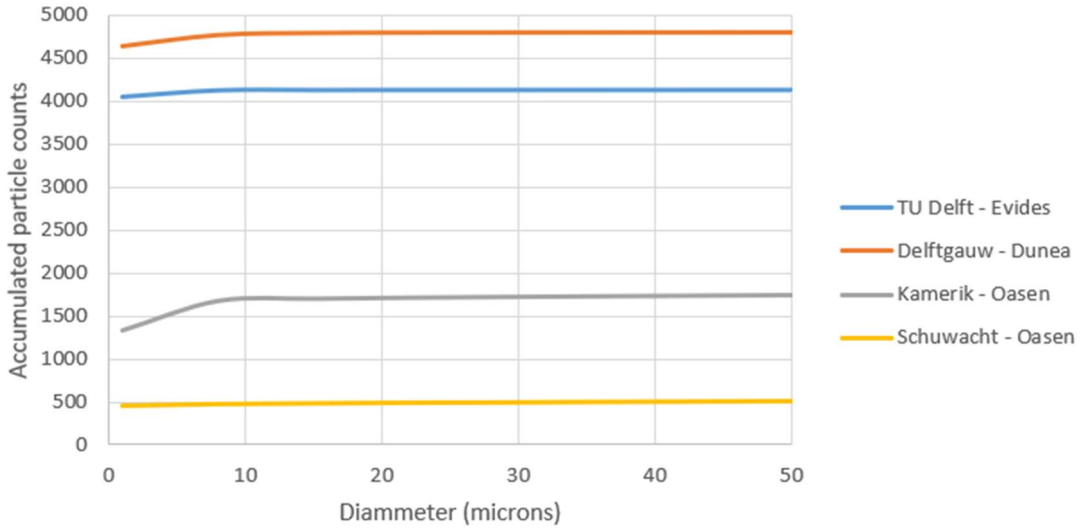

Figure 4-22 Average particle size distribution of the influent water in four locations.

As illustrated in Figure 4-22, particle size distribution of the water samples collected from four locations provided by three drinking water companies are distinct. Water samples collected in Delftgauw provided by Evides contains the most particles on average while those collected in Schuwacht contains the least. Although water quality is influenced by multi-factors like treatment process, pipe material and length, one of the most possible reasons could be the application of reverse osmosis in Lekkerkerk area which greatly removes particles except water molecules. The setup in Kamerik is installed inside the drinking water treatment station while the rest three ones are at end users. The drinking water distribution network will deteriorate the water quality to a certain extent due to complicated interactions inside it even under normal conditions, leading to an increase number of particles in the water.

4.3.3 Removal rate

Table 4-7 Removal rate of particles ranging from 1-50 microns of filter bags in four locations.

Location \ Diameter (mm)	1	8	15	22	29	36	43	50
Delft - Evides	80.58%	87.67%	87.66%	94.36%	100.00%	100.00%	100.00%	100.00%
Delftgauw - Dunea	42.97%	86.47%	96.62%	100.00%	100.00%	100.00%	100.00%	100.00%
Kamerik - Oasen	35.91%	83.21%	94.01%	93.17%	100.00%	100.00%	100.00%	100.00%
Schuwacht - Oasem	25.71%	80.66%	76.33%	100.00%	100.00%	100.00%	100.00%	100.00%

As listed in Table 4-7, filter bags reveal reliable removal ability for particles larger than 22 microns in the first operation hour. Although the pore size of filter bags is 10 microns, still a small fraction of particles around 15 microns failed to be retained inside bags while particles smaller than 10 microns or even around 1 micron could be removed to a certain extent,

especially for the size close to it. Possible reasons can be surmised that the retained materials inside the filter bag may both hinder particles larger than 10 microns and induce the ones smaller than 10 microns due to clogging or adherence. Stable removal rate can be achieved for particles larger than 29 microns.

4.3.4 Visual Observation

Figure 4-23 Visual observation of the filter bag after simulating for one month's water usage; a) TU Delft b) Kamerik c) Schuwacht d) Delftgauw first time e) Delftgauw second time.

Figure 4-24 Visual observation of the filter bag after simulating for six month's water; a) TU Delft b) Kamerik.

Figure 4-23 and 4-24 show the visual observation of the filter bag installed in four locations after simulating one and six months' water consumption separately. By comparing the two stages, a much deep color can be seen when the setup operates for a longer time, indicating that more particles are captured by the filter bag.

According to Figure 4-24, obvious different color of the inner surfaces are presented, indicating that the interrupted materials might be composed of non-identical components. Besides, although water samples taken from Delftgauw have the most particles among four locations, its filter bag displays the lightest color. This could also be influenced by the influent water quality. As stated by Imran et al., red materials may have a significant relationship with the release of corrosion by-products. There is also a possibility that red is resulted from red colonies like Enterococcus spp (Botsaris et al., 2015). As mentioned above, brown or black color usually proves the existence of old deposits in the drinking water distribution network especially organic matters. According to the electron microscopy analysis of brown deposits conducted by Echeverria et al., main components in most samples are C, O, Al, Si, Mn, Fe, Ca and Mg, revealing that principally aluminosilicates compounds, quartz and organic compounds, most probably humic acids may be contained by the filter bag.

Figure 4-25 Visual observation of the 50 microns filter bag inner surface in Schuwacht (Jiaxing, 2017)

Figure 4-25 presents the inner surface of 50 microns filter bag in Schuwacht right after the supply water switch when the filter bag was set to be replaced every two months. The newly selected 25 microns filter bag could seize more particles compared with 50 microns' as in this research, filter bags were set to be replaced once per month.

4.3.5 Elements analysis

Table 4-8 Elements concentrations of the filtrates retained by filter bags.

Water consumption	Sampling location	As (ug/l)	Ca (mg/l)	Fe (mg/l)	Mn(mg/l)
One month (12 m^3)	TU Delft (1st)	<0.5	<0.5	1.16	0.01
	TU Delft (2nd)	1.65	1.18	4.94	0.04
	Delftgauw (2nd)	1.74	1.97	0.16	0.04
	Delftgauw (3rd)	0.57	1.18	0.09	0.01
	Kamerik (2nd)	<0.5	0.62	2.95	0.01
	Schuwacht (3rd)	0.49	1.3	0.13	0.02
Six months (72 m^3)	TU Delft (3rd)	1.74	1.97	0.16	0.04
	Kamerik (3rd)	0.75	3.54	5.49	0.13

3 cut pieces of filter bags with the surface area of 2 cm^2 were filled with 50 ml DNA free water for ultrasonication and then mixed with nitric acid for five elements analysis. The elements concentration of the filtrates listed in Table 4-8 refer to the average value of the analysis. In general, more elements were accumulated on the inner surface of the filter bag when the setup operates for a longer time with the exception of iron in TU Delft. This might be effected by the iron pipe material. According to Gang et al., plastic pipes are hotspots for accumulation of Ca, Fe and Al coming from loose deposits and biofilm matrix. Iron and calcium are the main elements in the filtrates while arsenic takes up the least, which might indicate that part of the DNHMs come from the detached biofilms instead of loose deposits as calcium is critical for biofilm formation and arsenic can only accumulate inside the sediments.

To have a better understanding of the filter bag performance, average five elements concentrations (bottom, middle, upper part) of both influent and effluent in these four locations were also collected and analyzed for comparison in Table 4-9. Influent and effluent samples were taken at an interval of 5 minutes on the sampling date for one hour for convenience as two of these locations are rather far away.

Table 4-9 Five elements concentrations of influent and effluent in four locations.

Element concentration	Location	Influent	Effluent
As (ug/l)	TU Delft	0.17	0.16
	Schuwacht	0.08	0.07
	Kamerik	0.12	0.11
	Delftgauw	0.11	0.1
Ca (mg/l)	TU Delft	43.2	44.2
	Schuwacht	39.7	39.4
	Kamerik	42.7	43.8
	Delftgauw	45	43.7

Fe (ug/l)	TU Delft	64.2	41.2
	Schuwacht	1.1	0.7
	Kamerik	0.03	0.01
	Delftgauw	2	1.7
Mn (ug/l)	TU Delft	5.85	4.27
	Schuwacht	4.71	3.95
	Kamerik	4.9	4.4
	Delftgauw	5.27	5.12
Al (ug/l)	TU Delft	7.13	6.51
	Schuwacht	7.37	5.11
	Kamerik	2.79	1.44
	Delftgauw	4.7	5.22

In general, concentrations in the effluent are lower than those in the influent, indicating that part of the elements were retained inside filter bags. Calcium is still of the highest concentration in both influent and effluent water samples in four locations. The iron concentration in Delft is much higher than others as the process water is delivered through iron pipes inside the lab instead of plastic ones.

Elements concentrations of the influent and effluent are difficult to be compared with the ones of filtrates for that the previous two parameters were instant value while the filtrates concentration was an accumulation process. Mass balance is not possible to be established when elements concentrations of influent and effluent were not continually monitored.

Elements and microorganisms were difficult to be retained under normal conditions due to their extremely small size. Slight transition effects could be observed by monthly filter bag replacement and analysis while serious transition effects may be reflected directly from the sudden pressure drop.

4.3.6 Biological activity

Table 4-10 Biological activity of the filtrates retained by filter bags.

Sampling time	Location	Aeromonas (kve/100 ml)	ATP (ng/l)	TCC (kve/ml)
1st	Delft	1500	78.6	>1000
2nd	Delft	>3000	317.3	>1000
2nd	Kamerik	35	35.0	>1000
2nd	Delftgauw	<10	51.4	>1000

3rd	Delft	>3000	245.3	>1000
3rd	Kamerik	983	627.3	>1000
3rd	Delftgauw	<10	40.8	>1000
3rd	Schuwacht	<10	86.4	>1000

When Aeromonas is smaller than 10, it means that none of its was detected while on the contrary, there are too many to be counted when the value is over 3000. This also applies to TCC, which requires to be diluted before analysis. Biological activity inside the filter bag increased and accumulated when running for longer time.

In the previous research when the pore size of the filter bag was selected to be 50 microns, ATP concentration for two filter bags collected in Schuwacht in September and November is all below 5 ng/l, which is much lower than the one in this research.

The existence of the Aeromonas indicates that part of the harbored materials might originate from loose deposits. According to Table 4-10, little resuspended material from loose deposits was detected in Delftgauw and Schuwacht, which corresponding with the results of As concentration. In addition, more Aeromonas can be retained as the operation time increases in Delft and Kamerik.

From Table 4-11, although the ATP value of the influent at four locations are relatively same with the exception of Schuwacht where RO is applied, ATP concentration decreased in the effluent in four locations, indicating that part of the living cells were retained inside filter bags. Biological activity analysis of influent and effluent water samples were conducted by myself and due to lab limitations, Aeromonas and TCC tests were not done.

Table 4-11 Biological activity of influent and effluent in four locations.

Flow type	Location	ATP (ng/l)
Influent	Delft	3.68
	Kamerik	3.77
	Delftgauw	3.24
	Schuwacht	2.12
Effluent	Delft	2.56
	Kamerik	3.68
	Delftgauw	3.20
	Schuwacht	2.02

5 Conclusions

Great amount of data is obtained after performing three experiments designed for answering the research questions. Conclusions for each experiment will first be given and then combined to summarize the performance of the Smart Water Meter.

5.1 Filter bag selection

After three stages tests, 10 microns filter bag is recommended for the next setup version. Firstly, more particles were retained by 10 microns filter bag based on the facts of a dirtier inside, higher elements concentration with the exception of Fe and ATP value, as well as more total cells of filtrates. Secondly, no significant pressure drop was observed although pressure resistance of 10 microns filter bag increased when the interval of filter bag replacement is set to be one to even eight months, indicating that pores of the filter bag was indeed gradually being blocked while the cake layer was not formed under normal conditions (takes longer time).

The selected 10 microns filter bag was supposed to be tested under serious transition effects condition like discoloration to check if obvious pressure drop would occur as the Smart Water Meter is also expected to set an early alarm right after it happened. However, limited by the unavailable pump and solution samples, this part was not completed.

By replacing the filter bag every one to two months and analyzing its filtrates from chemical and biological aspects, a certain range of measured parameters results are able to be collected along the time. With these data, an upper and lower limit, referring to the normal conditions, could be roughly labeled. Abnormal data locates outside this area may point out the possible transition effect, even the slight one which will not be reflected from the pressure drop. While for serious transition effects, one can directly know according to the pressure drop jump and by closing the influent valve on the setup, further damage on customers will be avoided.

Compared with the 50 microns filter bag used in the previous research, 25 microns filter bag did seize more DNHMs thus provide more materials and data for future analysis.

5.2 Stagnation test

The lab test may vary from the field scale as it cannot simulate all conditions in the real life, especially the daily water consumption mode. To simplify experiments, water was set to flow

through the Smart Water Meter without stop each time. However, long stagnated time of it inside the filter bag in real daily life should be considered which might deteriorate the water quality due to the microorganisms regrowth in that environment.

According to the results, microorganisms inside the filter bag did regrow after stagnated for 23 hours while the daily water pattern in household will not induce the regrowth of them as they could be flushed out after valves reopen for several minutes, both chemical and biological indicators could go back to the value as the one in the influent in general, meaning that the water stagnated inside the filter bag did deteriorate in terms of its quality but has little impact on households as it will go back to normal after flushing for a while. This also means that the simplification of the simulation in lab is acceptable.

The size of most bacteria in the drinking water is smaller than 10 microns according to the Water Quality Association created in 1974, thus they can always be flushed out from the filter bag. However, metal elements existed in complicated forms in the water and their concentration is rather low, making it difficult to predict the accumulation or detachment on the filter bag. The filter bag shows great removal ability of Fe while for the other four elements, no significant concentration decrease was observed compared to that in the influent. Both five elements accumulated under stagnation for 23 hours. For Al and Ca, it takes longer time to be flushed out as no obvious increase of concentration is observed until after flushing for 10 minutes. For Mn and As, they could be easily flushed out and due to great amount accumulated inside the filter bag, 30 minutes' flushing is not enough to bring the concentration back to the one in the influent. However, no harm will be aroused as these concentrations are all lower than the regulated value according to the Drinking Water Directive.

5.3 Smart Water Meter under different water quality

Smart Water Meters installed in two households with different influent pressure showed distinct pressure loss, which might resulted from different influent water quality (total particle numbers). Under normal conditions, no obvious pressure drop was observed when the filter bag replacement was set to be switched once per month in four locations.

In these four locations with distinct particle size distribution, the Smart Water Meter can not only reject particles whose size are larger than 10 microns, but also can remove part of the particles that are smaller than 10 microns or even around 1 micron. 100% removal rate is achieved for particles over 29 microns for particles ranging from 1 to 50 microns under these four different water types.

Obvious different color of the filter bags inner surface provides an idea of what is the possible entrapped materials composition. Origins of DNHMs could be roughly deduced by combining chemical and microbial results. For these four locations, most of the DNHMs might come from detached biofilms as calcium is crucial for biofilm formation. In Delft and Kamerik setup locations, part of the retained materials may also originate from loose deposits for that arsenic and Aeromonas could only accumulate in it.

Small removal rate of the elements was observed in filter bags mainly due to tiny size of irons. However, filter bag could retain some microorganisms and thus deduce the biological activity when the flow kept flowing through it.

6 Recommendations

In this chapter the advices for future projects study are listed.

- Internet connection methods of the monitor box are better to be re-designed in a more feasible way like remote control instead of hardware programming and integrate the present four sensors together with one multi-probe would be much convenient for installation and transportation.
- Clogging test caused by serious transition effects like discoloration is strongly recommended to check if the new filter bag could set an early alarm. Otherwise, other optimizations would be suggested like using single refractive index (RI) to simplify the detection process or install some spectrometer probes for biological indicators monitor.
- Pressure loss under different influent pressure is advised to be tested.
- DNA extraction combined with 16s rRNA sequencing is able to provide deeper understanding of the inner filter bag and make the track of destabilized DNHMs footprint more convenient and reliable.
- Pore size of the filter bag is better to be reconsidered when applying to a new drinking water supply area due to different influent pressure, particle size distribution, particle numbers and drinking water distribution networks conditions.
- Remember to consider the dilution necessity before sample analysis.

Bibliography

Abdelrasoul, A., Doan, H., & Lohi, A. (2013). Fouling in membrane filtration and remediation methods. Mass transfer-advances in sustainable energy and environment oriented numerical modeling, 195.

Al-Mutaz, I.S., M. A. Al-Ghunaimi and S. A. Al-Busaili. (1999). PH Increase in Water Distribution Pipes. IDA World Congress on Desalination and Water Re-Use, San Diego, USA.

Ainsworth, R., 2013. Safe piped water: managing microbial water quality in piped distribution systems. Water Intell. Online 12, 9781780405841.

ANSI-ASHRAE. (1992). Thermal environmental Conditions for Human Occupancy.

Bacteria and Viruses. (n.d.). Water Quality Association. Retrieved from: https://www.wqa.org/learn-about-water/common-contaminants/bacteria-viruses (Accessed: 20 November 2019)

Badu, S. (2016) Advances in chemical mechanical planarization (cmp) (Woodhead publishing series in electronic and optical materials, number 86). Waltham, MA: Woodhead Publishing.

Berney, M., Vital, M., Hülshoff, I., Weilenmann, H.-U., Egli, T., & Hammes, F. (2008). Rapid, cultivation-independent assessment of microbial viability in drinking water. Water Research, 42(14), 4010–4018.

Cook, D. M., & Boxall, J. B. (2011). Discoloration material accumulation in water distribution systems. Journal of Pipeline Systems Engineering and Practice, 2(4), 113–122.

Dahlberg, E.T., American Winesecrets, LLC, 2019. Methods for producing color-concentrated wine products. U.S. Patent Application 16/182,493.

Dusseldorp, J. (2013). The effect of pre-treatment with Reverse Osmosis on biological stability in a drinking water distribution network.

Drinkwater: Dunea Duin & Water. Retrieved from https://www.dunea.nl/drinkwater (Accessed: 24 August 2019)

Echeverría, F., Castaño, J. G., Arroyave, C., Peñuela, G., Ramírez, A., & Morató, J. (2009). Characterization of deposits formed in a water distribution system. Ingeniare. Revista chilena de ingeniería, 17(2), 275-281.

EU, C. D. (1998). 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. Official Journal L, 330, 05-12.

Evides Waterbedrijf, De Zuiveringsprocessen. Retrieved from https://www.evides.nl/drinkwater/de-zuiveringsprocessen. (Accessed: 14 August 2019)

Gunasekera, T. S., Attfield, P. V., & Veal, D. A. (2000). A flow cytometry method for rapid detection and enumeration of total bacteria in milk. Appl. Environ. Microbiol., 66(3), 1228-1232.

Hammes, F., Berney, M., Wang, Y., Vital, M., Köster, O., & Egli, T. (2008). Flow-cytometric total bacterial cell counts as a descriptive microbiological parameter for drinking water treatment processes. Water research, 42(1-2), 269-277.

Hammes, F., Goldschmidt, F., Vital, M., Wang, Y., & Egli, T. (2010). Measurement and interpretation of microbial adenosine tri-phosphate (ATP) in aquatic environments. Water Research, 44(13), 3915–3923.

Henne, K., Kahlisch, L., Brettar, I., & Höfle, M. G. (2012). Analysis of structure and composition of bacterial core communities in mature drinking water biofilms and bulk water of a citywide network in Germany. Applied and Environmental Microbiology, 78(10), 3530-3538.

Jiaxing F. (2017) The study of potential transition effects on water quality during distribution by smart water meters (SWMs).

Lautenschlager, K., Boon, N., Wang, Y., Egli, T., & Hammes, F. (2010). Overnight stagnation of drinking water in household taps induces microbial growth and changes in community composition. Water Research, 44(17), 4868-4877.

Lautenschlager, K., Hwang, C., Liu, W.-T., Boon, N., Köster, O., Vrouwenvelder, H., Egli, T., Hammes, F. (2013) A microbiology-based multi-parameter approach towards assessing biological stability in drinking water distribution networks. Water Research, 47, 3015-3025.

Learbuch, K., Lut, M., Liu, G., Smidt, H., & Van der Wielen, P. (2019). Legionella growth potential of drinking water produced by a reverse osmosis pilot plant. Water Research, 157, 55-63.

Lebaron P, Servais P, Agogue H, Courties C, Joux F. (2001). Does the high nucleic acid content of individual bacterial cells allow us to discriminate between active cells and inactive cells in aquatic systems? Appl Environ Microbiol 67: 1775–1782.

Lebaron P, Servais P, Baudoux A-C, Bourrain M, Courties C, Parthuisot N. (2002). Variations of bacterial-specific activity with cell size and nucleic acid content assessed by flow cytometry. Aquat Microb Ecol 28: 131–140.

Liu, G., Bakker, G. L., Li, S., Vreeburg, J. H., Verberk, J. Q., Medema, G. J., Liu, W. T., Dijk, J. C. (2014). Pyrosequencing reveals bacterial communities in unchlorinated drinking water distribution system: an integral study of bulk water, suspended solids, loose deposits, and pipe wall biofilm. Environmental Science & Technology, 48(10), 5467-5476.

Liu, G., Tao, Y., Zhang, Y., Lut, M., Knibbe, W.-J., van der Wielen, P., van der Meer, W. (2017). Hotspots for selected metal elements and microbes accumulation and the corresponding

water quality deterioration potential in an unchlorinated drinking water distribution system. Water Research, 124, 435–445.

Liu, G., Van der Mark, E. J., Verberk, J. Q. J. C., & Van Dijk, J. C. (2013). Flow cytometry total cell counts: a field study assessing microbiological water quality and growth in unchlorinated drinking water distribution systems. BioMed research international, 2013.

Liu, G., Verberk, J., & Van Dijk, J. (2013). Bacteriology of drinking water distribution systems: An integral and multidimensional review. Applied Microbiology and Biotechnology, 97(21), 9265-76.

Liu, G., Zhang, Y., Knibbe, W., Feng, C., Liu, W., Medema, G., & Van der Meer, W. (2017). Potential impacts of changing supply-water quality on drinking water distribution: A review. Water Research, 116, 135-148.

Liquid Dynamic Viscosity. (0AD). Retrieved from http://ddbonline.ddbst.de/VogelCalculation/VogelCalculationCGI.exe?component=Water (Accessed: 10 April 2019)

Low Cost Water Quality Monitoring for Multiple Parameters. (2019). Retrieved from http://www.i-scan.at/index.php/versions/low-cost-online-water-quality-monitoring (Accessed: 14 May 2019)

Long-Term Bacterial Dynamics in a Full-Scale Drinking Water Distribution System. PLOS ONE, 11(10).

Lytle, D. A., Sorg, T. J., & Frietch, C. (2004). Accumulation of arsenic in drinking water distribution systems. Environmental Science & Technology, 38(20), 5365–5372.

Mays, L.W., 1999. Water Distribution System Handbook. McGraw-Hill Professional Publishing

Modifired, Q.O. & Kit, Q. T. (2010). Test Kit Instructions, 33 (0), pp.1-6.

National Water Plan 2016-2021. (2015). Our Water.

Nerbrand, C., Agréus, L., Lenner, R. A., Nyberg, P., & Svärdsudd, K. (2003). The influence of calcium and magnesium in drinking water and diet on cardiovascular risk factors in individuals living in hard and soft water areas with differences in cardiovascular mortality. BMC public Health, 3(1), 21.

NRC. (2006). Drinking water distribution systems: assessing and reducing risks. National Academies Press.

Oasen Levert Altijd Onberispelijk Drinkwater. Retrieved from https://www.oasen.nl/. (Accessed: 24 August 2019)

Ochromowicz, K. & Hoekstra, E. J. (2005) ATP as an indicator of microbiological activity in tap water. European Commission: Joint Research Centre.

Prest, E. I., Hammes, F., van Loosdrecht, M. C. M., & Vrouwenvelder, J. S. (2016b). Biological stability of drinking water: controlling factors, methods, and challenges. Frontiers in Microbiology, 7.

Prest, E. I., Weissbrodt, D. G., Hammes, F., van Loosdrecht, M. C. M., & Vrouwenvelder, J. S. Tadonleke RD, Planas D, Lucotte M. (2005). Microbial food webs in boreal humic lakes and reservoirs: ciliates as a major factor related to the dynamics of the most active bacteria. Microb Ecol 49: 325–341.

Rao, R. N., & Talluri, M. K. (2007). An overview of recent applications of inductively coupled plasma-mass spectrometry (ICP-MS) in determination of inorganic impurities in drugs and pharmaceuticals. Journal of pharmaceutical and biomedical analysis, 43(1), 1-13.

Ratkowsky, D. A., Olley, J., McMeekin, T. A., & Ball, A. (1982). Relationship between temperature and growth rate of bacterial cultures. Journal of bacteriology, 149(1), 1-5.

Reynolds, K. A. (2007). Water quality control in premise plumbing. Water Conditioning & Purification.

Ricordel, C., Darchen, A., & Hadjiev, D. (2010). Electrocoagulation–electroflotation as a surface water treatment for industrial uses. Separation and purification Technology, 74(3), 342-347.

Servais P, Casamayor EO, Courties C, Catala P, Parthuisot N, Lebaron P. (2003). Activity and diversity of bacterial cells with high and low nucleic acid content. Aquat Microb Ecol 33: 41–51.

Tadonleke RD, Planas D, Lucotte M. (2005). Microbial food webs in boreal humic lakes and reservoirs: ciliates as a major factor related to the dynamics of the most active bacteria. Microb Ecol 49: 325–341.

The WaterWiSe multi sensor probe. (n.d.) Real-time monitoring platform to improve the drinking water network efficiency. WaterWiSe & Visenti.

Van der Kooij, D., 1992. Assimilable organic carbon as an indicator of bacterial regrowth. J./Am. Water Works Assoc. 84 (2), 57-65.

Verberk, J.Q.J.C., Vreeburg, J.H.G., Rietveld, L.C., Van Dijk, J.C., 2009. Particulate fingerprinting of water quality in the distribution system. Water SA 35 (2), 192-199.

Vreeburg, J., Schippers, D., Verberk, J., & Van Dijk, J. (2008). Impact of particles on sediment accumulation in a drinking water distribution system. Water Research, 42(16), 4233-4242.

Zewei, C. (2016). The Smart Water Meter: a new method to monitor fouling issue.

Appendix A Filter bag pore size data

A.1.1 First stage-particle size distribution of the influent process water

Table App.A-1.1.1 Particle size distribution of the influent process water of the 25 microns filter bag.

D (µm) / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	2988.7	62.2	4.4	0.9	0.3	0.1	0	0
1	3734.5	86.5	6.6	1.2	0.2	0.1	0.1	0
2	3846.0	88.0	6.1	1.1	0.2	0.1	0	0
3	1006.4	13.4	0.8	0.1	0	0	0	0
4	3906.8	96.8	9.5	1.5	0.5	0.1	0.1	0.1
5	3662.2	78.5	9.8	1.8	0.5	0.2	0.1	0.1
6	3419.4	95.8	13.4	3.2	1.0	0.4	0	0.1
7	3253.7	78.8	10.3	2.6	0.9	0.4	0.1	0
8	2150.7	31.1	2.7	0.5	0.2	0.1	0	0
9	4407.1	100.3	11.2	2.0	0.5	0.2	0	0
10	3132.6	79.9	10.3	2.5	0.7	0.3	0.1	0
11	2170.2	49.1	5.1	1.4	0.3	0.1	0.1	0

Table App.A-1.1.2 Particle size distribution of the influent process water of the 10 microns filter bag.

D (µm) / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	1028.8	3.7	0.2	0.0	0.0	0.0	0	0
1	3003.9	89.2	12.3	3.2	0.8	0.2	0.1	0
2	3837.9	111.7	19.3	5.3	1.7	0.6	0	0
3	2204.7	46.6	6.6	1.9	0	0	0	0
4	2090.4	49.6	7.2	1.7	0.5	0.2	0.0	0.0
5	4526.2	105.3	18.7	5.2	1.4	0.4	0	0.3
6	4221.1	92.5	11.3	1.7	0.4	0.1	0.0	0
7	2421.2	38.1	3.9	1.1	0.2	0.1	0	0
8	2963.0	48.2	6.6	1.6	0.3	0.1	0	0
9	1999.1	31.7	4.0	0.0	0.2	0.0	0.1	0
10	3416.4	71.4	15.2	5.8	2.3	0.8	0.5	0

A.1.2 First stage-particle size distribution of the effluent

Table App.A-1.2.1 Particle size distribution of the influent process water of the 25 microns filter bag.

D (µm) / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	2322.7	30.2	1.9	0.2	0.0	0.0	0	0
1	1331.1	8.8	0.4	0.0	0.0	0.0	0.0	0
2	1849.9	19.8	0.9	0.2	0.1	0.0	0	0
3	919.8	5.1	0.1	0.0	0	0	0	0
4	2155.8	22.7	1.0	0.1	0.0	0.0	0.0	0.0
5	1472.4	13.2	0.6	0.1	0.0	0.0	0.0	0.0
6	1827.5	19.4	1.1	0.1	0.0	0.0	0	0.0
7	2066.9	18.7	1.2	0.2	0.0	0.0	0.0	0
8	5572.4	16.1	0.6	0.1	0.1	0.0	0	0
9	3002.4	22.8	0.7	0.1	0.1	0.0	0	0
10	2598.8	18.0	0.9	0.2	0.1	0.0	0.0	0
11	1514.8	9.2	0.4	0.0	0.0	0.0	0.0	0

Table App.A-1.2.2 Particle size distribution of the influent process water of the 10 microns filter bag.

D (µm) / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	1043.6	1.6	0.0	0.0	0.0	0.0	0	0
1	3687.1	21.8	0.8	0.0	0.0	0.0	0.0	0
2	2891.7	22.3	1.1	0.2	0.1	0.1	0	0
3	1780.0	8.8	0.5	0.2	0	0	0	0
4	1688.7	7.8	0.5	0.0	0.0	0.0	0.0	0.0
5	1880.1	10.2	0.5	0.0	0.0	0.0	0	0.0
6	1868.8	7.7	0.3	0.0	0.0	0.0	0.0	0
7	2745.9	9.2	0.2	0.0	0.0	0.0	0	0
8	5841.5	29.6	1.0	0.5	0.0	0.0	0	0
9	1615.2	4.3	0.2	0.0	0.0	0.0	0.0	0
10	4112.5	30.6	1.3	0.1	0.1	0.0	0.0	0

A.1.3 First stage-removal rate of filter bags

Table App.A-1.3.1 Removal rate of the 25 microns filter bag.

Removal rate / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	-4.16%	55.56%	85.05%	93.94%	100.00%	100.00%	100.00%	100.00%
1	30.60%	92.25%	96.77%	100.00%	100.00%	100.00%	100.00%	100.00%
2	10.82%	71.30%	87.50%	100.00%	100.00%	100.00%	100.00%	100.00%
3	0.06%	51.53%	73.33%	80.00%	100.00%	100.00%	100.00%	100.00%
4	14.54%	73.64%	83.33%	66.67%	100.00%	100.00%	100.00%	100.00%
5	22.76%	79.56%	87.50%	100.00%	100.00%	100.00%	100.00%	100.00%
6	32.77%	72.38%	84.20%	90.52%	95.45%	100.00%	100.00%	100.00%
7	38.99%	52.66%	64.29%	77.78%	50.00%	100.00%	100.00%	100.00%
8	49.80%	80.76%	91.40%	96.30%	100.00%	100.00%	100.00%	100.00%
9	36.47%	87.21%	92.86%	100.00%	100.00%	100.00%	100.00%	100.00%
10	33.68%	52.78%	65.38%	83.33%	100.00%	100.00%	100.00%	100.00%

Table App.A-1.3.2 Removal rate of the 10 microns filter bag.

Removal rate / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	-1.44%	56.76%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
1	-22.74%	75.56%	93.50%	100.00%	100.00%	100.00%	100.00%	100.00%
2	24.65%	80.04%	94.30%	96.23%	94.12%	83.33%	100.00%	100.00%
3	19.26%	81.12%	92.42%	89.47%	75.00%	100.00%	100.00%	100.00%
4	15.12%	82.24%	92.45%	93.41%	100.00%	100.00%	100.00%	100.00%
5	19.22%	84.27%	93.06%	100.00%	100.00%	100.00%	100.00%	100.00%
6	58.46%	90.31%	97.33%	100.00%	100.00%	100.00%	100.00%	100.00%
7	55.73%	91.68%	97.35%	100.00%	100.00%	100.00%	100.00%	100.00%
8	13.00%	73.75%	89.74%	100.00%	100.00%	100.00%	100.00%	100.00%
9	19.20%	86.44%	95.00%	100.00%	100.00%	100.00%	100.00%	100.00%
10	-20.38%	57.14%	91.45%	98.28%	95.65%	100.00%	100.00%	100.00%

A.1.4 First stage-Pressure resistance of filter bags

Table App.A-1.4.1 Pressure resistance of 25 and 10 microns filter bags.

Operation hours	25 microns	10 microns
0	46.36	53.05
1	48.54	59.01
2	52.02	63.94
3	56.55	66.63
4	58.43	65.13
5	55.73	65.14
6	55.42	66.10
7	54.78	64.64
8	53.95	68.25
9	53.57	64.87
10	53.44	64.50
11	53.41	64.05

A.2.1 Second stage-Removal rate of the 25 microns filter bag

Table App.A-2.1 Removal rate of the 25 microns filter bag.

Removal rate / Time (hr)	1	12.29	23.57	34.86	46.14	57.43	68.71	80
0	10.49%	76.52%	72.73%	100.00%	100.00%	100.00%	100.00%	100.00%
1	1.19%	68.33%	92.86%	100.00%	100.00%	100.00%	100.00%	100.00%
2	11.97%	30.23%	80.00%	100.00%	100.00%	100.00%	100.00%	100.00%
3	10.85%	48.15%	85.71%	100.00%	100.00%	100.00%	100.00%	100.00%
6	5.14%	37.25%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
7	34.18%	73.45%	85.32%	85.71%	100.00%	100.00%	100.00%	100.00%
23	98.30%	99.86%	99.24%	96.15%	100.00%	100.00%	100.00%	100.00%
24	59.57%	91.04%	97.09%	95.00%	100.00%	100.00%	100.00%	100.00%
25	49.59%	87.90%	94.90%	97.66%	96.43%	94.74%	100.00%	100.00%
27	25.33%	45.59%	50.00%	50.00%	100.00%	100.00%	100.00%	100.00%
44	26.63%	75.68%	66.67%	100.00%	100.00%	100.00%	100.00%	100.00%
45	91.34%	95.58%	91.30%	100.00%	100.00%	100.00%	100.00%	100.00%

46	44.54%	82.76%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
49	17.84%	67.21%	66.67%	100.00%	100.00%	100.00%	100.00%	100.00%
50	12.79%	88.50%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
51	29.66%	31.25%	87.50%	100.00%	100.00%	100.00%	100.00%	100.00%
72	32.17%	53.61%	25.00%	100.00%	100.00%	100.00%	100.00%	100.00%
73	56.20%	90.83%	80.00%	100.00%	100.00%	100.00%	100.00%	100.00%
74	26.10%	89.58%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
75	54.63%	42.50%	60.00%	100.00%	100.00%	100.00%	100.00%	100.00%
77	53.55%	87.23%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

A.2.2 Second stage-Pressure resistance of the 25 microns filter bag

Table App.A-2.2 Pressure resistance of the 25 microns filter bag.

Time	R	Time	R	Time	R	Time	R	Time	R
1	70.81	**51**	46.05	**88**	42.46	**128**	39.48	**165**	40.42
2	73.12	**52**	43.71	**89**	40.56	**129**	39.61	**166**	40.20
3	69.04	**53**	43.15	**90**	40.28	**130**	39.92	**170**	41.25
4	64.84	**54**	43.30	**91**	40.95	**131**	40.20	**171**	41.09
5	62.99	**55**	43.15	**92**	39.87	**132**	40.35	**172**	41.42
6	55.54	**56**	42.53	**93**	40.05	**133**	40.91	**173**	42.78
7	52.11	**57**	42.94	**94**	39.81	**134**	42.39	**174**	43.05
8	48.80	**58**	43.15	**95**	39.66	**135**	43.36	**175**	43.42
9	47.32	**59**	40.13	**96**	40.26	**136**	41.94	**176**	43.73
10	43.46	**60**	40.29	**97**	40.45	**137**	43.05	**177**	43.19
24	48.22	**61**	39.21	**98**	41.10	**138**	41.35	**178**	41.70
25	46.28	**62**	39.50	**99**	43.41	**139**	41.07		
26	44.96	**63**	39.80	**100**	46.08	**140**	40.46		
27	45.61	**64**	39.52	**104**	40.65	**141**	40.45		
28	42.66	**65**	39.59	**105**	39.92	**142**	40.16		
29	40.38	**66**	40.06	**106**	39.85	**143**	39.93		
30	39.90	**67**	40.48	**107**	39.80	**144**	39.82		
31	41.43	**68**	41.66	**108**	40.21	**145**	40.15		
32	41.00	**69**	43.86	**109**	39.23	**146**	40.55		
33	39.59	**70**	45.37	**110**	39.65	**147**	41.44		
34	40.11	**71**	44.43	**111**	39.54	**148**	40.66		
35	42.64	**72**	45.11	**112**	39.51	**149**	42.60		

36	45.20	**73**	43.60	**113**	39.42	**150**	42.91		
37	46.04	**74**	40.81	**114**	39.63	**151**	43.24		
38	43.94	**75**	40.98	**115**	39.97	**152**	43.51		
39	43.25	**76**	40.60	**116**	40.21	**153**	43.08		
40	43.24	**77**	40.17	**117**	40.56	**154**	41.63		
41	43.10	**78**	39.50	**118**	41.45	**155**	40.27		
42	42.32	**79**	39.00	**119**	42.35	**156**	40.29		
43	42.01	**80**	38.55	**120**	42.84	**157**	41.05		
44	42.40	**81**	39.74	**121**	43.24	**158**	42.39		
45	42.82	**82**	40.12	**122**	42.21	**159**	43.03		
46	42.33	**83**	40.43	**123**	42.91	**160**	42.30		
47	42.39	**84**	41.04	**124**	42.06	**161**	42.51		
48	42.97	**85**	41.02	**125**	40.79	**162**	41.95		
49	44.77	**86**	41.09	**126**	40.06	**163**	41.04		
50	47.28	**87**	42.54	**127**	39.59	**164**	40.42		

A.3.1 Third stage-Pressure resistance of the filter bag

Table App.A-3.1.1 Pressure resistance of the 25 microns filter bag.

Time	R	Time	R	Time	R	Time	R
1	51.00	**21**	44.46	**41**	38.89	**65**	36.89
2	51.79	**22**	45.56	**42**	38.73	**66**	38.06
3	52.07	**23**	44.38	**43**	38.62	**67**	37.06
4	53.54	**24**	43.09	**44**	39.62	**68**	37.64
5	54.86	**25**	43.03	**45**	39.16	**69**	37.48
6	54.14	**26**	39.65	**46**	41.16	**70**	38.07
7	53.28	**27**	39.10	**47**	41.01	**71**	38.80
8	48.93	**28**	40.13	**48**	43.74	**72**	39.90
9	46.27	**29**	39.73	**49**	44.81	**73**	39.68
10	45.68	**30**	39.01	**50**	45.27	**74**	40.18
11	41.93	**31**	39.24	**51**	45.85	**75**	42.75
12	41.84	**32**	38.64	**52**	44.83	**76**	43.45
13	41.00	**33**	41.22	**53**	43.53		
14	40.22	**34**	41.03	**54**	41.42		
15	40.33	**35**	46.10	**55**	42.40		
16	39.41	**36**	43.41	**60**	41.14		
17	39.98	**37**	41.52	**61**	37.13		
18	40.60	**38**	38.90	**62**	37.55		

19	42.42	**39**	39.03	**63**	37.78		
20	43.68	**40**	39.50	**64**	37.29		

Table App.A-3.2.2 Pressure resistance of the 10 microns filter bag.

Time	R	Time	R	Time	R	Time	R	Time	R
1	45.72	**16**	43.77	**31**	43.22	**46**	42.94	**63**	43.21
2	45.31	**17**	45.08	**32**	43.68	**47**	43.39	**64**	42.67
3	45.60	**18**	45.80	**33**	44.49	**48**	43.70	**65**	43.75
4	45.99	**19**	46.08	**34**	45.26	**49**	44.78	**66**	44.05
5	46.55	**20**	46.77	**35**	45.66	**50**	45.67	**67**	44.58
6	48.07	**21**	46.68	**36**	46.21	**53**	49.98	**68**	45.80
7	48.03	**22**	48.68	**37**	48.02	**54**	50.24	**69**	46.86
8	49.48	**23**	49.67	**38**	47.25	**55**	47.46	**70**	47.23
9	50.21	**24**	50.02	**39**	48.57	**56**	44.42	**71**	45.02
10	48.14	**25**	47.52	**40**	46.36	**57**	43.73	**72**	44.83
11	46.85	**26**	46.49	**41**	46.07	**58**	43.18	**73**	45.08
12	45.94	**27**	45.59	**42**	45.00	**59**	43.00	**74**	45.38
13	45.31	**28**	44.21	**43**	44.47	**60**	42.46	**75**	43.80
14	44.27	**29**	43.67	**44**	43.16	**61**	42.01	**76**	43.41
15	44.14	**30**	42.86	**45**	42.78	**62**	42.26		

Appendix B Overnight stagnation data

B.1Tempature within 18 days

Table App.B-1 Temperature within 18 days from 6.29 to 7.23.

Date	T (degrees)	Date	T (degrees)
6.29	29.22	**7.14**	27.16
6.30	29.54	**7.16**	26.36
7.1	26.78	**7.17**	26.94
7.2	27.29	**7.18**	27.31
7.3	27.28	**7.19**	27.54
7.4	27.20	**7.20**	27.58
7.5	27.03	**7.21**	26.57
7.9	27.40	**7.22**	26.98
7.11	27.21	**7.23**	27.04

B.2 ATP

Table App.B-2 ATP in five water types within 18 days from 6.29 to 7.23.

Date	Influent	0 min	10 min	20 min	30 min
6.29	2.71	60.426	2.456	1.274	1.857
6.30	1.873	68.287	3.868	2.925	2.262
7.1	2.314	21.367	2.446	1.532	0.879
7.2	2.619	33.68	2.614	2.272	2.884
7.3	2.402	51.099	2.367	2.264	2.372
7.4	3.25	26.668	2.931	1.906	2.512
7.5	2.387	35.214	2.392	2.341	1.815
7.9	3.212	43.533	3.013	2.514	1.467
7.11	2.874	27.872	2.663	1.486	2.321
7.14	3.424	24.139	3.158	2.253	1.924
7.16	5.721	21.73	3.509	3.171	3.864
7.17	3.835	21.041	1.999	2.017	2.704
7.18	3.577	15.435	1.803	0.614	1.049
7.19	4.35	25.793	2.3911	2.698	2.881

7.20	4.106	18.866	2.168	2.341	2.725
7.21	7.444	31.711	5.857	6.186	5.022
7.22	4.159	16.805	2.657	3.748	3.249
7.23	5.242	29.359	3.651	3.144	3.155

B.3 TCC

Table App.B-3.1 TCC in five water types within 18 days from 6.29 to 7.23.

Date	Influent	0 min	10 min	20 min	30 min
6.29	494169	1778458	601924	525191	535535
6.30	550305	1819313	580791	527538	524446
7.1	531409	1380491	551351	505538	507767
7.2	493960	1289145	542776	503789	495217
7.3	486212	1138416	499288	480547	475219
7.4	475894	1066777	475241	496830	469324
7.5	467325	922711	480291	456678	461213
7.9	605305	1368446	519797	486080	476265
7.11	502846	1199264	518129	494238	498954
7.14	588677	1295139	548426	530141	519997
7.16	798554	914392	514514	508749	498713
7.17	616561	884239	489556	475124	481246
7.18	589433	719007	471871	478967	471256
7.19	642642	897537	473951	454209	467154
7.20	534923	828094	477866	463207	474085
7.21	623056	1016149	512901	500323	510399
7.22	656067	898120	512946	507118	502179
7.23	676398	907540	549227	550161	539939

Table App.B-3.2 HNAC in five water types within 18 days from 6.29 to 7.23.

Date	Influent	0 min	10 min	20 min	30 min
6.29	195258	1456175	335446	254554	261750
6.30	242831	1443519	306017	245748	247069
7.1	283561	946541	310777	282415	263691
7.2	267956	912125	289333	264549	270581
7.3	264503	799855	260204	246568	249660
7.4	255551	680647	247291	228951	215801
7.5	241217	607307	245145	230808	231429

7.9	338138	1010221	275642	239728	254432
7.11	266062	869163	276654	255922	264831
7.14	279746	930930	288477	287298	262417
7.16	491691	598131	258280	258336	246960
7.17	332877	576220	236981	226378	220532
7.18	327672	445078	222945	251649	233765
7.19	357635	594739	226159	206306	219312
7.20	276343	523334	226815	219942	218474
7.21	358047	681548	252674	262810	246846
7.22	395284	616071	252285	240429	284751
7.23	392870	672183	336302	352129	322867

Table App.B-3.3 LNAC in five water types within 18 days from 6.29 to 7.23.

Date	Influent	0 min	10 min	20 min	30 min
6.29	298910	322300	266477	270637	273784
6.30	307474	375794	274774	271789	277377
7.1	247847	433949	240573	223123	244076
7.2	226003	377019	253442	239239	224635
7.3	221709	338560	239083	233978	225558
7.4	271226	294594	249538	240373	245412
7.5	226108	315404	235146	225870	229784
7.9	267167	358224	244155	246279	221832
7.11	236784	330101	241474	238316	234123
7.14	308931	364208	259948	242842	257579
7.16	306862	316260	256234	250413	251753
7.17	283683	308019	252574	248746	260714
7.18	261761	273929	248926	227318	237491
7.19	285007	302797	247792	247903	247842
7.20	258580	304760	251051	243265	255611
7.21	264809	334601	260226	237512	263552
7.22	260783	282048	260660	266688	217428
7.23	283527	335357	212924	198031	217072

B.4 Five elements

Table App.B-4.1 Al concentration in five water types within 18 days from 6.29 to 7.23.

	in	0	10	20	30
6.29	2.87	2.69	2.73	2.97	2.83
6.30	2.07	1.16	1.50	1.94	1.89
7.1	1.91	5.35	1.85	1.45	1.83
7.2	1.74	2.47	2.96	4.11	2.66
7.3	2.23	0.98	2.75	2.24	2.01
7.5	1.74	1.29	1.94	1.75	2.45
7.9	4.39	1.67	3.78	3.25	3.33
7.11	2.60	2.37	3.56	2.40	2.91
7.14	14.25	12.57	14.72	15.41	15.19
7.16	0.06	1.94	2.25	2.52	2.41
7.17	12.37	14.56	15.24	14.59	15.16
7.18	0.16	1.93	2.09	2.24	2.03
7.19	0.92	1.67	2.85	3.49	3.22
7.20	3.48	2.85	3.49	3.22	3.20
7.22	0.40	2.38	2.49	2.92	2.74
7.23	1.21	2.05	2.30	2.45	2.83

Table App.B-4.2 Ca concentration in five water types within 18 days from 6.29 to 7.23.

	in	0	10	20	30
6.29	37.00	36.91	37.42	37.36	37.53
6.30	38.72	37.90	37.50	37.71	37.49
7.1	43.00	37.5	42.53	43.44	41.30
7.2	43.24	42.12	43.40	43.00	43.98
7.3	44.00	41.96	41.60	43.00	42.90
7.5	41.76	41.33	41.83	43.40	42.92
7.9	47.86	41.42	43.44	44.65	43.57
7.11	42.49	41.27	43.15	41.85	43.35
7.14	42.59	40.12	41.96	41.79	42.04
7.16	41.08	41.16	41.93	42.23	42.47
7.17	42.70	41.32	42.42	41.40	43.56
7.18	43.50	41.74	43.25	42.69	42.16
7.19	41.61	41.2	42.25	42.15	41.99
7.20	42.01	41.25	42.20	42.02	41.88
7.22	41.72	41.32	42.50	41.90	42.51

7.23	41.57	41.01	44.30	44.93	44.82

Table App.B-4.3 Mn concentration in five water types within 18 days from 6.29 to 7.23.

	in	**0**	**10**	**20**	**30**
6.29	7.57	7.49	7.69	7.65	7.61
6.30	7.79	7.45	7.46	7.51	7.50
7.1	6.36	6.68	6.37	6.39	6.41
7.2	5.15	5.26	5.61	4.82	4.88
7.3	5.00	5.28	4.87	4.92	4.86
7.5	5.10	5.10	4.78	4.91	4.91
7.9	5.42	6.30	5.18	5.45	5.40
7.11	5.02	5.74	6.05	5.86	6.04
7.14	6.00	6.32	6.08	5.85	5.85
7.16	3.70	6.02	5.76	5.85	5.75
7.17	4.67	6.14	6.09	5.65	5.94
7.18	4.82	6.22	6.05	5.76	5.71
7.19	4.58	6.20	5.89	5.74	5.75
7.20	4.91	5.10	5.94	5.76	5.77
7.22	4.86	6.71	6.23	5.88	5.95
7.23	4.52	6.54	5.02	4.47	4.46

Table App.B-4.4 Fe concentration in five water types within 18 days from 6.29 to 7.23.

	in	**0**	**10**	**20**	**30**
6.29	12.48	61.84	10.97	4.54	4.31
6.30	11.93	60.98	8.12	3.76	2.54
7.1	19.47	48.86	15.57	2.71	0.59
7.2	9.09	53.68	5.99	0.43	0.11
7.3	11.22	60.82	4.42	0.55	/
7.5	10.42	31.61	2.48	0.52	0.14
7.9	31.88	82.54	3.2	1.7	0.39
7.11	29.03	76.35	1.56	0.42	/
7.14	37.69	85.18	5.44	/	/
7.16	19.25	68.01	2.76	/	/
7.17	10.94	32.58	4.47	/	/
7.18	5.02	14.64	2.68	0.03	/

7.19	15.7	37.66	2.44	0.12	/
7.20	30.28	79.85	3.93	0.77	0.16
7.22	7.14	9.83	3.74	0.64	0.36
7.23	11.88	33.69	9.65	1.09	/

Table App.B-4.5 As concentration in five water types within 18 days from 6.29 to 7.23.

	in	**0**	**10**	**20**	**30**
6.29	0.14	0.20	0.13	0.15	0.14
6.30	0.12	0.18	0.14	0.13	0.13
7.1	0.15	0.15	0.17	0.16	0.15
7.2	0.16	0.20	0.16	0.17	0.17
7.3	0.16	0.21	0.16	0.15	0.15
7.5	0.15	0.20	0.17	0.17	0.16
7.9	0.27	0.18	0.16	0.16	0.15
7.11	0.15	0.17	0.16	0.14	0.16
7.14	0.15	0.16	0.16	0.14	0.25
7.16	0.14	0.17	0.15	0.16	0.16
7.17	0.14	0.16	0.15	0.15	0.17
7.18	0.13	0.16	0.15	0.15	0.16
7.19	0.13	0.16	0.16	0.15	0.16
7.20	0.13	0.15	0.16	0.15	0.16
7.22	0.13	0.14	0.16	0.16	0.15
7.23	0.14	0.18	0.16	0.17	0.16

Appendix C Setup under different water quality data

C.1 Particle size distribution

Table App.C-1.1 Particle size distribution of the influent in Delft Waterlab.

T (min) \ D (µm)	1	8	15	22	29	36	43	50
10	3207.9	48.7	3.1	0.7	0.3	0.1	0	0.2
20	4847.9	102.1	9.4	1.9	0.6	0.2	0.1	0.1
30	6127.1	132.3	3.3	0.4	0.1	0	0	0
40	3910.7	52.7	1.9	0.1	0	0	0	0
50	1221.6	12	0.5	0.1	0	0	0	0.1
60	4970.9	76.9	2.3	0.4	0.1	0.1	0	0.3

Table App.C-1.2 Particle size distribution of the influent in Delftgauw.

T (min) \ D (µm)	1	8	15	22	29	36	43	50
10	4718.7	118.2	19.2	3.6	0.9	0.5	0.4	0.4
20	4215.8	95.2	21.5	4.5	0.8	0.3	0.5	0.3
30	3974.4	79.1	14.3	2.7	0.6	0.3	0.6	0.4
40	4897.3	136.8	25.4	5.1	1.5	0.7	0.8	0.7
50	4359.8	124.5	18.6	4.1	0.7	1.1	0.9	0.4
60	5718.6	156.7	30.5	2.4	2.1	1.5	1.3	2.1

Table App.C-1.3 Particle size distribution of the influent in Kamerik.

T (min) \ D (µm)	1.0	8.0	15.0	22.0	29.0	36.0	43.0	50.0
10	237.8	91.0	21.7	7.9	0.0	0.0	0.0	0.0
20	556.9	151.3	32.0	0.0	0.0	0.0	0.0	0.0
30	189.8	86.5	19.7	0.0	0.0	0.0	0.0	0.0
40	875.2	148.3	27.8	0.0	0.0	0.0	0.0	0.0
50	616.1	84.8	14.8	0.0	0.0	0.0	0.0	0.0
60	492.4	1130.1	27.6	8.5	0.0	0.0	0.0	0.0

Table App.C-1.4 Particle size distribution of the influent in Schuwacht.

T (min) \ D (µm)	1	8	15	22	29	36	43	50
10	231.3	7.2	4.5	4.0	3.9	3.8	3.8	3.8
20	557.9	10.1	3.1	5.1	3.1	2.9	7.4	5.5
30	294.9	6.6	4.2	6.7	2.9	5.5	4.9	4.5
40	1098.1	85.0	34.8	18.9	7.9	14.0	9.8	11.2
50	188.1	5.0	2.7	2.7	2.7	1.9	0.9	1.7
60	312.3	8.8	4.1	8.9	2.2	10.0	2.1	4.2

Table App.C-1.5 Particle size distribution of the effluent in Delft waterlab.

T (min) \ D (µm)	1	8	15	22	29	36	43	50
10	381.6	1.2	0.3	0.2	0	0	0	0
20	560.2	3.7	0.2	0.1	0	0	0	0
30	1032	2.4	0.1	0	0	0	0	0
40	868.6	2.2	0.2	0	0	0	0	0
50	554.3	6.9	0.2	0	0	0	0	0
60	430.6	3.4	0.2	0	0	0	0	0

Table App.C-1.6 Particle size distribution of the effluent in Delftgauw.

T (min) \ D (µm)	1	8	15	22	29	36	43	50
10	1420.8	97.5	18.8	0.0	0.0	0.0	0.0	0.0
20	1812.0	89.6	21.0	0.0	0.0	0.0	0.0	0.0
30	870.0	68.9	14.2	0.0	0.0	0.0	0.0	0.0
40	2845.3	115.8	25.0	0.0	0.0	0.0	0.0	0.0
50	2696.5	119.5	16.2	0.0	0.0	0.0	0.0	0.0
60	2453.9	116.6	30.3	0.0	0.0	0.0	0.0	0.0

Table App.C-1.7 Particle size distribution of the effluent in Kamerik.

T (min) \ D (µm)	1	8	15	22	29	36	43	50
10	237.8	91.0	21.7	7.9	0.0	0.0	0.0	0.0
20	556.9	151.3	32.0	0.0	0.0	0.0	0.0	0.0
30	189.8	86.5	19.7	0.0	0.0	0.0	0.0	0.0
40	875.2	148.3	27.8	0.0	0.0	0.0	0.0	0.0
50	616.1	84.8	14.8	0.0	0.0	0.0	0.0	0.0
60	492.4	1130.1	27.6	8.5	0.0	0.0	0.0	0.0

Table App.C-1.8 Particle size distribution of the effluent in Schuwacht.

T (min) \ D (μm)	1	8	15	22	29	36	43	50
10	32.6	5.0	3.8	4.0	0.0	0.0	0.0	0.0
20	145.0	9.0	3.0	5.1	0.0	0.0	0.0	0.0
30	57.7	5.2	4.1	6.7	0.0	0.0	0.0	0.0
40	759.2	67.9	34.5	18.9	0.0	0.0	0.0	0.0
50	21.4	4.1	2.4	2.7	0.0	0.0	0.0	0.0
60	80.3	7.1	3.1	8.9	0.0	0.0	0.0	0.0

C.2 Removal rate of the setup in four locations

Table App.C-2.1 Removal rate of the Smart Water Meter in Delft waterlab.

T (min) \ Removal rate	1	8	15	22	29	36	43	50
10	88.10%	97.54%	90.32%	71.43%	100.00%	100.00%	100.00%	100.00%
20	88.44%	96.38%	97.87%	94.74%	100.00%	100.00%	100.00%	100.00%
30	83.16%	98.19%	96.97%	100.00%	100.00%	100.00%	100.00%	100.00%
40	77.79%	95.83%	89.47%	100.00%	100.00%	100.00%	100.00%	100.00%
50	54.63%	42.50%	60.00%	100.00%	100.00%	100.00%	100.00%	100.00%
60	91.34%	95.58%	91.30%	100.00%	100.00%	100.00%	100.00%	100.00%

Table App.C-2.2 Removal rate of the Smart Water Meter in Delftgauw.

T (min) \ Removal rate	1	8	15	22	29	36	43	50
10	30.11%	82.51%	98.15%	100.00%	100.00%	100.00%	100.00%	100.00%
20	42.98%	94.12%	97.55%	100.00%	100.00%	100.00%	100.00%	100.00%
30	21.89%	87.14%	99.14%	100.00%	100.00%	100.00%	100.00%	100.00%
40	58.10%	84.65%	98.54%	100.00%	100.00%	100.00%	100.00%	100.00%
50	61.85%	95.97%	87.15%	100.00%	100.00%	100.00%	100.00%	100.00%
60	42.91%	74.44%	99.20%	100.00%	100.00%	100.00%	100.00%	100.00%

Table App.C-2.3 Removal rate of the Smart Water Meter in Kamerik.

T (min) \ Removal rate	1	8	15	22	29	36	43	50
10	23.15%	74.56%	91.45%	84.12%	100.00%	100.00%	100.00%	100.00%

20	35.27%	84.82%	98.77%	100.00%	100.00%	100.00%	100.00%	100.00%
30	19.65%	91.56%	99.52%	100.00%	100.00%	100.00%	100.00%	100.00%
40	47.15%	89.44%	97.52%	100.00%	100.00%	100.00%	100.00%	100.00%
50	56.14%	76.11%	84.56%	100.00%	100.00%	100.00%	100.00%	100.00%
60	34.11%	82.77%	92.24%	74.91%	100.00%	100.00%	100.00%	100.00%

Table App.C-2.4 Removal rate of the Smart Water Meter in Schuwacht.

Removal rate / T (min)	**1**	**8**	**15**	**22**	**29**	**36**	**43**	**50**
10	14.10%	69.56%	84.23%	100.00%	100.00%	100.00%	100.00%	100.00%
20	25.99%	89.52%	98.22%	100.00%	100.00%	100.00%	100.00%	100.00%
30	19.56%	78.94%	97.53%	100.00%	100.00%	100.00%	100.00%	100.00%
40	69.14%	79.85%	99.10%	100.00%	100.00%	100.00%	100.00%	100.00%
50	11.36%	82.60%	90.54%	100.00%	100.00%	100.00%	100.00%	100.00%
60	25.71%	80.66%	76.33%	100.00%	100.00%	100.00%	100.00%	100.00%