Potential impacts of supply water quality change on aged household connection pipes

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Potential impacts of supply water quality change on aged household connection pipes

By

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Preface

This study was supported by the Delft University of Technology and Oasen drinking water company. I would like to express my sincere gratitude to these two institutions for providing me such a good opportunity to do the scientific research having my personal interest.

I would like to express appreciation to everyone who contributed to the this study. I would like to thank Professor Luuk Rietveld for the guidance and support throughout the study. I would like to express my sincere gratitude to my daily supervisor Gang Liu, with excellent guidance and assistance on scientific thinking and writing during whole thesis period. I would like to thank the help and comments from Edo Abraham. I also would like to express my sincere gratitude to the colleagues from Oasen, Vitens and lab of Sanitary Engineering at TU Delft for the efforts during my experimental periods.

Last but not the least, I would like to thank my lovely family and friends for accompanying, understanding, encouraging and supporting me during the study period.

I hope you enjoy your reading.

Qiuman Tan
Delft, May 2018

Abstract

Driven by solving water shortage problems and meeting the increasing strict regulations of water quality, changes of supply water quality are commonly happening worldwide. These kinds of irregular changes can have impacts on drinking water distribution systems with accumulated material, leading to chemical, physical and microbiological deteriorations in water quality with (in)organics release and biofilm detachment. Household connection pipes (HCPs) are the last obstacle reaching customers' taps. The long stagnation time, non-continuous flow, high surface to volume ratio and high water quality deterioration potential make the HCPs deserve more attention. In this study, the impacts of changing supply water quality from conventional treated groundwater to reverse osmosis treated water on aged HCPs were studied.

Aged HCPs were collected from customers and used for building test rigs in the lab. Three types of water quality were supplied to these HCPs, including Kamerik water by conventional treatment (KA), remineralized RO permeate (RE) and mixed water (MX, 70% RO permeate and 30% KA). Water samples were taken every week and the biofilm were compared before and after switching supply water from KA to MX and RE to reveal the potential changes on water quality and accumulated material in pipes. Whether and to what extent the deterioration would occur in the aged HCPs could therefore be determined.

Changes of water quality revealed that the release of ATP, *Aeromonas*, Fe and Al may happen in the first 8 weeks and then become stabilized again, no effects on As and Mn, and no release of Ca were observed. From the study related to changes of pipe harbored material, the results showed that less bacterial activity and elements' accumulation (except for Ca) were observed, suggesting the impacts of changing supply water not only represented by the accumulation of bacterial, but also by inorganic material.

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1 Introduction

1.1 Drinking water supply system

At the centralized purification plants, raw water is extracted from rivers, lakes or the underground and passes various processes to remove the contaminants. Afterwards, drinking networks(DNs), including the pipes, pumps, valves, storage tanks and other hydraulic facilities, carry the treated water from the centralized treatment plants to customer's taps (Coffee et al., 2005). The drinking water distribution system (DWDS) is a part of the DNs and is a pressurized piped network, consisting of transportation pipes, distribution pipes and household connection pipes (HCP). All these pipes vary in diameter (25mm->200mm), material (PVC, steel, iron, HDPE) and surface to volume ratio (Fish et al., 2017). HCPs are the last obstacle for the water to reach the households and the water quality needs to be maintained during transportation. How to maintain the treated water quality during long residence times in the DWDS is always a concern for water supply companies and researchers.

The treated drinking water entering the DWDS is not pure water, it still containing many physicochemical and microbiological matter, such as nutrients, particles and microorganisms (G. Liu et al., 2013). Although treated water leaves the treatment plant with a high quality, the water quality degradation may happen during distribution, since the distribution pipes can act as a biological and physicochemical reactors with accumulated material inside. To control the deterioration of the biological water quality during transportation, many actions can be taken: providing disinfection residual or producing biological stable water (Prest et al., 2016a). In the Netherlands, treated water enters the DWDS without residual disinfectant, such as chlorine. The target of limiting microbiological regrowth during distribution is achieved by providing biologically stable water, with a low nutrient and AOC (<10 μg/L) concentration (Kooij et al., 1992). In addition, to reach physicochemical stability, the saturation index and re-suspension potential should be low in the treated water (G. Liu et al., 2017b).

1.2 Accumulated material within DWDS

During water distribution, the microorganisms can settle and attach to the inner surface of pipes and form biofilm (Rożej et al.,2014). The suspended solids can sediment and deposit to become loose deposits in distribution pipes. These harbored material in distribution pipes are described below (shown in Figure 1.1):

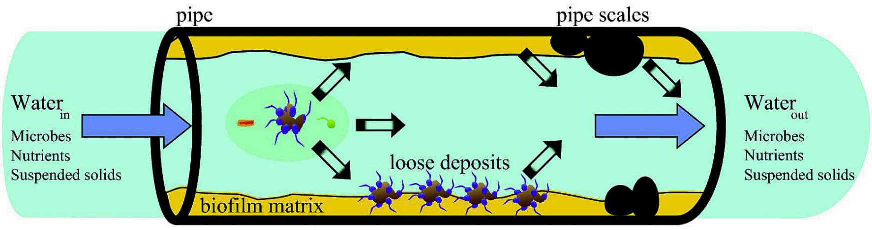


Figure 1.1 Illustration of pipe harbored material

1.2.1 Biofilm

Biofilms are microbial aggregates embedded within a self-produced matrix of extracellular polymeric substances (EPS), as shown in Figure 1.3 (a) (Tierra et al., 2015). The matrix offers a spatial structure on the biofilms and also protects the microorganism within biofilms from external adverse conditions (Douterelo et al., 2016). The life cycle of biofilms is characterized as a series of steps, as shown in Figure 1.2 (S. Liu et al., 2016), which typically starts with formation of conditioning films composed of macromolecules on surfaces, then the attachment and adhesion of microorganisms on the films will happen. This initial stage is highly reversible (A Garnett & Matthews, 2012) and the formation of conditioning films is very important in environment like drinking water which is nutrient-depleted (S. Liu et al., 2016). The bacteria subsequently start to divide and stick together in small micro-colonies, followed by the formation of sticky matrix of EPS, proteins and lipids, which can provide the components of formation of three-dimensional structures of biofilm. When the biofilm reaches the maturation stage, a heterogeneous distribution of cells will be developed and the production of water filled channels will be produced, which will, subsequently, lead to the dispersal of cells from cellular mass (A Garnett & Matthews, 2012). The biofilm development depends on several factors, such as pipe material, water characteristics and operational conditions (Fish et al., 2015; S. Liu et al., 2016).

In addition, organic, inorganic and pathogens can accumulate in the matrix (Makris et al., 2014). The cells harbored in biofilm, vary from 10^4-10^8 cells/cm^2 and the biomass accumulation is in the range of 10^2-10^4 pg ATP/ cm^2, depending on specific conditions (Prest et al., 2016). Inorganic accumulation (e.g. Fe, Mn, Al, Ca) in biofilms can also be enhanced by some microorganisms (Ginige et al., 2011). Previous studies have mainly focused on the biofilm formation on inner surfaces of pipes (Rożej et al., 2014).

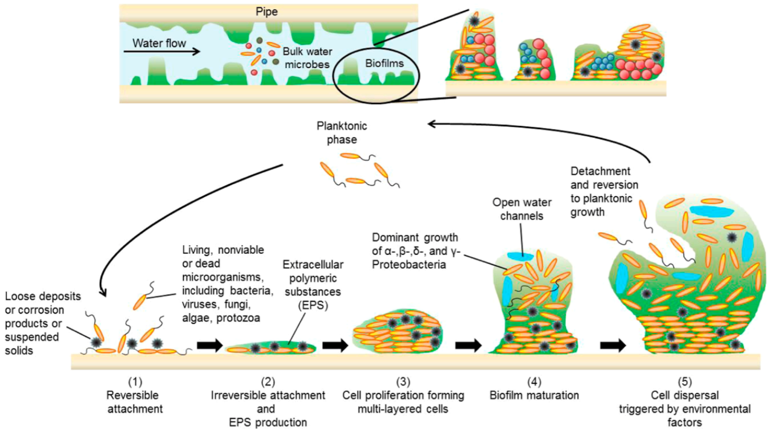


Figure 1.2 Biofilm life cycle in DWDS

1.2.2 Loose deposits

Particles in the DWDS have different resources, including particles existing in the treated water due to incomplete removal or those induced by a certain treatment step(e.g. activated carbon powder or sand particles), or that released from biofilm detachment and pipe corrosion, and particles induced by precipitation and flocculation processes (Vreeburg et al., 2007). Particles can accumulated and settle at the bottom of the pipes and forms the loose deposits. During hydraulic condition changes, the loose deposits are easy to be re-suspended into the water, potentially reaching the customer's tap (G. Liu et al., 2013). Sedimentation and re-suspension are the processes happening with loose deposits until they have been stabilized and cannot be (re-)suspended by the daily hydraulic disturbances (G. Liu et al., 2017a). Then, loose deposits with accumulated organic and inorganic nutrients offer micro-environments for bacterial to growth (G. Liu et al., 2014a).

Loose deposits normally are sampled from hydrants by flushing (Gauthier et al., 1999).The principle of this method is to use high flow velocities (e.g. 1.5 m/s) to remove sediments (Poças et al., 2013). The flushing of loose deposits is shown in Figure 1.3 (b). From previous studies, it is found that the active biomass harbored in loose deposits can be as high as 780-3900 ng ATP/g (G. Liu et al., 2014a). Besides, *Aeromonas* has been found, only existing in this niche inside aged HDPE and PVC pipes, not in biofilms or bulk water (G. Liu et al., 2017b). Both organic and inorganic matters can also be co-accumulated in this niche (Fish et al., 2015).

Previous studies on loose deposits have mainly focused on discoloration problems induced by mobilization of loose deposits during sudden hydraulic perturbations (e.g. firefighting, demand peaks or flushing of pipes) (Blokker and Schaap, 2015). However, once loose deposits are suspended, other water quality parameters may also change, such as microbes' concentration and minerals' concentration.


(a) *(b)*

Figure 1.3 Accumulated material in distribution pipes.(a): the picture of biofilm on the inner surface of HDPE pipe; (b): flushing of loose deposits out of distribution water main (110mm, PVC).

1.3 Household connection pipes

HCPs connect the distribution pipes to customer's houses which are the last few meters reaching the customer. Different from other distribution pipes, the water is not continuously running but depend on the pattern of customer's water usage. As a result, the stagnation time of water within household connection pipes varies from hours to weeks (if the customer goes on holiday) (Zlatanović et al., 2017). The longer stagnation time and non-continuous flow in the pipe makes the HCP special, harboring even higher densities of bacteria and elements than distribution pipes (Lautenschlager et al., 2010; G. Liu et al., 2017b). In addition, monitoring of the water quality changes in these pipes is hardly conducted due to the difficulties in access. The surface to volume ratio, reaching 1.6 cm^{-1} of household connection pipes with a diameter of 25 mm, is much higher than that of distribution pipes (0.36 cm^{-1}) with a diameter of 110 mm (Tsvetanova and Hoekstra., 2010). Based on a previous study, it is found that the water quality deterioration potential (defined as releasing accumulated material with 1 m pipe section into water) with HCP is higher than distribution pipes, including the increase in the concentrations of microbes and elements of biofilms (G. Liu et al., 2017b). Considering that HDPE household connection pipes are located closer to customer's tap and contribute to such high deterioration potential , it deserves more research attention. The development and detachment of biofilms within HCP should therefore be better evaluated and understood.

1.4 Supply water quality changes and transition effects

1.4.1 Supply water quality changes

Changes of supply water quality are commonly happening worldwide as a result of water shortage problem and to meet the increasing strict regulations of water quality, for example by using alternative water sources or updating treatment (Yang et al., 2017). Switching water sources to desalinated water, changing coagulant and disinfection strategy and updating treatment steps (e.g. using advanced treatment process of membrane technology) can also cause the changes of supply water quality within DWDS. These kinds of changes are defined as irregular changes as compared to regular changes, such as the variations of source water quality and treatment performances. Irregular supply water quality changes can have impacts on DWDS with accumulated material, the release of which can cause problems on bulk water quality, such as discoloration.

1.4.2 Transition effects

The DWDS is a complex system, acting as a sink during regular operation for contaminants' accumulation (e.g. associated with biofilm and loose deposits). Some changes can happen, like daily water demand peaks and seasonal temperature changes, although this does not have much impacts on the stabilized inner environment of the DWDS. However, the complex system with biofilms and loose deposits can be destabilized and become the source for water quality deterioration in case of transition to other water sources. The transition effects can thus be the consequence of chemical, physical and microbiological destabilization of DWDS due to irregular operation (G. Liu, et al., 2017a). Once the destabilization happens, the accumulated material like bacteria (including pathogens and opportunistic pathogens) and (in)organic matters can enter into the water which may lead to water quality deterioration and discourage the customer and even threaten their health.

However the timeline of transition effects also varies based on the dominant destabilization process. If the transition effects are dominated by chemical destabilization processes, it takes a short time (e.g. weeks) to detect transition effects to happen; while if the transition effects are dominated by microbiological destabilization, the changes will be noticed and detected over a much longer period (e.g. months to years) (G. Liu et al., 2017b). As a result, assessment, monitoring and management are required before and after switching supply water quality.

1.4.3 Destabilization and associated risks

Physicochemical and microbiological destabilizations can happen after switching to a different supply water quality. The mechanisms and the associated risks of these stabilizations are summarized below:

1) Physicochemical destabilization. Changes in supply water quality can lead to a destabilized physical equilibrium resulting in smaller particles that are easier to be transported and re-suspended. Changes in water chemistry, corresponding to the supply water change, like the changes in PH, alkalinity, (in) organic concentrations of residual of disinfects, can lead to dissolution of pipe corrosion (Kim et al., 2011), which can cause (heavy) metals and other contaminants entering the water.
2) Microbiological destabilization. For the microbiological destabilization, changes of nutrients level and disinfectants can lead to biofilm detachment (Hunt et al. 2004).Supply water quality changes not only impact the cells and deposition of biofilm, the community and diversity of biofilm would also be re-shaped (Li et al. 2016; Revetta et al. 2016). In addition, the accumulated elements can correspondingly be released into bulk water with the detachment of biofilm (Ginige et al., 2011).
3) Associated risks. The subsequent water quality deterioration caused by these physicochemical and microbiological destabilization happens worldwide, such as a sudden increase in Pb concentration in Washington DC (Kim et al., 2011); or red water with high Fe concentration due to change in source water to water containing a higher SO_4^{2-} concentration in Beijing (Yang et al. 2017); or the release of pathogenic microorganisms into water in Flint after switching the water source (Schwake et al., 2016). Such kinds of problems with changes in source water should be determined and monitored before and after the switch.

1.5 Objective and research questions

In summary, the changes in supply water quality can thus destabilize the DWDS harbored material and lead to physicochemical and microbiological deteriorations in water quality within the pipes. These (in)organics releases and biomass detachments can cause contaminants entering the bulk water and cause aesthetic and hygienic problems. Therefore, determining the transition effects before switching of source water is essential and the effort should be focused on developing strategies of how to prevent and control these transition effects. This is especially true regarding the HCPs, because of their high contaminants' concentration, short distance to customers, and their high surface to volume ratio. In this study, the impacts of changing supply water quality from conventional treated groundwater to reverse osmosis (RO) treated groundwater with lower nutrients', biomass and elements' concentration on HCPs were studied and discussed. Three types of water quality were supplied to field collected HCPs in duplicates, including Kamerik water by conventional treatment (KA), remineralized RO permeate (RE) and mixed water (MX, 70% RO permeate and 30% KA). To reveal the potential transition effects, water samples were taken every week and the biofilm were compared before and after conducting the study. The main objective was to determine whether and to what extent the transition effects will occur in the aged HCPs subjected to supply water quality changes and the following research questions were answered:

1. Do transition effects occur in old household connection pipes after switching supply water quality?
2. What are the water quality changes under these conditions?
3. What changes could happen with pipe associated material?

2 Materials and methods

This chapter mainly introduces how the experiments were designed and performed. The reasons for chosen experiment conditions and the methods for analyzing the samples are also explained. The chapter starts with the treatment plant, the various water types, and the experimental design, and followed by sampling and performed analyses.

2.1 Treatment plant

Oasen, a drinking water company in the Netherlands, produces and offers reliable fresh drinking water from seven purification plants. For meeting the higher standards in the future and offering drinking water with the best quality, Oasen proposes a new treatment scheme based on reverse osmosis (RO) membranes. A RO pilot scale plant was installed at treatment plant Kamerik, which has one of the conventional groundwater purification stations. The detailed information about these two treatment schemes are briefly outlined below.

2.1.1 Conventional treatment at Kamerik

Anaerobic groundwater is fed to the full-scale treatment facilities, flowing through aeration, sand filtration, softening, sand & activated carbon filtration and followed by UV disinfection before pumping to the distribution network. The capacity of this plant is 300 m^3/h and the illustration of the purification steps is shown in Figure 2.1.

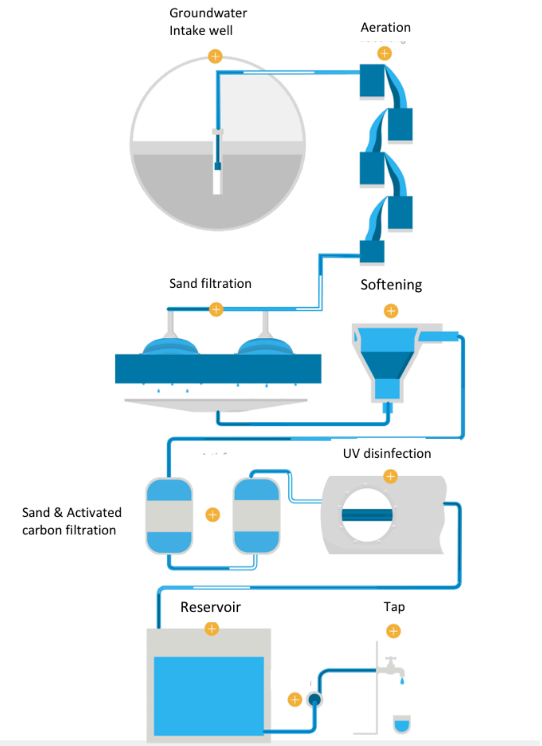


Figure 2.1 Conventional treatment steps at Kamerik

2.1.2 Water treatment with reverse osmosis at Kamerik

The pilot plant, using RO, is also located at Kamerik and the flow chart of the treatment processes is given in Figure 2.2. Several sample collection points are set along the treatment train and the water samples are regularly analyzed, which can offer some additional background information about the water quality after specific treatment steps.

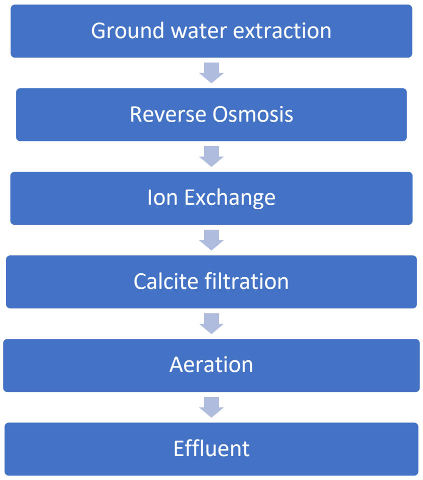


Figure 2.2 Treatment process of RO pilot plant at Kamerik

The effluent of the RO, also called permeate, is not suitable for drinking and requires a post-treatment step, called remineralization to improve the saturation index, chemical stability and the taste of the water (Vingerhoeds et al., 2016).

Two methods of remineralization were included within this study. The first method was directly dosing of minerals by adding calcium carbonate (by passing the RO permeate through a calcite dissoluting filter) to obtain the required hardness. Another option for increasing the mineral concentration in the permeate that was used was mixing the RO permeate with effluent after conventional treatment, blending 70% (volume fraction) permeate with 30% treated water.

2.1.3 Water quality of these three types of water

In total, three types of supply water can be obtained at the treatment plant: Kamerik water by conventional treatment (KA), Remin water (RE) by directly adding minerals back to RO permeate and Mixed water (MX) by mixing RO permeate with KA. Summarized information about the water quality of each type of water is shown in Table 2.1.

Table 2.1 Water quality parameters of different types of supply water

		KA	MX	RE	Unit
Biological aspect	AOC	7.1	2.8	2.0	µg C/l
	ATP	12.2±4.2	4.2±2.3	10.3±6.4	ng/l
	Aeromonas	56.6±41.1	36.7±21.6	UD*	CFU/100 ml
Elemental aspect	Ca	23.6±3.9	47.0±10.9	8.4±3.8	mg/l
	Al	2.92±0.94	UD	UD	µg /l

U.D. = under the detection limit (As, Mn and Fe concentration of these three types of water were all under the detection limit)

2.2 Experimental design and setup

For characterizing the potential transition effects when switching the supply water types, a pilot study was built at lab-scale with a consistent temperature of 12℃. The sequence of the experiments were: 1) collecting aged household connection pipes from customers; 2) building the stagnant test rigs in climate lab at TU Delft; and 3) regular refreshing the pipes and sampling every week for 18 weeks.

Two locations were selected within the distribution area supplied by the current conventional treated water from Kamerik to collect aged HCPs (HDEP, D=25 mm). The locations of the treatment plant and these two places where the pipes were obtained are shown in Figure 2.3.

At each location, six pieces of pipe with a length of one meter were prepared and divided into three sets in duplicates and transported to the lab, presented in Figure 2.7. Meanwhile, two pieces were sent to the lab directly for physicochemical and microbiological analyses (shorter pipes, L=30cm, as shown in Figure 2.4 (b)). The procedures of the experiments are described in details in next section.

Figure 2.3 Map of pilot plant and locations for pipe obtaining

(a) *(b)*

Figure 2.4 Illustration of dug out pipes; (a) Scene of where the pipes were obtained;(b)Pictures of pipe sets for analyses as original state

2.2.1 Water types and preparation

KA water, RE water and MX water were taken from the pilot plant at Kamerik to the lab weekly to refresh the water in the pipe sets. The water was transported and stored on ice, and the refreshment was performed within 24h after collecting the water. Detailed information about each type of water is summarized as follows:

- Conventionally treated water, also labeled as KA water, is the effluent from the conventional treatment process at the Kamerik plant. The tap located at the end of the treatment sequence inside the plant was chosen as the sample collection point. The sampling tap was kept open for a few minutes before the water was taken.
- Mixed water, labeled as MX water, prepared by mixing of 30% KA water with 70% RO permeate for remineralization, was directly prepared at Kamerik. RO permeate was obtained from the running pilot system.
- The effluent of the RO based treatment process including remineralization, also called as RE water, was obtained from the tap installed at the storage tank, which is located at the end of running pilot RO system. The sampling tap was kept open for a few minutes before the water was taken.

Figure 2.5 Prepared water from the pilot plant

2.2.2 Control test

As stated in the results of biomass production potential (BPP) test, the material in contact with water prompted microbiological water quality deterioration and the HDPE material was confirmed to enhance the bio-activity in the contacted water samples (van der Kooij et al. 2006). The present study focused on the changes by pipes' harbored material instead of pipe material itself. For distinguishing the difference between impacts on water quality with clean HDPE pipes and aged HDPE pipes (with biofilm attached), a control test with clean HDPE pipes was conducted (Figure 2.6). A clean HDPE pipe, aged household connection pipe (HDPE) and a clean particle-free bottle were chosen as the holders for the control test study. KA, MX and RE water were kept in these kinds of holders for one week. All holders were kept in the dark and at constant temperature of 12℃. Obtained water samples were analyzed to study the water quality variations.

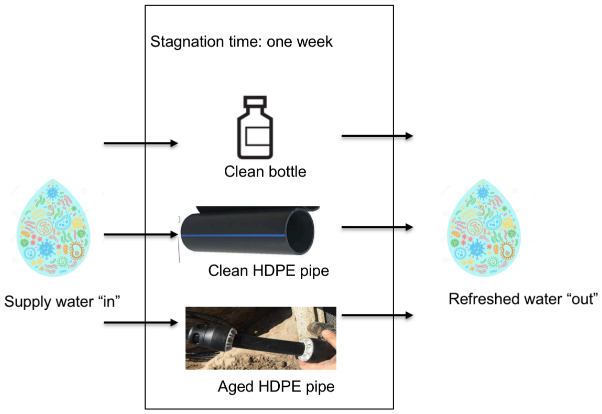


Figure 2.6 Set-up of the control test

2.2.3 Water quality

Six pieces of pipes from each location were transported to the lab and divided into three sets in duplicate. Thus, two pipes, obtained from one location, were used for each type of water for post study. These pipes were put horizontally on a constructed board and kept at constant temperature of 12°C, as shown in Figure 2.7.

The prepared water ("in") samples were collected just after preparation and refreshed water ("out") samples were collected by gently pouring the water out of pipes. Around 400 ml refreshed water (Figure 2.8 (a)) per pipe and 400 ml prepared water per type were taken for analyses. In total, the experiments with each pipe sets lasted for 18 weeks. Experiments with pipes obtained from the first location were conducted from May to October 2017 and experiments with pipes obtained from the second location were conducted from June to October 2017. No samples were taken at week 14 and 16, due to the limitations of lab capacity for processing the analyses.

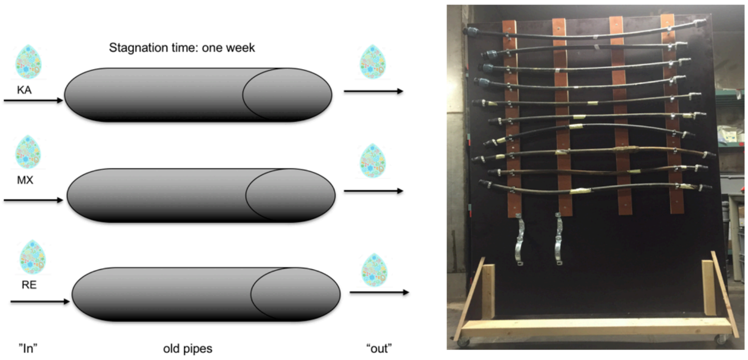


Figure 2.7 Set up at campus and the water samples for testing

2.2.4 Pipe study

To see the impacts of the feed water quality changes on attached material on the inner surface of pipe, the original conditions and final state of HDPE pipes after the study period were investigated and compared. Pipe samples with a length of around 30 cm each, shown in Figure 2.8 (b), were obtained in duplicate from each pipe for parameter analyses. These pipe sections were filled with DNA-free water (REF 10977-035) to keep material wet and decrease disturbance during transportation, followed by closed using with caps.

(a) *(b)*

Figure 2.8 Water samples(a) and pipe samples (b) transported to lab

2.3 Parameters and analyses

2.3.1 Sampling and parameters

The sampling procedure involved the following steps:

1. Pipe samples presenting original conditions were sent directly to the lab for analyses when collecting the aged HDPE pipe in the distribution system.
2. KA,MX and RE water were taken back to the lab weekly to refresh the water in the pipes. Both the prepared water and water staying in the pipes for one week after refreshment were sampled for analyses.
3. At the end of experiment period, pipe sets in the lab were cut into specimens for studying the conditions after feeding with different types of water.

In total, both water and pipe samples were collected for chemical and microbiological parameters (presented in Table 2.2). The measurements were done at Vitens lab. All samples were delivered immediately on ice after collection and processed at the lab within 24 h.

Table 2.2 Parameters of experiment with two pipe sets

	Pipe sets 1	Pipe sets 2
Experiment period	23/5/2017-4/10/2017	8/6/2017-18/10/2017
Sample types	Water samples (weekly); pipe samples (only at start and end)	
Parameter	ATP, HPC, *Aeromonas*, Fe, As, Ca, Mn, Al, DNA extraction	

2.3.2 Methods of sample analyses

- **Water samples**

  For water samples' analyses, ATP was measured by BacTiter Go reagent and luminometer. *Aeromonas* concentration was detected by culture-based method. Water samples filtered through a suitable membrane filter and followed by incubation of the filter on a solid and selective feed base to let *Aeromonas* bacteria form colonies. The elemental information(Fe, Mn, Al, As, and Ca) was characterized by ICP-MS.

- **Pipe samples**

  Each pipe sample was filled with DNA-free water (REF 10977-035) and was pre-treated three times for 2 mins by ultra-sonication to detach the accumulated material into the water(G. Liu et al., 2014b). For each time of ultra-sonication, 90 ml DNA-free liquid per pipe was used and would be collected. In total, 270 ml suspension was collected for each pipe and analyzed with the same method as the water samples. The results were normalized to mass per inner surface area of each section, calculated with Equation 2.3.

$$\frac{m}{s} = \frac{\mathrm{C}*270}{S_{inner}} \qquad (2.3)$$

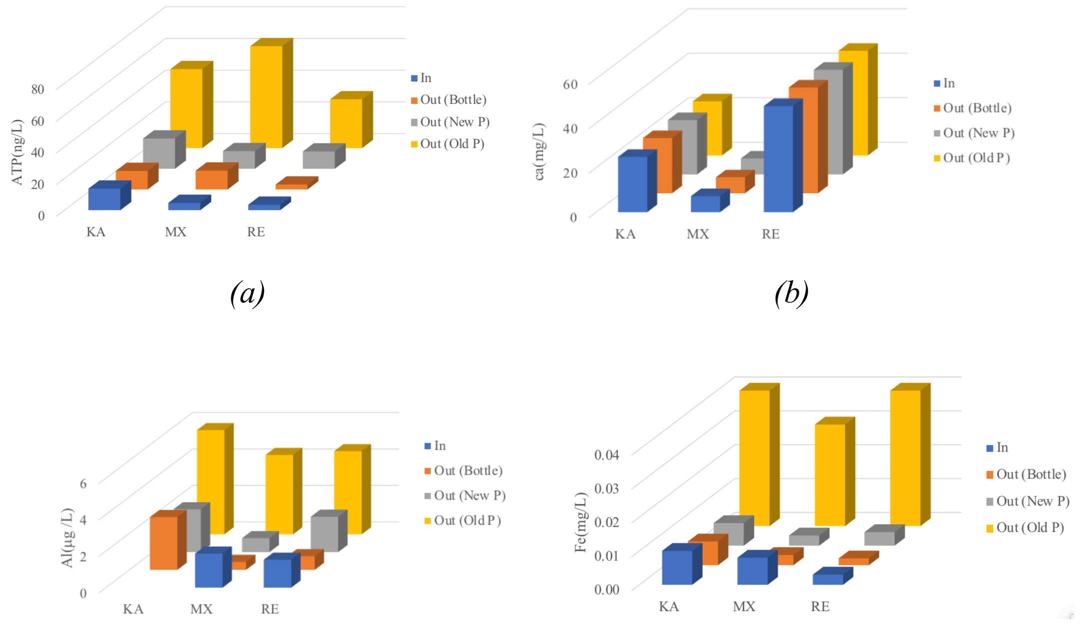
Where: C- the measured concentration obtained from lab directly (mg/l)

S_{inner}- the surface area calculated by length and Diameter of each section

3 Results and discussion

This study was carried out from the March 2017 to November 2017, including methods development and experiment conduction. Aged distribution pipes were taken from two locations and brought back to the lab for post experiments. Different supply water qualities were prepared at and taken from the pilot plant of Oasen at Kamerik weekly. Water samples were collected and analyzed weekly during the whole period and pipe samples were analyzed at the beginning and the end. This results and discussion section contains three parts: 1) control test, offer controlling identification of impacts either from old pipes or from other material contact with water; 2) influences on water quality; and 3) changes in pipe harbored material, respectively.

3.1 Control test



(a) *(b)*

(c) *(d)*

Figure 3.1 ATP(a), Ca(b), Al(c) and Fe(d) concentration in different water samples(”in” indicates the feed water; ”out” states the distributed water staying one week)

Three different kinds of material were used in the control test: 1) particle-free bottle; 2) clean/new HDPE pipe; and 3) aged HDPE pipe collected from the distribution system. The ATP was chosen as the indicator for presenting the active biomass in water. For elemental composition, Ca, Fe, Al, As and Mn were chosen as the key elements, among which the concentration of As and Mn were always below the detection limit (0.5 µg /L for As and 0.005 mg/L for Mn).

Figure 3.1(a) shows the ATP concentration changes of these three water types (KA, MX and RE) with different containers (clean bottle, new HDPE pipe and old HDPE pipe) after a week (7 days). From biological perspective, it was observed that for KA water, ATP decreased slightly in the bottle test which is accordance with the widely observed ATP decreased in field distribution systems (Van der Wielen and Van der Kooij, 2010). Differently, ATP increased in the tests with both new and old pipes, of which the ATP increase caused by old pipes was as high as 5 times of that caused by new pipes. In the test with new pipe, the increase might be caused by release of AOC from pipe material (Van der Kooij and Veenendaal, 2001; Silhan et al. 2006), while the much higher increase of ATP caused by old pipes was probably from the biofilm established on the pipes over the supply period that became suspended in the water (Liu et al., 2017a). Similar trends were observed for the test of MX and RE water, both of which confirmed that the major contribution of ATP increase was from bio-fouling material in the old pipe, while the influence from pipe material was limited. This is especially true when considering that material release from pipe material contact with drinking water occurred mainly during the first weeks, so that the increase observed from test with old pipes can be attributed to the old pipe harbored material rather than pipe material release (Wen et al., 2015).

The changes regarding elements (Ca, Al, Fe) caused by the test with different containers are shown in Figure 3.1 (b), 3.1 (c) and 3.1(d). No changes were observed for Ca in the tests with any types of water and containers. Whereas, for both Fe and Al, considerable increases were noticed in the test with old pipe material, which was probably because of the release of pipe harbored material, as mentioned above in the discussion of ATP. Additionally, a slight decrease of Fe and Al was observed in the test with the bottle and new pipe, which can be explained by the accumulation process of biomass and elements on the pipe surface acting as sink (Makris et al., 2014).

In summary, the control test showed that the old pipe with harbored material had the biggest influence on water quality regarding the biomass and elements, suggesting that pipe harbored material did affect the degradation of water quality rather than originated from the pipe material. Whether the source water change impacted the pipe associated material, and to what extent the stabilized pipe harbored material could be altered, how long it will take before the material may release, how long the release may last and will be discussed in the following sections of 3.2 and 3.3.

3.2 Water quality

According to the objectives of this project, three different types of water were chosen as the feed water---- KA water, MX water and RE water. This section mainly shows and discusses the feed water quality and its changes caused by the release of pipe harbored material during shifting supply water quality. Old pipes were taken from two different locations for experiments. Pipes from 1st location was named as pipe sets 1 and pipes from 2nd location was named as pipe sets 2.

3.2.1 Quality of these three types of studied water

- **AOC**

Figure 3.2 shows the AOC values in the three types of studied water and the RO permeate. The results showed great improvements regarding AOC concentrations after applying RO treatment, and the different options of remineralization, reducing from 7.1 μg C/L (KA water, also referred as Feed) to 2-3 μg C/L (MX and RE water). As the indicator for the regrowth potential of bacterial in bulk water, the AOC concentration below 10 μg C/L is regarded as biologically stable for unchlorinated water (Van der Kooij et al., 1992). The typical values reported in the Netherlands ranges from 3.5 to 41.4 μg C/L (Prest et al., 2016). The AOC values in this study were all below the standard of biological stability and the values with MX and RE water were much lower than the KA (feed) water.

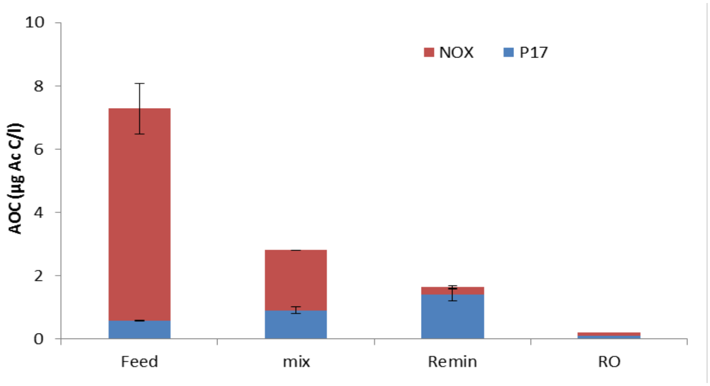
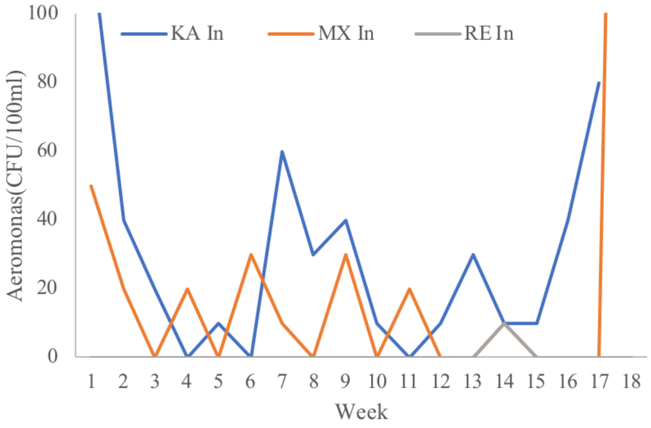


Figure 3.2 AOC values among different types of supply water

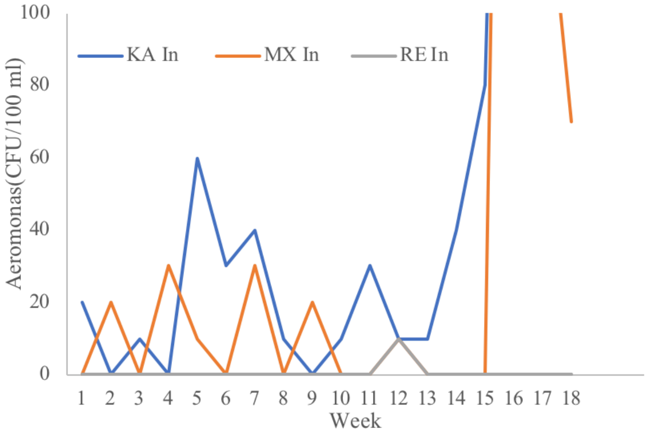
Such low value of AOC indicated the high removal efficiency of RO treatment, offering more bio-stable water. However, the decrease of substrate and nutrient could also lead to decrease of bio-activity of biofilm and lead to detachment from pipe surface, which would also cause biological destabilization, deteriorating the water quality (Liu et al., 2017a).

• *Aeromonas* spp.

Aeromonas concentration varied over the studied period, as shown in Figure 3.3. *Aeromonas* was hardly detected in RE water, occasionally detected in MX water, while frequently detected in KA water. The *Aeromonas* concentration in KA water was in the range reported in a previous study (10-160 CFU/100ml) and the presence of *Aeromonas* in MX water was possibly due to the mixture with KA water (G. Liu et al,2017c). The results confirmed the complete removal of *Aeromonas* by RO treatment.



(a)

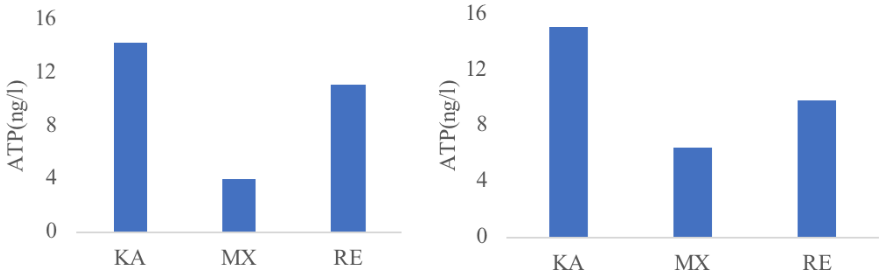


(b)

Figure 3.3 *Aeromonas* concentrations in different types of studied water; (a) indicates the result with pipe sets 1, (b) indicates the result with pipe sets 2

• ATP

The ATP values in different types of water are shown in Figure 3.4. In the KA system, the values of ATP were in the range of 9 to 20 ng/L and sometimes even reached 40 ng/l. The average value 14 ng/L was slightly higher than the typical value of ATP (8.6 ±1.3 ng/l) in the drinking water of the Netherlands (G. Liu et al., 2017c). For the ATP value in MX water, it was almost the 30% of the value of KA which could also represents the ratio of dilution of KA water with RO permeate.



(a) *(b)*

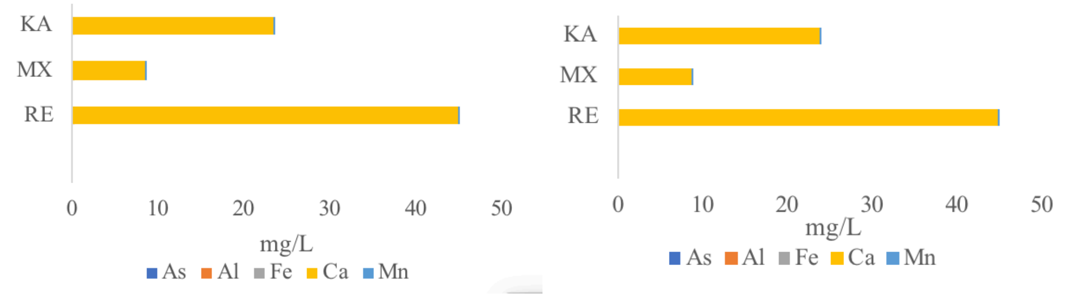
Figure 3.4 ATP values of feed water for two pipe sets; (a) indicates the result with pipe sets 1, (b) indicates the result with pipe sets 2

Combining the results of AOC, *Aeromonas* and ATP values of these three types of water, the values of RE and MX water were found to be much lower than that of KA water. Which indicates that the upgrading of treatments to RO offered much better quality of water with lower biomass and nutrients, while much higher biological stability.

- **Elements**

Figure 3.5 below summarizes the average of accumulated elements concentrations of different water types. Among the studied elements, the Ca concentration in each type of water was several orders higher than the others. The concentrations of As, Mn and Fe in each water were all under the detection limit. For Al, the variations among different supply water were not large and the average values in each type of water were almost just reached the minimum detection value of 2 μg/L.

The Ca concentration showed clearly differences among these water types. In the KA system, the average value of Ca was around 23 mg/L; Which was in the range of typical value in comparison with the value from previous studies (23±0.4 ng/L) (G. Liu et al., 2017c). MX water had the lowest Ca value among these three types of water just because the dilution of KA with RO permeate. For the RE water, the average Ca concentration reached almost 45 mg/L. It was caused by only adding calcium back in the Remineralization process at pilot study site during experiment period to adjust the hardness.



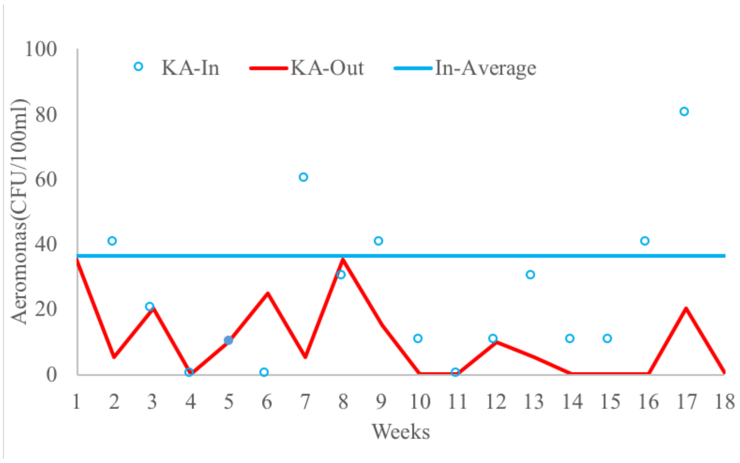
(a) *(b)*

Figure 3.5 Average accumulated elements concentration in different types of studied water; (a) indicates the result with pipe sets 1, (b) indicates the result with pipe sets 2

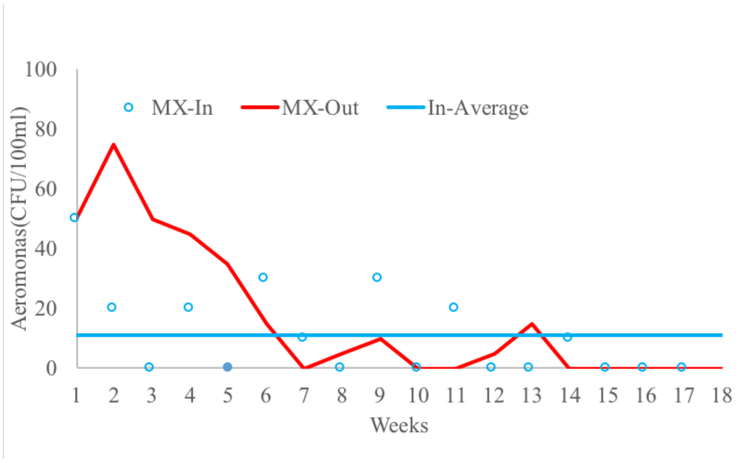
3.2.2 Changes of water quality caused by the pipe harbored material

The water in the pipes was refreshed weekly and both the "in" and "out" water were collected and analyzed for comparison. By observing the changes and differences between "in" and "out" water, the possible influence caused by the release of pipe harbored material were identified. From the visually observation during the whole period, no color changes or detachment of material in collected water samples were found, declaring that no critical transition effects like suddenly leaking material from accumulated pipe surface into the water samples after altering supply water types happened. The same parameters discussed above were used for studying the changes, those are *Aeromonas*, ATP, Fe, Mn, As, Ca and Al.

- ***Aeromonas* spp.**



(a)



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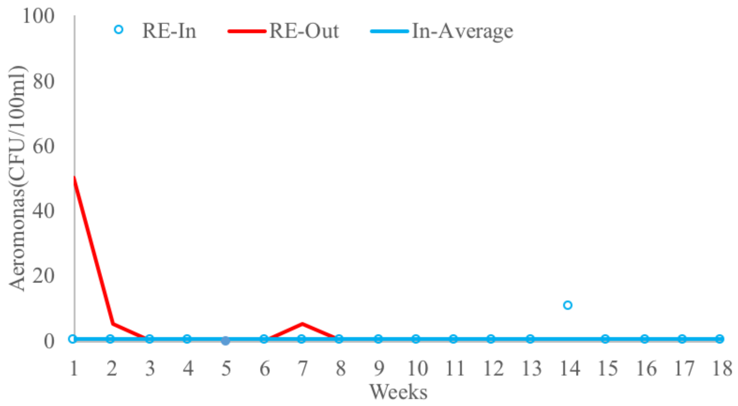
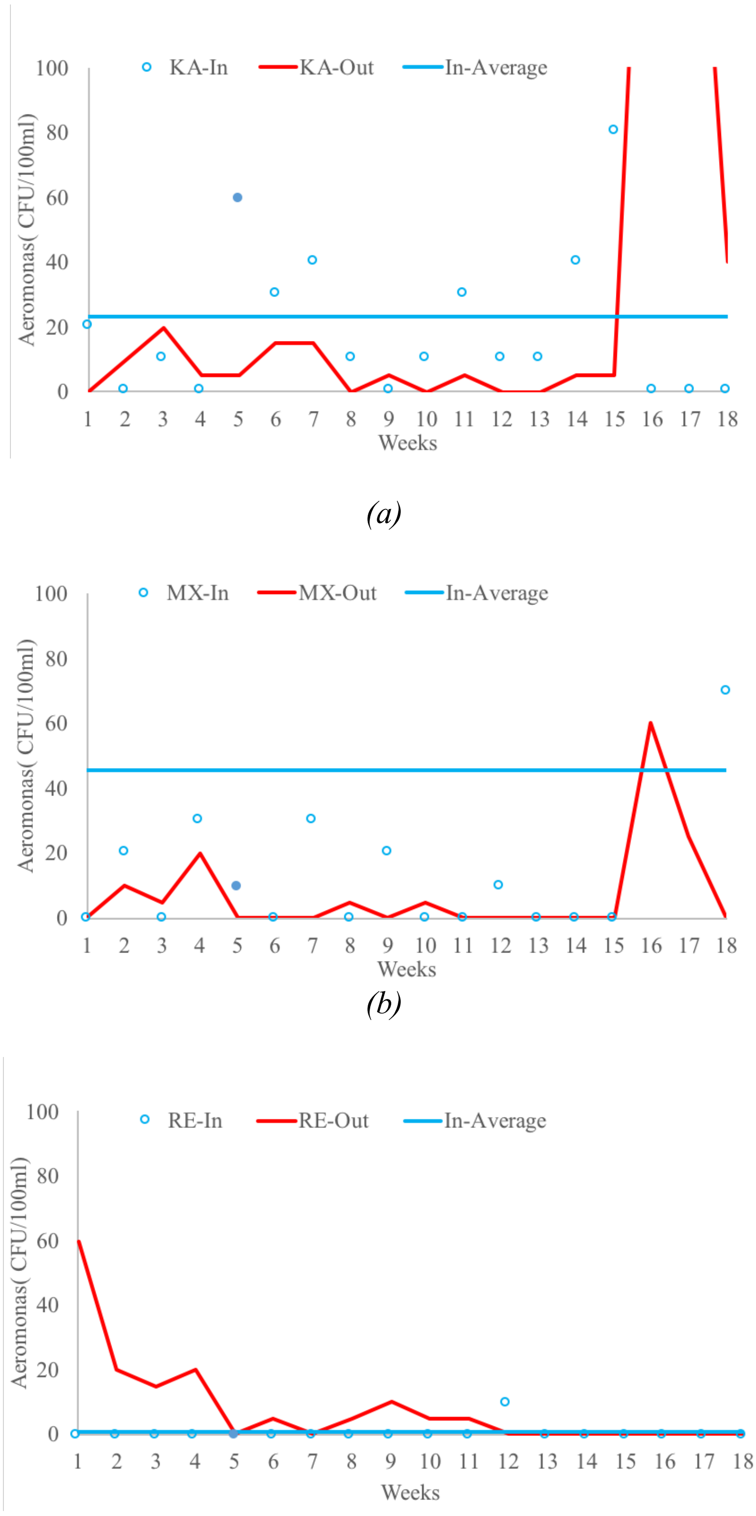


(c)

Figure 3.6 *Aeromonas* concentration in different types of studied water with pipe sets 1

The result, illustrated in Figure 3.6 and 3.7, shows the *Aeromonas* concentrations changes of the water "in" and water "out" of pipe sets that were supplied with different water types. For the test with KA water, comparing the *Aeromonas* in prepared water and distributed water, refreshed from the pipe sets, a clear decrease was found along the whole experiment period. The comparison revealed similar trends in MX and RE tests that *Aeromonas* concentrations increased at the beginning and the increase faded away after 7-8 weeks, indicating a release of pipe harbored material occurring in the first several weeks, which is the so-called transition effect (van der Wielen and Lut, 2016;Liu, Zhang et al. 2017). The variations of *Aeromonas* concentrations in water samples indicated a risk release of pipe harbored material at the beginning of water quality switching. In addition, fluctuations of *Aeromonas* concentrations in the KA and MX system also occurred, especially in middle and last period of experiments.



(a)

(b)

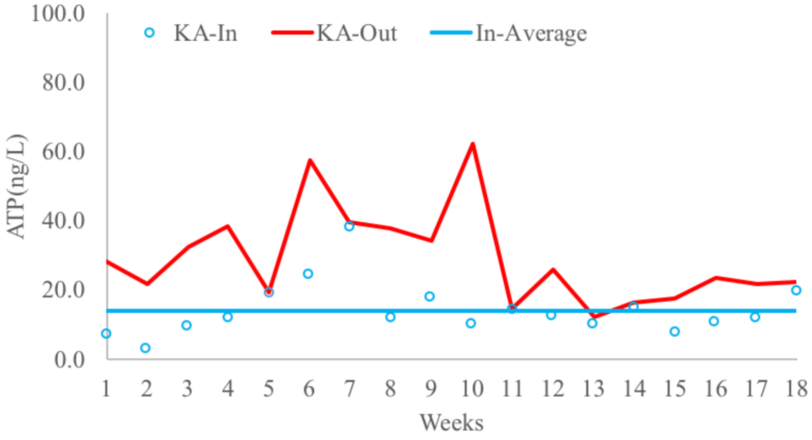
(c)

Figure 3.7 *Aeromonas* concentration in different types of studied water with pipe sets 2

- **ATP**

Figure 3.8 shows the ATP value variations over the period of 18 weeks in each type of studied water before and after staying in the pipe sets. For the pipe sets tested with KA water, the “out” values varied with the variations of the “in” values of KA water collected from treatment plant.

In most of the samples, the “out” was comparable with the “in” values. Whereas, for the results from week 6 to week 10, the “out” values were considerable higher than that of the “in” values, which may either be due to the fluctuations of treated water quality at the pumping station Kamerik, or because of the summer season that the water experienced higher temperature during transportation. As the KA is the water quality that the pipe is supplied with over decades, it is not expected to be caused by the detachment of pipe harbored material, which can be confirmed by the results of measuring the pipe samples at the end of the study (given in the next section).



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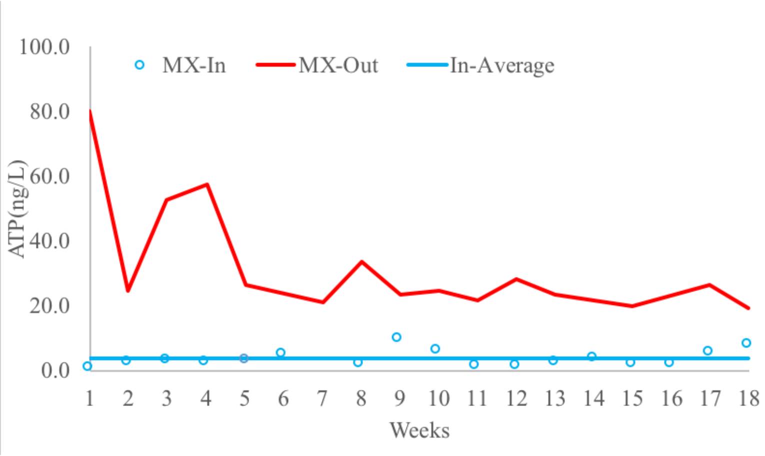

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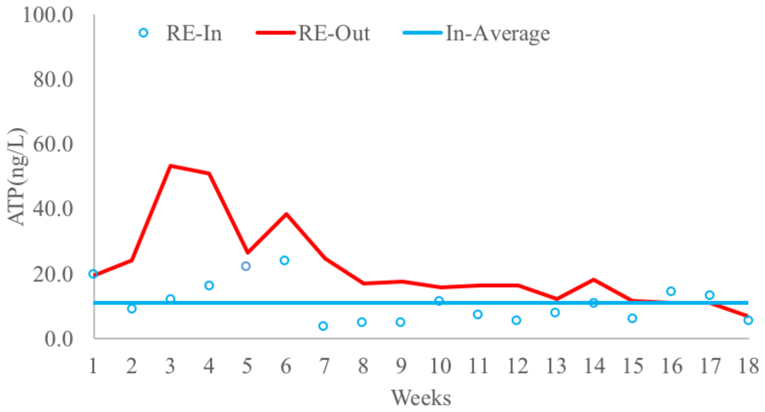
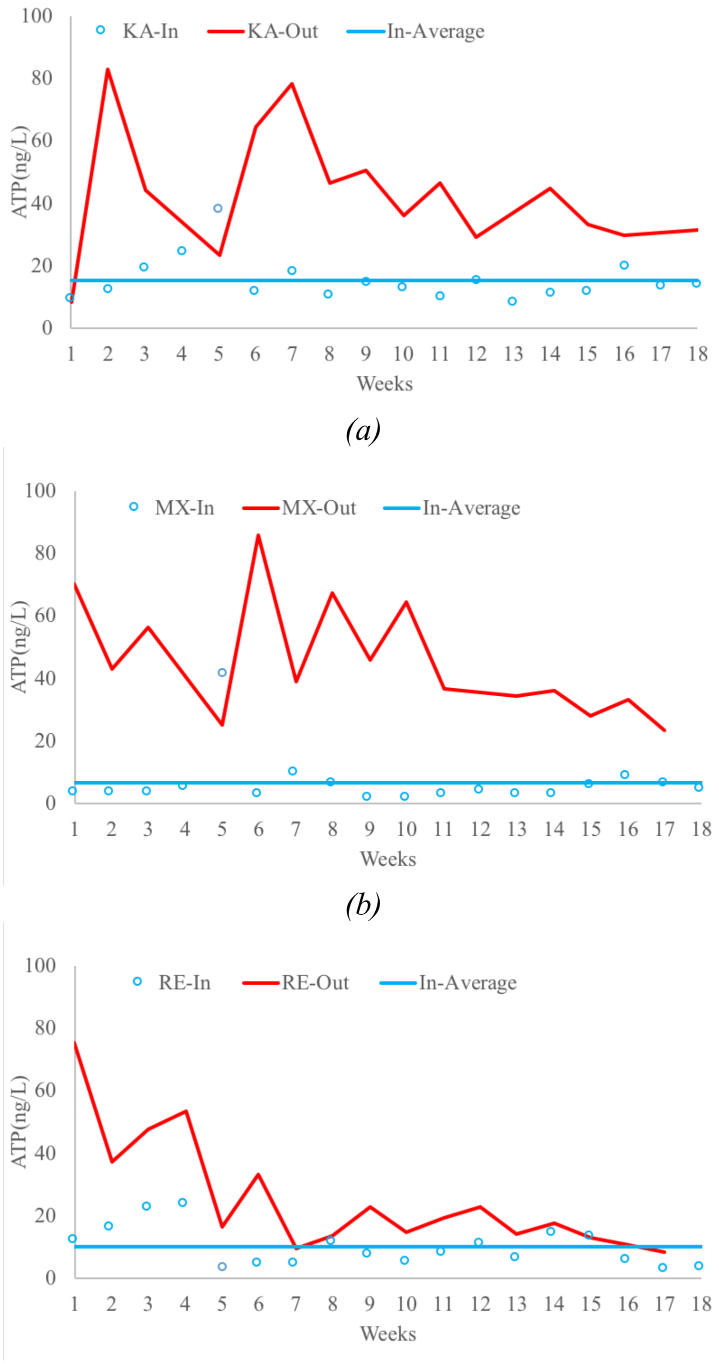


(c)

Figure 3.8 ATP value changes among different water types with pipe sets 1, the water prepared to feed in the pipe was labelled as "in", while water flowed out of the pipe after one week was marked as "out”

For the MX system, the value of ATP in “out” water (~20 ng/L) was always much higher than that of “in” water (4 ng/L), indicating clear increase caused by either the regrowth in the water or the release of material harbored by the pipe. Even until the end of the experimental period, the value between in and out water did not reach the same level, suggesting that the increase was caused by pipe harbored material destabilization, since the destabilization may last longer than 18 weeks. Taking the results, obtained from control test into consideration, the regrowth in water could contribute to the ATP increase by almost the same range, from 4 to 20 ng/L. As such, the transition effects caused by switching to MX water will only be the peaks until week 8, which was observed at week 1, 3, 4 and 8. Afterwards, the system became stabilized again. As for the pipe sets with RE water, a clear transition effects’ shape of ATP changes was captured. Started from week 2, the ATP of RE water “out” increased to a peak value of 50 ng/L at week 3 and week 4. Afterwards, the peak increase faded away, and the ATP concentrations had the same as the RE “in” water from week 8 until the week 18 at the end of the study period. Similar observations were summarized in Figure 3.9 for the data collected on the 2nd pipe sets.

In summary, the results of ATP variations in the pipe tests with all RE and MX water were subjected to the transition effects caused by switching supply water quality, indicating the occurrence of material release from pipe harbored material. The release may happen in the first several weeks that can last for about 8 weeks, and afterwards becoming stabilized again.



(a)

(b)

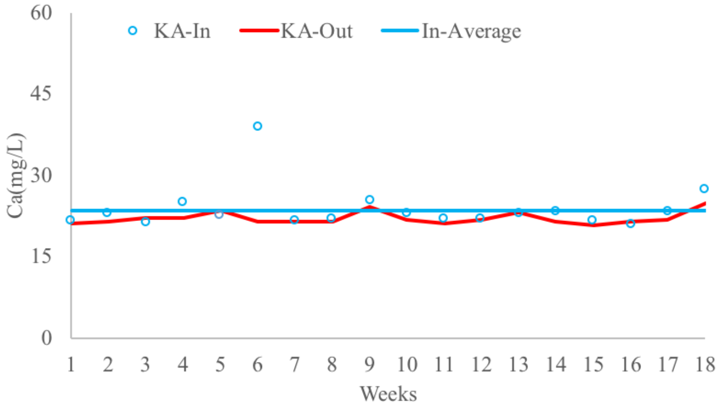
(c)

Figure 3.9 Summarize of ATP value of water samples with pipe sets 2

- **Elements**

As for the measurement of the elements' concentration changes, the most results of As and Mn were below detection limits. Therefore, the discussion below will be mainly focused on the elements of Ca, Al and Fe. It was obvious that the Ca concentrations in the water "out" was purely dependent on the Ca concentration in the corresponding water "in" (Figure 3.10 and Figure 3.11). There was no clear release of pipe harbored material observed from the view of

Ca concentration. This is compliance with our previous findings indicating that Ca mainly accumulated in the PVC pipe biofilm but not in the HDPE biofilm of the household pipes (Liu et al., 2017b).



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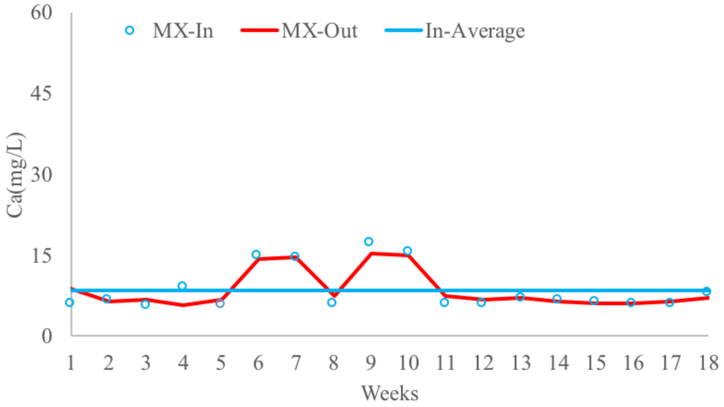

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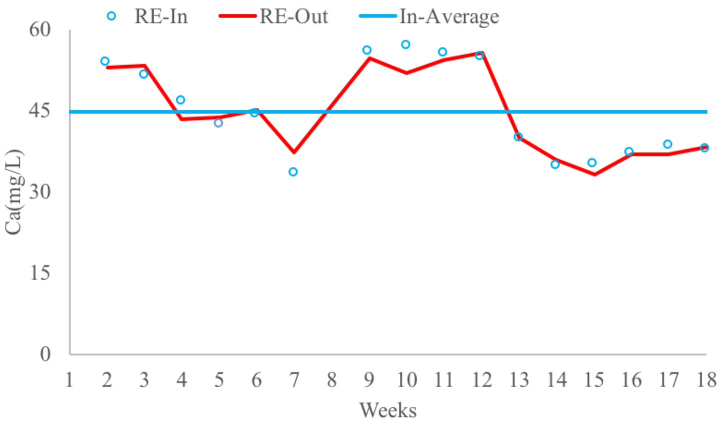
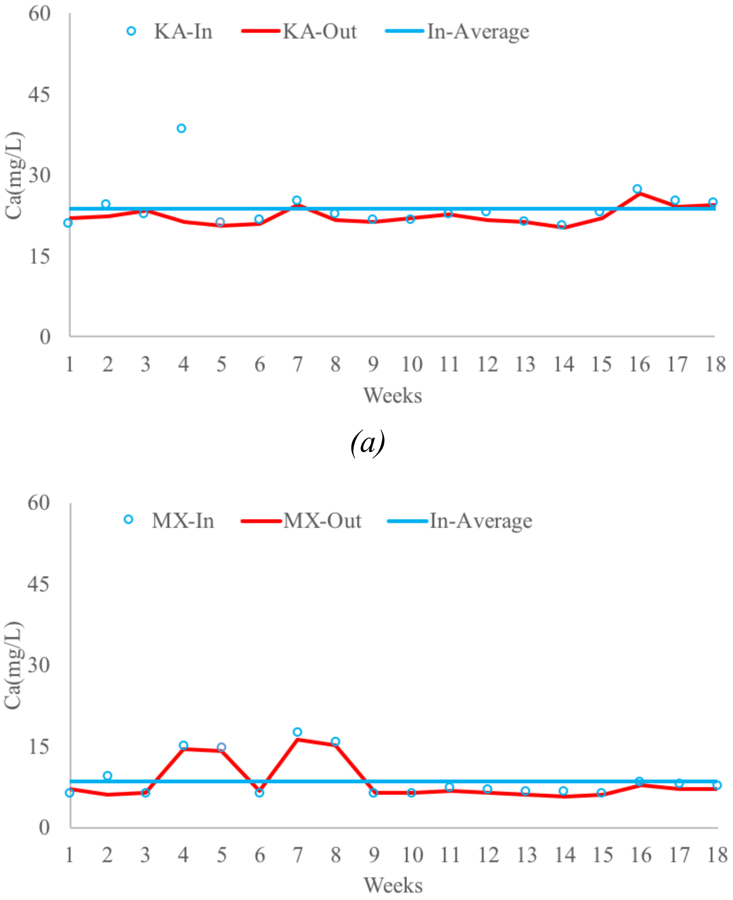


(c)

Figure 3.10 Ca concentration in different types of water before and after staying in pipe sets 1



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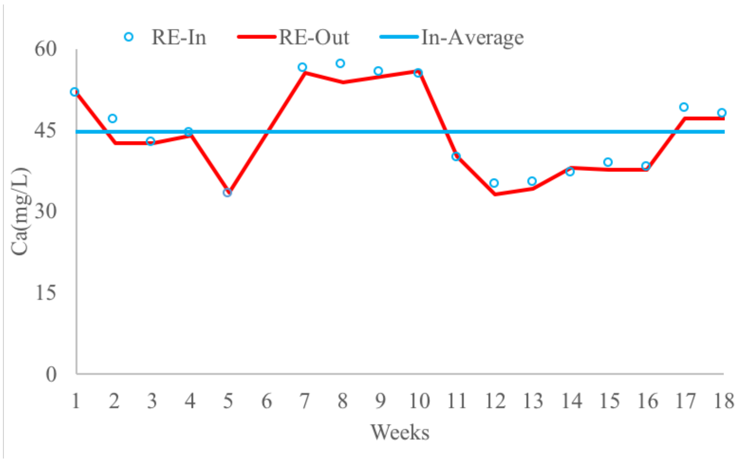
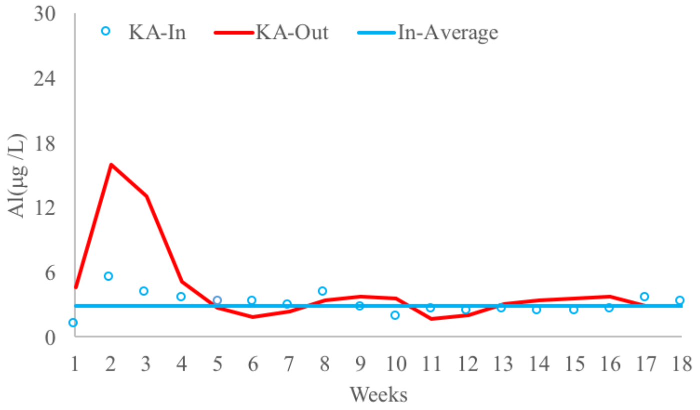


(c)

Figure 3.11 Ca concentration in different types of water before and after staying in pipe sets 2

For Al, its concentration varied over the study period and the release from pipe harbored material was noticed in the pipe tests with both MX and RE water (Figure 3.12). For the test with KA water, the Al concentrations of the water “in” and the water “out” was about the same in most of the samples. The increase of Al concentration was only observed at the beginning of the test, around week 2 and week 3 (~15μg/L), which can be attributed to the flushing out of loose associated material on the pipe. For the test with MX and RE water, similar trends were observed, but the increase of Al concentration (~20-25μg/L) was higher than that from KA water indicating the further release of Al caused by the differences in supply water quality. The same changes were observed in the second pipe set, as illustrated in Figure 3.13.



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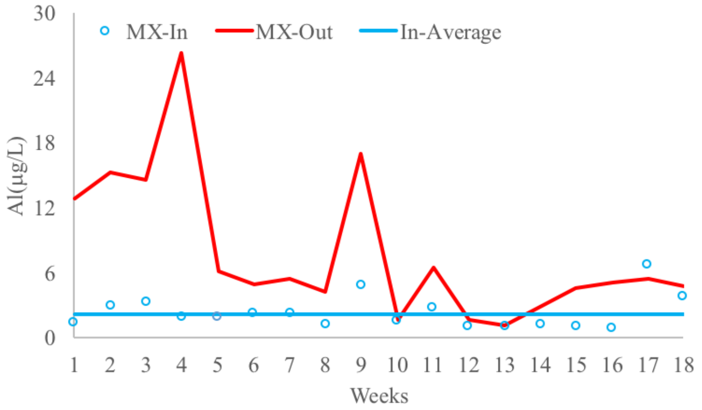

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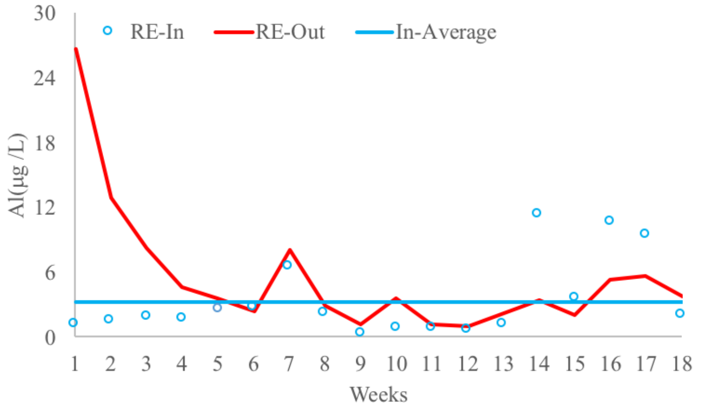

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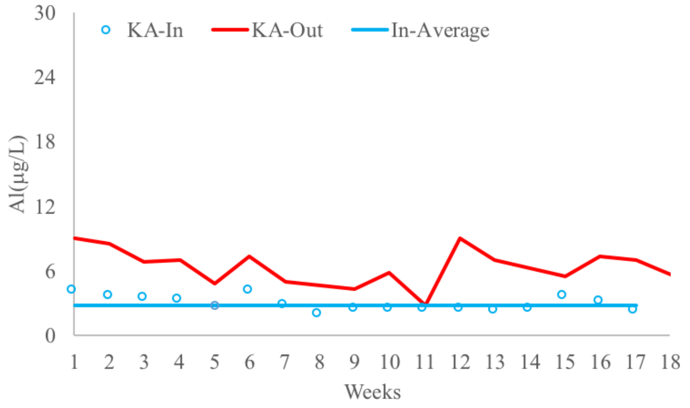
Figure 3.12 Al concentration in different types of studied water with pipe sets 1



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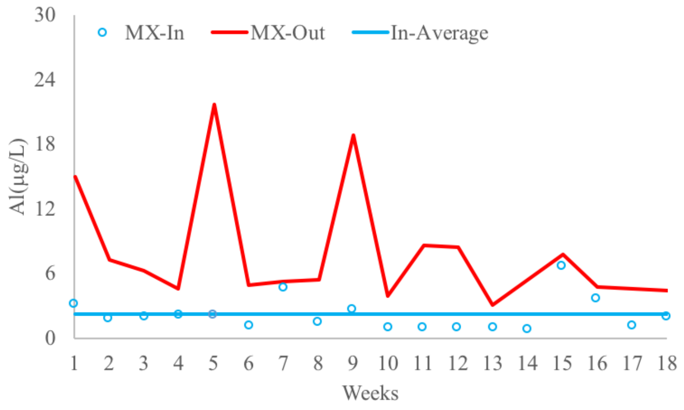

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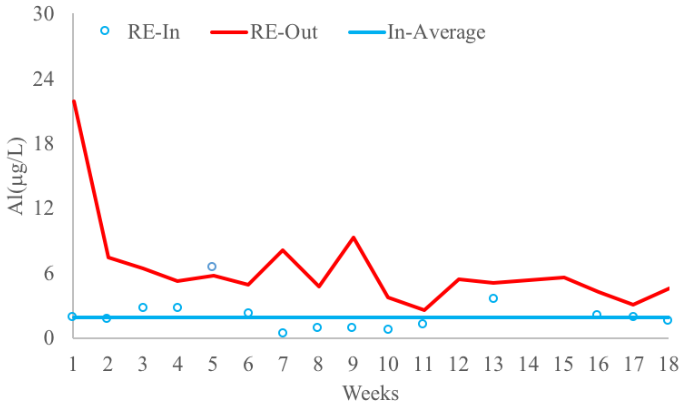
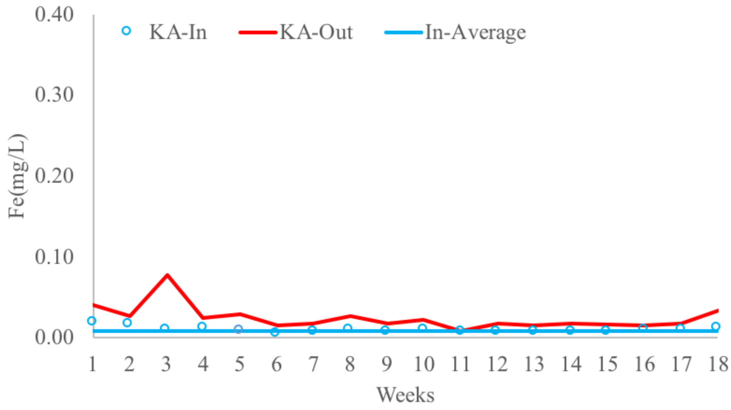


(c)

Figure 3.13 Al concentration in different types of studied water with pipe sets 2

Figure 3.14 and 15 show the Fe concentration of water "in" and water "out" from the tests with three water types on two pipe sets. The switch of supply water quality from KA to RE had less impact than the switch from KA to MX. Fe was reported to be one of the causes of discoloration in drinking water. An increase of Fe was found in the studied situations, but the concentration was always below the typical value (0.3 mg/L), which will not lead to discoloration problems (McFarland et al., 2004). Since both the loose deposits and biofilm can harbor Fe, the release of Fe may be attributed to the either the release of loose deposits or detachment of biofilm.



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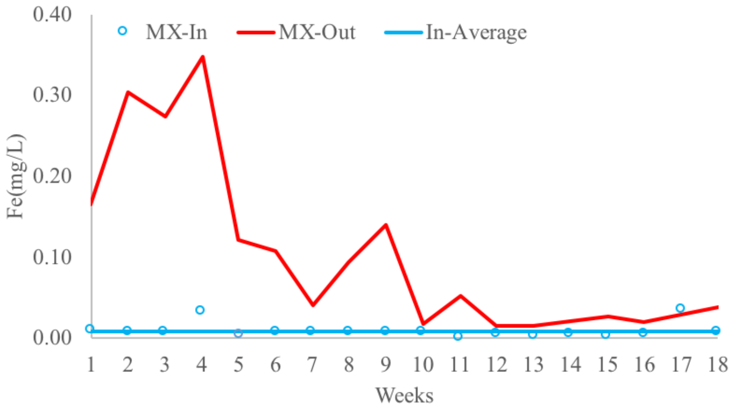

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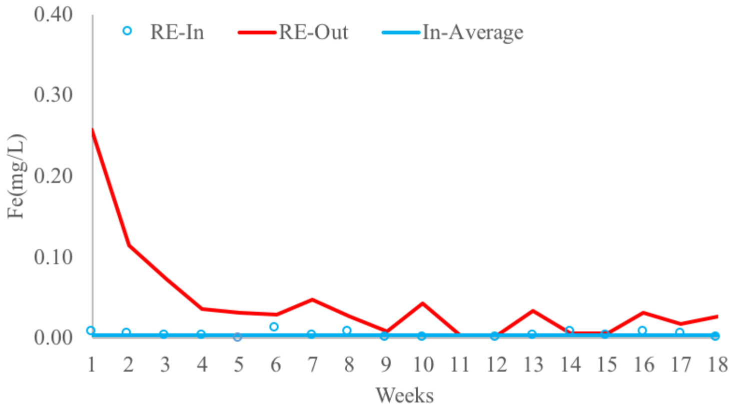

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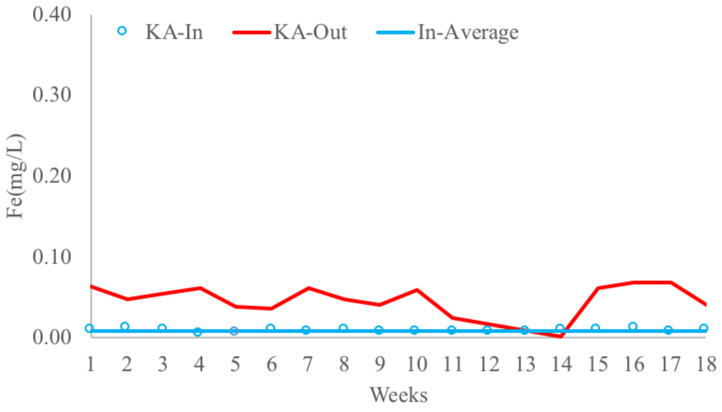
Figure 3.14 Fe concentration in three types of studied water with pipe sets 1



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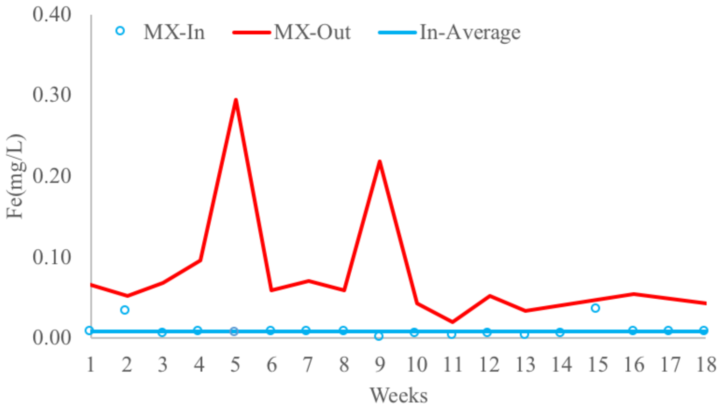

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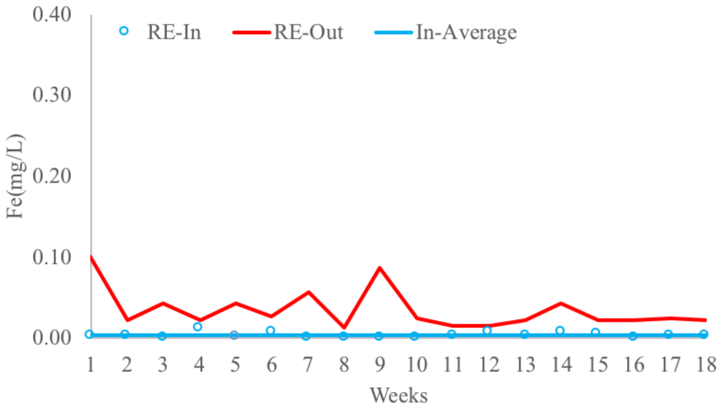


(c)

Figure 3.15 Fe concentration in three types of studied water with pipe sets 2

In summary, the variation of biological and elemental parameters illustrated the different patterns on different water quality parameters. For example, there was no effects on As and Mn in the bulk water (always below detection limit), and there was no release of Ca from pipe harbored material in any of the tests. The release of Fe, Al, ATP and *Aeromonas* were clearly observed, with the first release captured at week 2 and 3, and for a period of about 8 weeks.

Those are valuable findings that can help water utility to understand what may happen, when and how long the release may take, based on which actionable strategies can be developed to avoid un-wanted water quality deterioration during the switching of supply water quality. However, it is also confirmed that the water quality improved after the release, and the release will not lead to critical problems such as discoloration.s

3.3 Pipe harbored material and its changes after 18-weeks' test

3.3.1 Harbored material associated with household HDPE pipes

The pipe samples were taken from two locations in distribution system. The quantity and characteristics of pipe harbored material was studied regarding the *Aeromonas*, ATP, and elements. For all parameters, it is noticed that the two pipe sets showed clear differences. The observed variations were reasonable since the situation within the household pipes are subjected to intermittent flow which is highly depend on the consumption and water usage pattern per household.

- ***Aeromonas* SPP.**

Table 3.1 shows the results on *Aeromonas* among different pipe sets before and after the test with different water types for 18 weeks. As mentioned above, results from the two pipe sets collected from two locations varied. *Aeromonas* accumulation in pipes dug from the 1st location was 810 CFU/ 100ml, while that in pipes from the 2nd location was under the detection limit. This might be due to the uneven distribution of accumulated material (e.g. *Aeromonas* accumulated only in loose deposits) in DWDS, which has been reported before (Vreeburg and Boxall, 2007; van der Wielen and Lut, 2016; Liu et al. 2017b). Furthermore, the not detectable *Aeromonas* might also be caused by not efficient recovery of *Aeromonas* from pipe samples by the applied pre-treatment protocol.

Table 3.1 *Aeromonas* concentration in pipe sections at the start and end of study

	Pipe sets 1	Pipe sets
Start	810±558 CFU/ 100ml	UD*
end	UD	UD

* UD= under the detection limit(10 CFU/100ml)

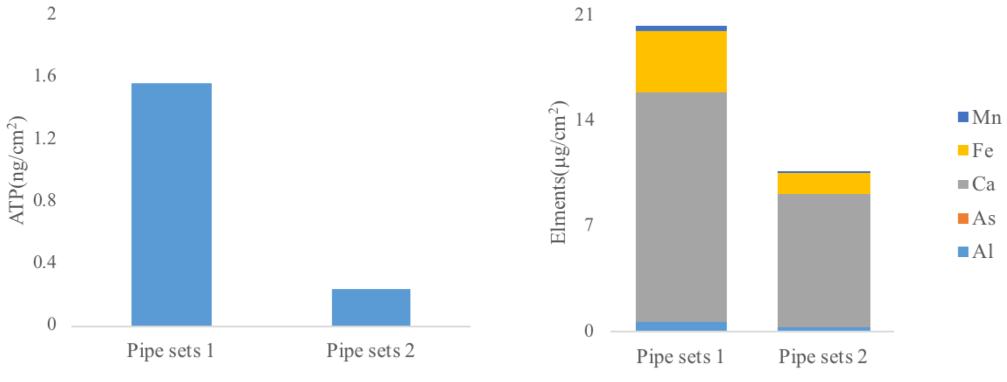
- **ATP**

Regarding the active biomass measured by ATP, similar variations were observed as the results on *Aeromonas*. The pipes at 2nd location harbored much less ATP than the 1st location (1.53

ng/cm^2 vs. 0.24 ng/cm^2), both of which were not in the range of typical ATP values in the unchlorinated systems (10^2-10^4 pg ATP/ cm^2) (Prest et al., 2016).

- **Elements**

As for the elemental composition, all of the selected elements (e.g. As, Al, Ca, Fe and Mn) were in the range of typical values from Dutch systems(G. Liu et al., 2017b). While the differences between two locations were also obvious, as shown in Figure 3.13. There were much higher Ca, Fe and Mn on the pipes from 1st location than the 2nd location, which is consistence with the higher biomass accumulation at 1st location as indicated by the ATP results given above. This can be explained by the reported accumulation of Ca in biofilm and the co-accumulation of Fe and Mn favored by the presence of related microbiome (Ginige et al., 2011b).



(a) (b)

Figure 3.16 General information of pipe sets before transition effect study; (a) indicated the results with ATP, (b) indicates the results with element

3.3.2 Changes of pipe harbored material after 18-weeks's test

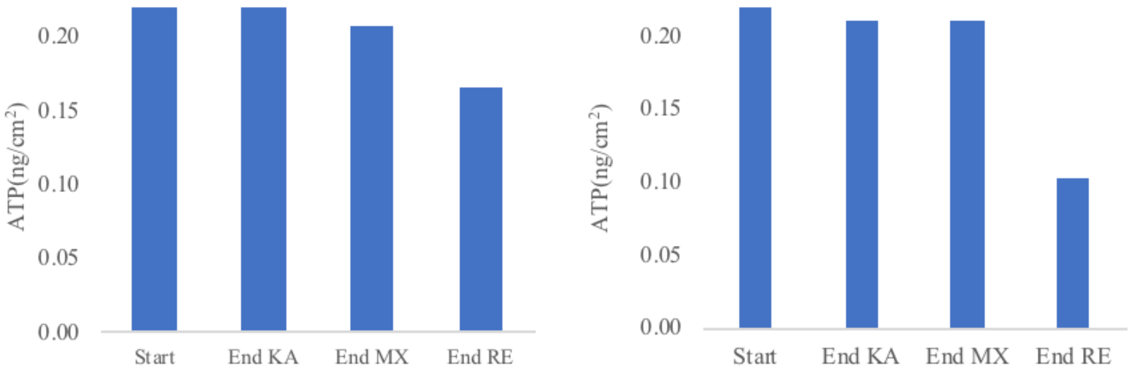
- ***Aeromonas* spp.**

Table 3.1 presents the *Aeromonas* concentration in pipes before and after study with different water types, showing that the detected *Aeromonas* in pipe set 1 was released from the pipe and flushed out, this is corresponding to the observation of *Aeromonas* increase in the water samples until week 11 (mentioned and discussed in section 3.2). As it is all below detection limit for the pipe samples after the study, the cross comparison on the effects of different water types is not possible here.

- **ATP**

The biomass harbored by HDPE pipes before and after switching to different supply water types as measured by ATP is given in Figure 3.17. From both pipe sets, clear decrease of ATP was observed. In the test with pipe set 1, the ATP decreased from 1.56 to ~0.17 ng/cm^2, while for the test with pipe set 2, the ATP decreased from 0.24 to ~0.10 ng/cm^2. Although the original amount of ATP in the pipes from two location varied (1.56 vs. 0.24 ng/cm^2), the finished ATP were comparable (0.10 to 0.22 ng/cm^2), confirming that under the same operational situation, the biomass on pipe surfaces is more dependent on the available nutrients in the supply water. The release and detachment may be caused by the not sufficient nutrients (e.g. AOC in Figure 3.2), maintaining the original biofilm activity.

Taking the pipe set 1 as an example to compare the ATP decrease among the tested water types, it was observed that compared to the reference pipe tested with KA water, the decreased caused by RE water was bigger than that of MX water. Although the MX and RE water had comparable levels of AOC, the RE water had probably a different AOC composition than MX water, compared to KA water, because the RE water was prepared by remineralization process that introduced AOC from chemicals, whereas MX water was more a dilution of KA water to a 70% of original AOC concentration in KA water. Therefore, the pipe harbored biofilm, and the associated matrix, might have been subject to heavier disturbances by RE water than the MX water. The finding suggested that the supply water quality changes did impact the pipe harbored biofilm and the influence varied based on the composition of the corresponding changes. However, it is also clear that there was no visual observation (discoloration or visual particle) with this detachment, suggesting no occurrence of “shock” release.



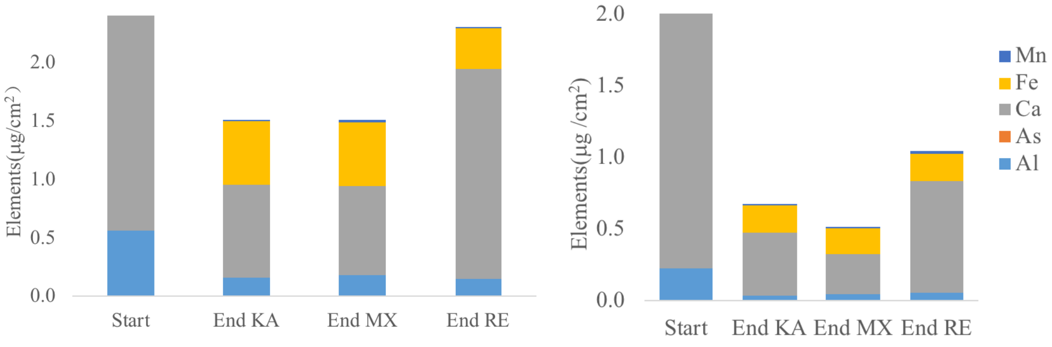
(a) *(b)*

Figure 3.17 ATP concentration of pipe harbored material before and after study;(a) indicates the result with pipe sets 1, (b) indicates the result with pipe sets 2

Interestingly, although the decline of ATP concentration in biofilm may correspond to the increase of biological activity in water, the decline magnitude of ATP was not the same as the observed increase in the water samples. As mentioned above, there was a much lower ATP value was found on pipe sets fed with RE water and only a slight decrease of that in the MX system. In water samples, the changes of ATP value in the MX system was higher, average 8-fold increase of ATP concentration. Whereas, the increase of ATP in RE water was gentler, average 3-fold increase of ATP concentrations. This observation indicated that the increase of biomass in water samples was directly corresponded to the decrease in bacterial activity in the biofilm. This was possibly due to the declined cell-specific bacterial activity and even bacterial death in the RE system with such low concentrations and different composition of nutrients (Boe-Hansen et al., 2002), because ATP actually only quantifies the energy-rich metabolic activity of bacterial (G. Liu et al. 2013b). In the MX system, the decreased biomass in the biofilm detached into water and caused the acute ATP concentration variations. However for the RE system, possibly due to the too low nutrient concentration with a different composition, the activity per bacteria also reduced which led to the observation of a higher decline of ATP in the biofilm and less increased bacteria activity in the test with RE water as compared to MX water. Furthermore, there might be shifts of bacterial community which could also be the reason in the observed differences (Li et al. 2016). Further investigations is need for a better understanding.

- **Elements**

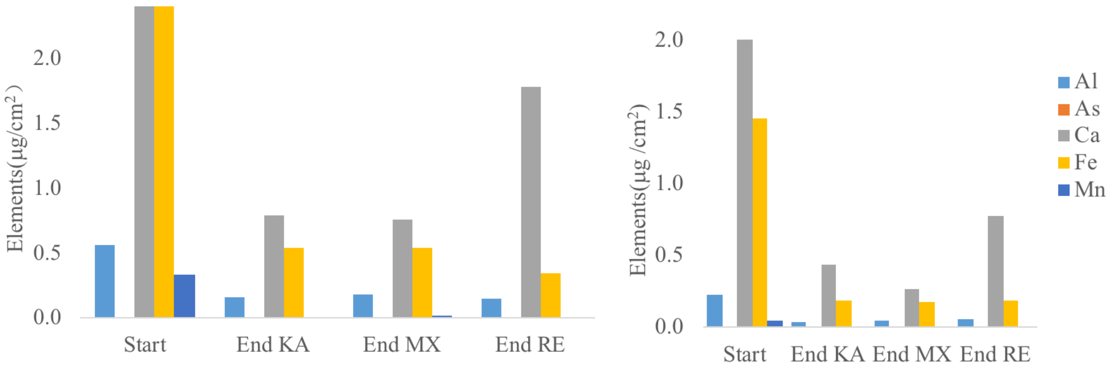
The accumulated concentration of elements within each system is summarized below (Figure 3.18 and Figure 3.18). Apparent decline was found in pipe samples at the end of experiment, possibly led by the weekly refreshment of the supply water. However, the variations of each system was also different. More accumulated elements was found in the RE system in each experiment and the difference between KA and MX system was not as obvious as that between KA and RE system. From the comparison of accumulated elements, the trend of total concentration could be identified and the dominant elements were Ca and Fe.



(a) *(b)*

Figure 3.18 Accumulated element comparison with two pipe sets;(a) indicates the result with pipe sets 1, (b) indicates the result with pipe sets 2

About the variations of Al and Fe concentrations in each system it can be said that the trend was similar in each experiment. A clear decrease was found between the beginning and the end of experiment, which corresponded to the discussion on the water samples. While the concentration in the pipe samples in these three systems at the end was more or less at the same level, changes on pipes were not directly related to the magnitude of increase in water samples. For example, much more increase of Al and Fe concentrations were found with MX system compared to the other water types, while the concentration in pipe samples did not decrease that much.



(a) *(b)*

Figure 3.19 The comparison of each specific element with these two pipe sets;(a) indicates the result with pipe sets 1, (b) indicates the result with pipe sets 2

Different trends were found with aspect to changes in Ca in pipe samples. As mentioned earlier, no variations of Ca concentration was found between "in" and "out" water, whereas in the pipe samples, almost 2-fold of Ca accumulated on pipe sets supplied with RE water compared to that of KA supplied pipes. This may be caused by the much higher Ca concentration in the RE water induced by remineralization for hardness purposes. This accumulation caused a decrease in the water sample Ca concentration to under the detection limit.

From the observation of changes in pipe samples, less bacterial activity and elements accumulation (except for Ca) were found after switching source water from KA to other types, suggesting that source water change had influence on the pipe harbored material/biofilm. This indicated the influence on biofilm not only presented by the accumulation of bacterial, but also some inorganic material.

4 Conclusions and recommendations

Combining the observation on the variations and changes in water quality and pipe samples, it is clearly shown that changes of supply water quality would destabilize the inner environment of distribution pipes and can turn the distribution pipes from sink to source. Not only the water quality would be altered, the material harbored by pipes would also change due to the destabilization. A lower bio-activity and less element accumulation was noticed on pipe surface after switching supply water to water with lower nutrient and substrate concentration, corresponding to the increase of bacterial activity and elements (except for Ca) in the bulk water. While the extent of influence on water and biofilm depends on the specific compositions of the new water. How to connect the magnitude of changes in bulk water quality and biofilm attached on pipes needs to be further investigated. The detailed conclusions and recommendations will be given in the following.

4.1 Conclusions

1. Water quality

   Water quality was improved by using RO based treatment, containing less biomass, nutrients and elements (except for Ca). However, transition effects were captured after switching supply water from conventional treated water (KA) to RO treated water (MX and RE) with aged HDPE household connection pipes, resulting in water quality deterioration. There were no effects on As and Mn in the water samples (always below detection limit) and no release of Ca into water samples (minor changes between concentrations of supply and refreshed water). The release of Fe, Al, ATP and *Aeromonas* were mainly captured in the first several weeks, for a period of around 8 weeks and afterwards becoming stabilized again. No critical problems were observed within the experimental period such as visible particles or discoloration.

2. Pipe harbored material

   The accumulation on two pipe sets showed clear differences, suggesting that household pipes were not only affected by the source water types and material but also the consumption and water usage pattern. Supply water changes from KA to MX and RE water had impacts on pipe harbored material, resulting in less bacterial activity and elements accumulation (except for Ca).

3. Transition effects with water compositions

   The magnitude of changes varied with the water compositions. Compared to the reference pipe sets fed with KA water, the decrease of biomass caused by RE water was bigger than that of MX water. For the changes of Ca in pipe samples, almost 2 times of Ca accumulated on pipe sets fed with RE water compared to that of pipe sets with KA and MX water at the end of experimental period. These findings suggested that the influence of supply water quality changes on pipe harbored material was also related to the specific water compositions.

4.2 Recommendations

Based on the results and conclusion, recommendations are put forward for improvement of experimental design for post research.

1. Loose deposits within household connection pipes

   Loose deposits represents the particles deposited in DWDS and can be re-suspended mainly by hydraulic turbulence. Although changes in source water would not alter the hydraulic regime too much, the physicochemical and biological changes within bulk water may also destabilize the loose deposits. Since high amounts of biomass and organic and inorganic matter are harbored in this niche. Possible destabilization of loose deposit can happen with biochemical process and caused water quality degradation. Not so much attention was put on loose deposits within this study. Further studies should therefore be addressed on the investigation of loose deposits during irregular supply water quality changes.
2. Mechanisms behind changes of parameters

   Changes of Fe and Al concentration were observed both in water and pipe samples and changes of Ca concentrations were only noticed in pipe samples. The mechanisms behind these changes were still not very clear and need to be further studied.
3. Relationship between changes in water and pipe samples

   Due to the switch to supply water with low nutrients, pipe harbored material may detach and enter into bulk water, which would cause water quality degradation. This conclusion could be confirmed by this study. However, how to connect the changes in bulk water and changes on biofilm was not determined. For example, compared to RE system, much more increase of Al and Fe concentrations were found in water samples with MX system, while the decrease of Al and Fe in pipe samples was not much. Further studies need to be addressed about this part.

4. Community study

   Previous studies also have shown that the community shift can be the reason for increase in bacterial activity and element concentrations in bulk water after supply water quality changes. This can be achieved by investigating the community of water and biofilm samples. The possible community shift in water and biofilm can also explain the changes in elements, like more iron-oxidizing bacterial can also be the reason for the increase in Fe concentration in bulk water.

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Appendix

A) Water samples of control test

Table A.1 Result of water samples of control test

		ATP ng/L	Al µg/L	Ca mg/L	Fe mg/L
In	KA	13.6	*	24.83	0.010
	MX	4.6	1.87	7.20	0.008
	RE	3.4	1.53	47.68	0.003
Out	KA	11.7	2.89	24.80	0.007
Bottle	MX	11.9	0.44	7.18	0.003
	RE	3.1	0.75	47.52	0.002
Out	KA	19.1	2.35	24.38	0.007
New P	MX	11.1	0.76	7.14	0.003
	RE	10.9	1.94	46.98	0.004
Out	KA	49.8	5.71	24.35	0.040
Old P	MX	64.3	4.35	7.16	0.030
	RE	30.8	4.56	47.05	0.040

* indicates that value is not accessible or reliable

B) Water samples of water quality study

Table B.1 *Aeromonas* concentration in different types of studies water with pipe sets 1, unit CFU/100 ml

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	120	30	40	35	50	50	*	50	0	0	100	50
2	40	0	10	5	20	60	90	75	0	0	10	5
3	20	10	30	20	0	20	80	50	0	0	0	0
4	0	0	0	0	20	70	20	45	0	0	0	0
5	10	20	0	10	0	20	50	35	0	0	0	0
6	0	30	20	25	30	30	0	15	0	0	0	0
7	60	0	10	5	10	0	0	0	0	0	10	5
8	30	20	50	35	0	10	0	5	0	0	0	0
9	40	0	30	15	30	20	0	10	0	0	0	0
10	10	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	20	0	0	0	0	0	0	0
12	10	0	20	10	0	0	10	5	0	0	0	0
13	30	10	0	5	0	0	30	15	0	0	0	0
14	10	0	0	0	10	0	0	0	10	0	0	0
15	10	0	0	0	0	0	0	0	0	0	0	0
16	40	0	0	0	0	0	0	0	0	0	0	0
17	80	20	20	20	0	0	0	0	0	0	0	0
18	*	*	*	*	*	30	60	0	0	0	0	0

Table B.2 *Aeromonas* concentration in different types of studied water with pipe sets 2, unit CFU/100 ml

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	20	0	0	0	0	0	0	0	0	20	100	60
2	0	20	0	10	20	10	10	10	0	10	30	20
3	10	0	40	20	0	10	0	5	0	30	0	15
4	0	0	10	5	30	20	20	20	0	40	0	20
5	60	0	10	5	10	0	0	0	0	0	0	0
6	30	0	30	15	0	0	0	0	0	0	10	5
7	40	0	30	15	30	0	0	0	0	0	0	0
8	10	0	0	0	0	0	10	5	0	10	0	5
9	0	0	10	5	20	0	0	0	0	20	0	10
10	10	0	0	0	0	10	0	5	0	10	0	5
11	30	0	10	5	0	0	0	0	0	10	0	5
12	10	0	0	0	10	0	0	0	10	0	0	0
13	10	0	0	0	0	0	0	0	0	0	0	0
14	40	10	0	5	0	0	0	0	0	0	0	0
15	80	0	10	5	0	0	0	0	0	0	0	0
16	*	*	*	*	*	0	*	0	0	0	0	0
17	*	*	*	*	*	0	50	25	0	0	0	0
18	*	50	30	40	70	0	0	0	0	0	0	0

Table B.3 ATP values of three types of studied water with pipe sets 1, unit ng/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-Mix	RE In	RE Out P1	RE Out P2	Out-Re
1	7.0	20.4	36.2	28.3	1.3	99.9	60.1	80.0	19.9	20.5	18.9	19.7
2	3.1	18.7	25.2	22.0	3.1	29.8	19.9	24.9	8.9	27.8	20.0	23.9
3	9.3	42.7	22.0	32.4	3.3	69.3	36.6	53.0	12.0	74.8	32.0	53.4
4	12.1	55.5	21.0	38.3	3.2	71.0	43.9	57.5	15.9	80.0	21.9	51.0
5	19.0	24.9	13.9	19.4	3.4	18.0	35.6	26.8	22.3	31.3	22.3	26.8
6	24.4	68.3	46.7	57.5	5.1	*	*	*	23.9	47.7	28.8	38.3
7	38.2	22.9	56.3	39.6	*	31.9	10.8	21.4	3.3	36.5	12.8	24.7
8	11.8	38.0	*	38.0	2.6	35.5	31.9	33.7	4.9	19.7	13.8	16.8
9	18.1	52.6	15.8	34.2	10.0	32.8	13.7	23.3	4.6	16.2	18.7	17.5
10	10.2	59.2	65.5	62.4	6.6	17.7	31.2	24.5	11.5	13.3	18.5	15.9
11	14.6	18.0	10.7	14.4	2.0	14.6	28.8	21.7	7.4	14.0	19.4	16.7
12	12.4	30.2	21.3	25.8	1.9	16.0	40.4	28.2	5.4	17.6	15.6	16.6
13	9.9	*	12.0	12.0	2.9	23.7	*	23.7	7.9	10.6	13.7	12.2
14	14.7	23.7	8.6	16.2	4.1	21.2	22.4	21.8	11.0	18.4	*	18.4
15	8.0	20.2	15.5	17.9	2.6	21.5	18.7	20.1	6.2	15.1	8.7	11.9
16	10.9	28.4	19.2	23.8	2.6	*	*	*	14.5	10.3	11.6	11.0
17	11.7	33.3	22.0	22.0	5.7	26.4	*	26.4	13.4	9.3	13.1	11.2
18	19.8	36.0	9.2	22.6	8.5	24.3	14.5	19.4	5.6	6.8	6.6	6.7

Table B.4 ATP values of three types of studied water with pipe sets 2, unit ng/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-Re
1	9.34	15.2	1.28	8.24	3.3	75.4	64.4	69.9	12.0	25.2	125	75.1
2	12.1	91	75.1	83.1	3.2	47.3	38.7	43.0	15.9	42.3	32.3	37.3
3	19.0	28.8	58.9	43.9	3.4	32.1	80.3	56.2	22.3	79.1	15.7	47.4
4	24.4	*	*	*	5.1	*	*	*	23.9	38.3	68.1	53.2
5	38.2	14.4	32.6	23.5	41.6	14.1	36.2	25.15	3.3	12.6	20.4	16.5
6	11.8	64.4	135	64.4	2.6	92.8	78.2	85.5	4.9	20.7	45.9	33.3
7	18.1	97.1	78.1	78.1	10	23.7	54.6	39.15	4.6	10.3	9.19	9.8
8	10.2	46.2	151	46.2	6.6	62.1	71.9	67	11.5	10.7	16.5	13.6
9	14.6	67.4	33.2	50.3	2.0	23	68.6	45.8	7.35	30.3	14.8	22.6
10	12.4	36.3	*	36.3	1.9	52	76.6	64.3	5.41	18.3	10.7	14.5
11	9.9	71.2	46.5	46.5	2.9	20.9	52.6	36.8	7.9	29.6	9.21	19.4
12	14.7	37.3	21.3	29.3	4.1	22.7	*	22.7	11	12.6	32.6	22.6
13	8.0	*	*	*	2.6	34.1	*	34.1	6.2	20.1	7.93	14.0
14	10.9	44.7	*	44.7	2.6	39	32.8	35.9	14.5	22.1	13.4	17.8
15	11.7	20.2	46.4	33.3	5.7	32	24.5	28.3	13.4	6.7	18.8	12.8
16	19.8	36.5	22.9	29.7	8.5	33	*	33	5.6	7.8	13.6	10.7
17	13.4	*	*	*	6.2	31.1	15.5	23.3	3.1	9.6	7.3	8.5
18	13.6	*	31.2	31.2	4.6	*	*	*	3.4	*	*	*

Table B.5 Ca values of three types of studied water with pipe sets 1, unit mg/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	21.4	21.5	20.4	21.0	6.0	8.4	9.2	8.8	*	*	*	*
2	22.6	21.2	21.9	21.6	6.8	6.2	6.9	6.6	53.7	53.3	52.6	53.0
3	20.9	22.4	22.0	22.2	5.7	6.6	7.0	6.8	51.5	53.9	52.9	53.4
4	24.5	22.0	22.1	22.1	9.2	5.5	6.0	5.7	46.8	41.6	44.9	43.3
5	22.6	23.3	23.6	23.5	5.9	6.6	6.8	6.7	42.6	43.2	44.2	43.7
6	38.4	21.6	21.0	21.3	14.7	14.1	14.4	14.3	44.1	44.5	45.6	45.1
7	21.3	21.4	21.5	21.5	14.5	14.8	14.7	14.8	33.3	37.9	36.4	37.2
8	21.6	21.4	21.2	21.3	5.9	7.5	7.4	7.5	*	*	*	*
9	24.9	24.3	23.9	24.1	17.2	15.5	15.5	15.5	56.0	55.0	54.7	54.9
10	22.7	21.9	21.5	21.7	15.4	15.0	15.1	15.1	56.8	51.1	52.6	51.9
11	21.5	20.8	21.2	21.0	6.0	7.6	7.6	7.6	55.5	54.6	54.1	54.4
12	21.7	21.8	21.9	21.9	5.9	6.5	6.8	6.7	54.9	55.9	55.7	55.8
13	22.5	23.0	22.9	23.0	6.9	7.0	7.1	7.0	39.7	40.9	39.2	40.1
14	22.8	20.9	21.8	21.4	6.7	6.6	6.2	6.4	34.7	34.9	36.7	35.8
15	21.3	21.0	20.7	20.9	6.2	6.4	6.2	6.3	35.2	33.5	32.5	33.0
16	20.6	21.6	21.3	21.4	6.1	6.2	6.3	6.2	37.0	36.5	37.4	37.0
17	22.8	21.5	22.1	21.8	6.0	6.4	6.6	6.5	38.6	36.1	37.8	37.0
18	27.0	23.3	26.6	25.0	8.1	7.3	7.2	7.3	37.8	38.2	38.6	38.4

Table B.6 Ca values of three types of studied water with pipe sets 2, unit mg/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	20.9	21.7	22.3	22.0	5.7	8.4	6.1	7.2	51.5	52.5	52.0	*
2	24.5	22.5	22.1	22.3	9.2	5.8	6.0	5.9	46.8	43.5	41.4	42.5
3	22.6	23.8	23.4	23.6	5.9	6.3	6.4	6.3	42.6	42.5	43.0	42.8
4	38.4	21.1	21.4	21.3	14.7	14.6	14.7	14.7	44.1	44.7	43.5	44.1
5	21.3	21.1	20.5	20.8	14.5	14.3	14.2	14.3	33.3	34.0	33.3	33.7
6	21.6	21.4	20.8	21.1	5.9	6.6	6.6	6.6	*	*	*	*
7	24.9	24.7	24.4	24.6	17.2	16.3	16.0	16.2	56.0	56.0	54.9	55.5
8	22.7	21.5	21.9	21.7	15.4	15.4	15.0	15.2	56.8	54.0	53.7	53.9
9	21.5	21.6	20.9	21.3	6.0	6.2	6.2	6.2	55.5	54.9	54.6	54.8
10	21.7	22.1	21.7	21.9	5.9	6.5	6.4	6.4	54.9	56.0	55.7	55.9
11	22.5	22.7	23.0	22.9	6.9	6.9	6.8	6.9	39.7	40.5	39.8	40.2
12	22.8	21.9	21.8	21.9	6.7	6.4	6.4	6.4	34.7	32.8	33.6	33.2
13	21.3	21.2	21.3	21.3	6.2	6.2	6.1	6.2	35.2	34.4	34.2	34.3
14	20.6	20.1	20.2	20.2	6.1	5.8	5.6	5.7	37.0	37.8	38.0	37.9
15	22.8	22.1	21.9	22.0	6.0	6.0	5.9	6.0	38.6	38.0	37.4	37.7
16	27.0	26.5	26.7	26.6	8.1	7.9	7.9	7.9	37.8	38.0	37.7	37.8
17	25.1	24.2	*	24.2	7.5	7.2	24.2	7.2	48.9	47.1	47.4	47.2
18	24.8	24.6	24.1	24.4	7.2	7.1	7.2	7.2	47.7	47.1	47.0	47.1

Table B.7 Al values of three types of studied water with pipe sets 1, unit μg/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	1.15	2.82	6.62	4.72	1.23	13.01	12.76	12.88	1.17	34.93	18.56	26.74
2	5.35	23.62	8.39	16.00	2.89	11.96	18.83	15.40	1.45	9.35	16.48	12.91
3	4.07	11.17	15.07	13.12	3.18	8.06	21.33	14.69	1.79	11.29	5.36	8.33
4	3.54	4.50	6.01	5.25	1.78	25.76	27.03	26.40	1.60	4.67	4.63	4.65
5	3.39	2.18	3.25	2.71	1.92	8.59	3.74	6.16	2.68	4.10	3.23	3.67
6	3.23	1.72	2.22	1.97	2.15	4.69	5.31	5.00	2.59	2.94	1.73	2.34
7	2.82	1.15	3.67	2.41	2.10	7.18	3.87	5.52	6.44	5.67	10.53	8.10
8	4.02	2.11	4.65	3.38	1.04	2.35	6.06	4.20	2.09	4.24	1.75	2.99
9	2.70	2.66	4.90	3.78	4.64	11.94	22.23	17.09	0.29	1.95	0.53	1.24
10	1.87	5.01	2.12	3.57	1.36	1.30	1.96	1.63	0.73	6.32	0.82	3.57
11	2.47	1.22	2.25	1.74	2.62	8.65	4.37	6.51	0.74	1.60	0.74	1.17
12	2.35	1.93	2.04	1.99	0.91	1.75	1.52	1.63	0.62	1.79	0.40	1.09
13	2.45	3.93	2.27	3.10	0.88	1.41	1.11	1.26	1.09	2.92	1.39	2.15
14	2.34	*	3.37	3.37	1.01	*	*	*	11.28	4.53	2.25	3.39
15	2.26	*	*	*	0.91	4.60	*	4.60	3.54	2.11	1.97	2.04
16	2.42	*	3.75	3.75	0.80	*	5.07	5.07	10.61	*	5.28	5.28
17	3.53	3.05	2.93	2.99	6.66	5.58	5.46	5.52	9.47	*	5.67	5.67
18	3.16	*	*	*	3.60	*	4.76	4.76	1.95	4.31	3.13	3.72

Table B.8 Al values of three types of studied water with pipe sets 2, unit µg/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	20.9	21.7	22.3	22.0	5.7	8.4	6.1	7.2	51.5	52.5	52.0	52.3
2	24.5	22.5	22.1	22.3	9.2	5.8	6.0	5.9	46.8	43.5	41.4	42.5
3	22.6	23.8	23.4	23.6	5.9	6.3	6.4	6.3	42.6	42.5	43.0	42.8
4	38.4	21.1	21.4	21.3	14.7	14.6	14.7	14.7	44.1	44.7	43.5	44.1
5	21.3	21.1	20.5	20.8	14.5	14.3	14.2	14.3	33.3	34.0	33.3	33.7
6	21.6	21.4	20.8	21.1	5.9	6.6	6.6	6.6	*	*	*	*
7	24.9	24.7	24.4	24.6	17.2	16.3	16.0	16.2	56.0	56.0	54.9	55.5
8	22.7	21.5	21.9	21.7	15.4	15.4	15.0	15.2	56.8	54.0	53.7	53.9
9	21.5	21.6	20.9	21.3	6.0	6.2	6.2	6.2	55.5	54.9	54.6	54.8
10	21.7	22.1	21.7	21.9	5.9	6.5	6.4	6.4	54.9	56.0	55.7	55.9
11	22.5	22.7	23.0	22.9	6.9	6.9	6.8	6.9	39.7	40.5	39.8	40.2
12	22.8	21.9	21.8	21.9	6.7	6.4	6.4	6.4	34.7	32.8	33.6	33.2
13	21.3	21.2	21.3	21.3	6.2	6.2	6.1	6.2	35.2	34.4	34.2	34.3
14	20.6	20.1	20.2	20.2	6.1	5.8	5.6	5.7	37.0	37.8	38.0	37.9
15	22.8	22.1	21.9	22.0	6.0	6.0	5.9	6.0	38.6	38.0	37.4	37.7
16	27.0	26.5	26.7	26.6	8.1	7.9	7.9	7.9	37.8	38.0	37.7	37.8
17	25.1	24.2	7.3	24.2	7.5	7.2	24.2	7.2	48.9	47.1	47.4	47.2
18	24.8	24.6	24.1	24.4	7.2	7.1	7.2	7.2	47.7	47.1	47.0	47.1

Table B.9 Fe values of three types of studied water with pipe sets 1 unit mg/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	0.02	0.03	0.05	0.04	0.01	0.10	0.23	0.17	0.01	0.37	0.15	0.26
2	0.02	*	0.03	0.03	0.01	0.04	0.56	0.30	0.00	0.10	0.13	0.11
3	0.01	0.07	0.09	0.08	0.01	0.05	0.50	0.27	0.00	0.12	0.03	0.07
4	0.01	0.03	0.02	0.02	0.03	*	0.35	0.35	0.00	0.05	0.02	0.04
5	0.01	0.04	0.02	0.03	0.01	0.17	0.08	0.12	0.00	0.04	0.02	0.03
6	0.00	0.02	0.01	0.02	0.01	0.08	0.14	0.11	0.01	0.05	0.01	0.03
7	0.01	0.01	0.02	0.02	0.01	0.04	0.04	0.04	0.00	0.04	0.05	0.05
8	0.01	0.02	0.04	0.03	0.01	0.05	0.13	0.09	0.01	0.04	0.01	0.03
9	0.01	0.02	0.01	0.02	0.01	0.07	0.21	0.14	0.00	0.01	0.00	0.01
10	0.01	0.03	0.01	0.02	0.01	0.01	0.03	0.02	0.00	0.08	0.00	0.04
11	0.01	0.01	0.01	0.01	0.00	0.06	0.05	0.05	0.00	0.00	0.00	0.00
12	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00
13	0.01	0.02	0.01	0.02	0.00	0.01	0.02	0.02	0.00	0.06	0.01	0.03
14	0.01	*	0.02	0.02	0.01	*	*	*	0.01	0.01	0.00	0.01
15	0.01	*	*	*	0.00	0.03	*	0.03	0.00	0.01	0.01	0.01
16	0.01	*	0.02	0.02	0.01	0.01	0.03	0.02	0.01	*	0.03	0.03
17	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.00	*	0.02	0.02
18	0.01	*	0.03	0.03	0.01	0.04	0.04	0.04	0.00	0.04	0.02	0.03

Table B.10 Fe values of three types of studied water with pipe sets 2 ,unit mg/L

Week	KA In	KA Out P1	KA Out P2	Out-KA	MX In	MX Out P1	MX Out P2	Out-MX	RE In	RE Out P1	RE Out P2	Out-RE
1	0.01	0.11	0.01	0.06	0.007	0.063	0.069	0.07	0.00	0.10	0.10	0.10
2	0.01	0.05	*	0.05	0.03	0.05	0.05	0.05	0.00	0.02	0.02	0.02
3	0.01	0.05	0.06	0.05	0.01	0.04	0.10	0.07	0.00	0.04	0.05	0.04
4	0.00	0.06	0.07	0.06	0.01	0.02	0.07	0.10	0.01	0.02	0.02	0.02
5	0.01	0.02	0.06	0.04	0.01	0.13	0.46	0.29	0.00	0.07	0.02	0.04
6	0.01	0.05	0.02	0.04	0.01	0.07	0.05	0.06	0.01	0.03	0.02	0.03
7	0.01	0.05	0.07	0.06	0.01	0.07	*	0.07	0.00	0.04	0.07	0.06
8	0.01	0.04	0.05	0.05	0.01	0.04	0.08	0.06	0.00	0.01	0.02	0.01
9	0.01	0.04	*	0.04	0.00	0.10	0.33	0.22	0.00	0.10	0.07	0.09
10	0.01	0.06	0.06	0.06	0.01	0.04	0.05	0.04	0.00	0.02	0.03	0.02
11	0.01	0.01	0.04	0.02	0.00	0.02	0.21	0.02	0.00	0.02	0.01	0.02
12	0.01	0.20	0.37	*	0.01	0.17	0.05	0.05	0.01	0.02	0.01	0.01
13	0.01	0.14	0.26	*	0.00	0.03	0.04	0.03	0.00	0.02	0.02	0.02
14	0.01	*	*	0.00	0.01	0.32	0.13	*	0.01	0.04	0.09	0.04
15	0.01	0.05	0.07	0.06	0.03	0.15	0.10	*	0.00	0.02	0.02	0.02
16	0.01	0.06	0.08	0.07	0.01	0.08	0.03	0.05	0.00	0.03	0.02	0.02
17	0.01	0.04	0.09	0.07	0.01	0.13	0.08	*	0.00	0.22	0.03	0.03
18	0.01	0.03	0.05	0.04	0.01	0.07	0.01	0.04	0.00	0.03	0.02	0.02

C) Pipe study

Table C.1 Harbored material associated with pipe sets 1 before study

	Pipe 1	Pipe 2	Pipe 3	Unit
Length	20	15	24	cm
Aeromonas	1240	180	1010	CFU/ 100ml
ATP	1330	542	805	ng/L
Al	210.0	188.4	635.4	µg/L
As	0.7	0.5	1.0	µg/L
Ca	8.1	8.0	9.5	mg/L
Fe	1.7	2.7	2.2	mg/L
Mn	0.1	0.1	0.4	mg/L

Table C.2 Harbored material associated with pipe sets 2 before study

	Pipe 1	Pipe 2	Pipe 3	Unit
Length	33	28	30	cm
Aeromonas	0	20	10	CFU/ 100ml
ATP	223	192	217	ng/L
Al	229.3	168.8	222.1	µg/L
As	0.4	0.4	0.4	µg/L
Ca	6.9	8.6	7.6	mg/L
Fe	1.3	1.1	1.4	mg/L
Mn	0.0	0.0	0.0	mg/L

Table C.3 Harbored material associated with pipe sets 1 after study

Pipe number	Length	Feed water	ATP	*Aeromonas*	Al	As	Ca	Fe	Mn
	cm		ng/L	CFU/100ml	µg/L	µg/L	mg/L	mg/L	mg/L
1	23	KA	164	0	90.9	0.2	0.9	*	0.01
2	30	KA	199	0	265.4	0.6	0.9	0.5	0.01
3	27	KA	160	0	93.8	0.1	0.4	*	0.01
4	29	KA	188	0	91.6	0.2	0.4	*	0.01
5	29	MX	153	0	134.9	1.4	0.6	0.4	0.01
6	30	MX	153	0	202.5	1.4	0.6	0.4	0.02
7	29	MX	149	0	122.8	1.6	0.6	0.5	0.02
8	29	MX	252	0	175.8	4.2	0.8	1.0	0.03
9	29	RE	150	0	102.1	0.9	1.5	0.3	0.02
10	28.2	RE	43	0	112.4	0.8	1.3	0.2	0.01
11	28	RE	125	0	107.8	0.6	1.4	0.3	0.01
12	30	RE	244	0	190.4	0.9	1.8	0.4	0.03

Table C.4 Harbored material associated with pipe sets 1 after study

Pipe number	Length	Feed water	ATP	*Aeromonas*	Al	As	Ca	Fe	Mn
	cm		ng/L	CFU/100ml	µg/L	µg/L	mg/L	mg/L	mg/L
1	26	KA	*	0	26.3	0.1	0.3	0.1	0.01
2	26	KA	177	0	44.2	0.1	0.4	0.3	0.01
3	26	KA	*	0	25.0	0.1	0.3	0.1	0.01
4	26	KA	133	0	30.3	0.1	0.3	0.1	0.01
5	26	MX	160	0	28.0	0.3	0.2	0.1	0.01
6	26	MX	*	0	60.3	0.3	0.2	0.1	0.00
7	26	MX	147	0	39.1	0.5	0.2	0.2	0.01
8	27	MX	162	0	33.8	0.4	0.2	0.1	0.01
9	29	RE	83	0	35.3	0.6	0.6	0.1	0.01
10	26	RE	95	0	28.4	0.6	0.5	0.1	0.01
11	26	RE	59	0	38.5	0.6	0.7	0.2	0.01
12	26	RE	87	0	81.7	0.6	0.7	0.2	0.01