Water age performance functions for water supply systems

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Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

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Resumo

A qualidade da água nos sistemas de distribuição de água sofre diversas alterações ao longo do tempo que a água permanece nos mesmos. Desde a origem até à torneira do consumidor ocorrem diversas reações químicas, crescimento microbiológico e formação e deposição de sedimentos. Todos estes processos, que podem originar não conformidades da qualidade da água e/ou colocar em risco a saude pública. Por essa razão, o parâmetro “idade da água” é utilizado como indicador da qualidade da água, apesar de não existirem à data, valores de referência que o permitam avaliar.

O objetivo principal da presente tese é desenvolver uma curva de desempenho que permita avaliar a idade da água num sistema de distribuição. Analisaram-se neste sentido dois sistemas de distribuição de agua, determinaram-se as correlações entre a idade da agua e a qualidade da agua que em conjunto com a curva de desempenho de qualidade da água gerada a partir da legislação e indicações da Organização Mundial de Saúde permitiram establecer as curvas de desempenho de idade da agua.

Foram observadas relações lineares entre a idade da água e o cloro residual. As curvas de desempenho encontradas variam de sistema para sistema e consoante a época do ano considerada, consequentemente desaconselha-se o uso de funções de desempenho universais, sendo que estas devem ser desenvolvidas para o caso particular de cada sistema. O uso de funções de desempenho mostrou ser útil na definição de objectivos e como metodología para avaliar os sistemas relativamente a cenários de operação múltiplos.

Palavras Chave: Qualidade da agua, cloro livre, EPANET, idade da agua, curva de desempenho, sistemas de distribuição de água.

Abstract:

The water quality in the water distribution systems undergoes several changes over the time that the water remains inside them. From the source to the consumer tap, there are several chemical reactions, microbiological growth and sediment formation and deposition. All of these processes, which can cause non-conformities in water quality and/or put public health at risk. For this reason, the parameter "water age" is used as an indicator of water quality, although there are no reference values at the time being that allow it to be evaluated.

The main objective of this thesis is to develop a performance curve that allows to assess the age of the water in a distribution system. In this sense, two water distribution systems were analyzed, determining the correlations between the age of the water and the quality of the water that together with the water quality performance curve generated from the legislation and guidelines of the World Health Organization allowed to establish water age performance curves.

Linear relationships were observed between water age and free chlorine. The performance curves found vary from system to system and depending on the time of year considered, consequently the use of universal performance functions is discouraged, and these should be developed for the particular case of each system. The use of performance functions has proved to be useful in defining objectives and as a methodology for evaluating systems against multiple operating scenarios.

Keywords: Water quality, free chlorine, EPANET, water age, performance curve, water distribution systems.

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ACRONYMS AND ABBREVIATIONS

DBP – Disinfection By-Products

DCI – Ductile Cast Iron

DMA – District Metered Areas

EA – Evolutionary Algorythm

EPS – Extended Period Simulation

HPC – Heterotrophic Plate Counts

mASL – Meters Above average Sea Level

PI – Performance Index

PVC – Polyvinyl Chloride

SOM – Self-Organizing Map

WA – Water Age

WDS – Water Distribution System

WHO – World Health Organization

WQ – Water Quality

WSS – Water Supply System

1 INTRODUCTION

1.1 Context

Water age, or residence time, has been associated to water quality deterioration within the distribution systems. Defined as the time it takes for the water to travel through the systems, from the source to the tap, water age is also the time available for a number of chemical and microbiological reactions to take place. These reactions lead to disinfectant residual depletion, carcinogenic disinfection by-products formation and microbial regrowth, among others. However, water age is barely included in the water distribution systems (WDS) performance assessment or optimization, mostly because there are no reference values for this parameter and only a few performance functions were found in the literature.

Water age can vary significantly within a given system and from one system to the other. It is primarily controlled by the system design, water demands and operating conditions. While some of these factors can be somewhat controlled by the water utilities, some operational measures have proven to be effective in preventing water stagnation and decreasing water age in the systems, such as re-routing water flows by changing valve status.

Nonetheless, the effect of water age on water quality depends on many factors, namely the amount and type of organics in the water, the pH, the temperature as well as the pipes materials and its conditions. Thus, while water may remain within a system for a long time (days to weeks) without compromising water quality, in other systems, water ages of only a few days can have a negative effect on water quality. This has hindered the determination of reference values.

The establishment of water age performance functions and its inclusion in systems' performance assessment would enable comparison of the systems' performance regarding water quality in different operating scenarios and help in setting optimisation goals.

1.2 Objectives and methodology

The objective of this thesis is to develop performance functions for the water age parameter that can be used to include water quality in the performance assessment of the WDS.

In the process the following specific objectives are to be pursued:

(i) to identify the water quality parameters that best relate to water age,

(ii) to establish relationships between the water age and the quality parameter(s),

(iii) to develop water age performance curves based on the observed correlations,

(iv) to compare the developed functions with the existing ones

(v) to demonstrate the usefulness of the performance functions for setting water age goals and to assess water quality performance in real systems

1.3 Thesis outline

This study was structured into seven (7) chapters, the first of which is an introduction describing the objectives and structure of this Thesis. In Chapter 2, the literature review regarding the previous studies on water age and performance functions is presented. A brief overview of causes and consequences of increased water age in WDS is also discussed. Chapter 3 includes the description of the methodology followed in the development of the Thesis. Chapter 4 includes the description of the case study 1 and of the data collected. Chapter 5 includes the description of the case study 2 and of the data collected. In Chapter 6, the most important findings of this research are presented and discussed. Chapter 7 summarizes the conclusions of the Thesis and points directions for future investigations. The cited references are presented at the end of the document, along with the annexes, where data used in this work is compiled.

2 LITERATURE REVIEW

In this chapter, a literature review on water age in distribution systems is presented. It starts by introducing the concept and explaining the reasons for high water age in WDS and its consequences. Studies on water age and its relationship with water quality are described as well as existing water age performance curves and optimization studies. The chapter ends with the identification of the current gaps of knowledge.

2.1 Water Age

Water age, or water residence time, is defined as the time it takes for the water to travel within the distribution systems from the source to the consumption locations. It depends on the pipes' lengths and diameters as well as on the water demand at the consumption nodes. Water age varies within a water distribution system (WDS) pipes, depending on their relative location in relation to the source and on the water demand of the downstream nodes. The water flow paths, determined by the distribution systems layout, valve settings and pump operation, also affect the water residence time within the system.

The water age at a given location in a WDS cannot be directly measured but inferred from a tracer test or computed using software for WDS simulation (AWWA, 2002) such as the widely known open source EPANET (Rossman, 2000). Ranges of water age values are quite variable from system to system, some typical values presented in AWWA (2002) can be found in Table 2.1.

Table 2.1– Summary of water age evaluations (AWWA, 2002)

Population served (*)	Length of Water Mains (km)	Range of water ages within system (Days)	Method of determination
750.000*	1770	<1-3	Fluoride Tracer
800.000	4425	3-7+	Hydraulic model
87.900*	576	>16	Chloramine conversion
24.000	138	12-24	Hydraulic model

* Estimated by using 2.5 multiplier on number of customers served.

Water age values of a few hours to several days are possible, even in the same WDS, due to daily and seasonal variations in water demand. Higher water ages are tendentially found on smaller WDS since it is more common to find oversized pipes in relation to the base demand of consumers and, consequently, lower flow velocities.

2.2 Causes and consequences of increased water age in WDS

Water age in a WDS is mainly a fuction of the WDS size, water demand and the system's storage capacity. Regarding the size, it is a common practice to size pipelines for water demands that will occur based on population growth forecasts for a 20/30 years' time span. Building distribution facilities that are large enough to accommodate these future demands, increase water age in the first years of operation as the storage volumes in the tanks and in the pipe systems, may be too large relative to the current daily demand. Particularly in countries like Portugal and most other european countries, where this population growth has not been verified, the WDS becomes oversized, and the water age is much higher than it would be in smaller capacity systems.

Changes in water demands or water use patterns also change the water residence time. For instance, the relocation of a large consumer, the integration of surrounding systems or the conection of new urban developments to the existing system, can have a significant impact on water age. Water demand variations also occur on a daily basis and usually become null during the night period, promoting water stagnation within the systems. Consequently, water age is highest in the early morning hours due to storage in the distribution system and is the lowest in the late evening. Daily demand patterns can also be very diferent in a WDS whether the predominant demands are of domestic users or industrial users, with consequences in daily variations of the water age.

Another aspect is the effect of firefighting flow requirements on WDS capacity. The high instant flows required for this use often require oversized pipes in relation to the water demand. The Portuguese regulations (Decreto Regulamentar 23/95), demands the use of minimum size pipes to comply with the fire fighting requirements which leads to an oversizing of pipes regarding the demand and consequently higher water ages in the WDS. The requirement for minimum pipe sizes in neighbourhood distribution mains (e.g., 150 mm pipes in loops and 200 mm in dead ends) (AWWA, 2008), where smaller pipes would be enough for the supply of potable water to domestic users, is one of the most important causes of increased residence time in a WDS. High storage capacity, for firefighting or other emergency situations, also increase water age in WDS.

In adition to design constraints, the operation conditions of the WDS can also impact flow direction and velocity, and thus water age, particularly valve operation (opening/closing distribution system valves) and changing pump operation settings. Storage tanks are often operated at high water levels, resulting in stagnation of the water and increased ageing.

While the water remains in the systems, many chemical and microbiological reactions take place, resulting in water quality changes. These reactions are mostly slow and their extent and importance increase with increasing water age. The water quality problems that can be caused or worsened by the increasing retention time inside the distribution network can be summarized in three linked categories: chemical, biological and physical issues.

The chemical issues are mainly those related with the reactions that occur between natural organic matter in the water and the disinfectants used in water treatment, like chlorine. These reactions will lead to the formation of disinfection by-products (DBP) and to disinfectant residual decay. Chlorine has been the main disinfectant used in potable water for over 100 years. Other important disinfectants used are chlorine dioxide, chloramines and ozone. All these substances reduce microbial growth in drinking water but create new potential risks by the formation of the potentially carcinogenic DBP’s. Each system’s water has a different potential for the formation of DBP’s, as a function of several chemical and physical characteristics, including nature and amount of organic matter, pH, temperature and contact time. As water age increases, the potential for DBP formation also increases. The most prevailing DBP’s identified in water are trihalomethanes (THM), including chloroform, dibromochloromethane, dichlorobromomethane and bromoform, haloacetic acids (HAA), which are slightly less prevalent than the THM, and haloacetaldehydes including chloroacetaldehyde, dichloroacetaldehyde and mono hydrate trichloroacetaldehyde. Also part of the DBP group are formaldehydes, haloacetones, haloacetronitriles, chloropicrin, cyanogen chloride, chlorophenols and dichloromethyl/furanone (AWWA, 2018).

Microorganisms remaining in the water after treatment can grow in a WDS if nutrients are available, particularly in waters with a temperature above 15°C, and may lead to the formation of biofilms on internal surfaces of pipes and storage tanks. Biofilms typically contain numerous heterotrophic bacteria, fungi and protozoa and can host pathogenic organisms, i.e., living organisms able to cause disease to humans (Ainsworth & WHO, 2004). Microbiological growth can also lead to taste and odour changes, particularly in chloraminated systems.

The physical issues are mostly related with temperature variations and loose deposits build-up. Higher water temperatures occurring during summer seasons can also be a factor of DBPs increase as the chemical reactions proceed faster and go further at higher temperatures. Higher water temperatures consequently cause a higher chlorine demand, requiring an increased disinfectant dose and resulting in higher DBP formation potential.

There are several indicators that may suggest increased water age that can be monitored to assist on operational activities decision making. These include aesthetic considerations that may be identified by consumers, as well as the results of distribution system monitoring campaigns. The most interesting parameters to be monitored in this regard are: taste, odour, colour, temperature, residual disinfectant, DBP levels and bacterial counts (AWWA, 2011).

In order to reduce water retention times, check valves can be either opened or closed to shorten water paths (Prasad and Walters, 2006). The storage tanks daily turnover rates can also be increased to reduce water ageing in storage facilities. Flushing may also be an important tool to remove stagnant water and loose deposits from the WDS and can be used as a maintenance task at the expense of water loss.

2.3 Determining water age

Water age can be determined by tracer studies and through mathematical modelling of a given WDS, but not measured. Tracer studies on WDS to calculate water age throughout the system are performed by injecting substances like fluoride, sodium chloride, calcium chloride and lithium chloride. The conservative substances are used to determine the time they take to run through the WDS from the point of injection to the point of monitoring and should be measureable on site. Alternatively, in systems with multiple sources with varying water quality characteristics (such as differences in water hardness or conductivity), these natural constituents can be used as the tracer. Tracer tests have been carried out to validate hydraulic models (Rubulis et al., 2010, Monteiro et al, 2016). Considerations of operational aspects and supply quality were taken during the making of these studies.

Mathematical models that represent the hydraulic behaviour of the water inside the WDS can be used to estimate water age in distribution systems. In this regard, user-friendly software like EPANET has been successfully used for this purpose, granted there is a careful calibration of the models, mandatory to generate an accurate prediction of water age and water quality conditions under varying demand scenarios. This calibration is often a considerable time and resources consuming task. Hydraulic models are limited in accurately predicting water age for the following reasons:

Skeletonization: simplification of the real networks may be needed according to software programming limitations. The impact of skeletonization on the accuracy of water age predictions is therefore dependent from system to system. Another aspect of the simplifications of the models, in particular the assumption of complete mixing in the nodes that may not actually occur. EPANET and all simulation software assume that the water age that leaves a junction node is an average of the age of the water that arrives, weighted by the flows. In fact, the water coming out of the nodes may not always follow the complete mixing assumption and be formed by varying age volumes.

Insufficient calibration: Typical calibration looks at a single time step (steady-state simulation) and not the variations occurring in extended period analysis used for water age estimation.

Water Storage Tanks: Tanks are modelled as completely mixed reactors in most models. This typically leads to an underestimation of the water age. EPANET can use four different types of models to characterize mixing within storage tanks: complete mixing, two-compartment mixing, *first-in-first-out* (FIFO) and *last-in-first-out* (LIFO) plug flow. These methods were designed to provide estimates of the mixing characteristics and may lack detail.

Inaccurate total demand or demand allocation: demand misallocation and innacurate total demand result in imprecise water flowrates in the pipes and, thus, in incorrect water age at the nodes.

Errors in model development: Inaccurate valve settings and pump characteristics will limit the accuracy of water age analysis.

Because water age calculations require extended period simulations they result in a more complex hydraulic analysis that can result in inaccuracy increase.

2.4 Water age as a surrogate for water quality

The relationship between water quality and water age has not been extensively studied. Machell and Boxall (2012) tried to determine if there is a discernible link between water age and the associated quality characteristics. The case study was a small UK drinking water distribution network in which no water quality events occurred and only small changes in water quality parameters were evident. The pipe network studied was of a single material and had a consistent demand attributable to serving predominately light industry. Water quality samples were collected from five network locations identified as containing a broad range of calculated water age. The work produced limited evidence of the association between calculated water age and water quality characteristics. Mean age proved a limited association with general water quality, and it was necessary to consider mixing effects, and the maximum age component, to obtain some association, demonstrated by iron, Heterotrophic Plate

Counts (HPC) and chlorine. Neither mean nor maximum-age simulations fully explained the observed patterns of water quality change in a localized area of the network. Reasons for this could include model uncertainty, especially in the diurnal demand patterns, lack of knowledge about the true condition and bacteriological colonization within the pipes, and source water variation. Machell and Boxall (2012) results also highlighted the limitations of the flow/volume-weighted assumption and of the complete mixing at node assumption made in most modeling software. The same authors further attempted to determine a relationship between water age and water quality in distribution networks (Machel and Boxall, 2014), by studying two distinct real WDS. Some association between water age and general water quality measurements was demonstrated, but no specific parameters exhibited ideal relationships. More detailed analysis revealed that most of the water quality parameters exhibited a stronger relationship to the calculated water age when the flow along specific unperturbed flow routes was considered. In this work, the authors developed tentative trends of variable quality and consistency between water quality parameters and water mean age. A dominant feature of many plots is the distinctly different aging / water quality deterioration relation of extremities area and within the pipe routes. The study remarks that water age has been shown to be useful, both for overall network evaluation and for the specifics of network performance. However, as only two networks were studied, the findings are not definitive. It is clear that knowledge of water age alone is not sufficient to describe changes in specific parameters, with many exhibiting behaviour dependent upon interactions with network assets along specific flow routes. Water age does however, seem to offer merit as a catch all parameter to evaluate overall water qualityembracing factors like temperature, chemical composition of water or pipe materials.

Blokker et al. (2016) used self-organising maps (SOM) to identify relationships between water age and water quality that are not discernible using univariate and/or linear analysis methods. For the multi-year datasets (Dutch and UK datasets), the SOM showed that water age and temperature may be treated as independent parameters. It also showed that there is a clear influence of temperature on Aeromonas and HPC at 22ºC. The correlation observed with water age was less apparent, and there was not much added value in considering maximum instead of average modelled water age. Water age as a result of the mathematical modelling tools, is considered an indicator that gathers all system specific degradation of water quality, but seems to be of poor correlation to specific microbial water quality. This is likely due to the need to improve hydraulic models beyond current best practice of assuming a repeating ideal 24 hours average demand pattern and more accurately represent the complex demand driven system dynamics.

In order to optimize water quality in a WDS, a few authors have developed methodologies to minimize water age in the systems. Prasad et al. (2006) demonstrated that it is possible to reduce water age in the WDS by closing valves and rerouting flows. Closing pipes in the network with excess carrying capacity resulted in increasing flow velocities in other pipes. The authors used an evolutionary algorithm to minimize water age in the studied system, without imposing water age goals or limits. The water quality parameters considered were maximum nodal water age, average nodal water age and demand weighted average water age. The use of the average nodal age of water as a water quality measure gave the best overall results.

2.5 Performance functions

Given the observed relationships between water age and water quality, water age may be a usefull surrogate parameter for assessing the global quality of the water in a WDS without having to analyse a variety of different compounds. In order to assess water age in WDS, performance functions (or penalty curves) have been developed. The first one, by Coelho (1996) is formulated as equation (1):

$$PI = 1 \ if \ water \ age \ \leq 6 \ hours$$

$$PI = -0{,}125 \times (WA - 6) + 1 \ if \ 6 \ hours < Water \ age < 10 \ hours \qquad (1)$$

$$PI = 0 \ \ if \ 10 \ hours \leq Water \ age$$

where PI is performance index and WA is water age (h). In this performance curve, if the water age is equal or less than 6 h, then the performance of the system is optimum and the performance index takes the value of “one” corresponding to optimum performance. If water age is equal to the upper limit of 10 h, the performance index is 0.5, that is, the performance is half of the optimum value and the service quality is on the acceptability threshold. If the water age is higher than the upper limit of 10 h, performance index will be null, which is, a no-service situation. For water age between 6 h and 10 h, performance index decreases linearly, from 1 to 0.5, as the water age increases. The upper and lower limits were set based on a single case study in Edinburgh, UK. The same author proposes the following performance function for chlorine (equation 2):

$$PI = 0 \ if \ Cl \ \leq 0.1 mg/l$$

$$PI = 10 \times (Cl - 0.1) \ if \ 0.1 mg/l < Cl \leq 0.2 mg/l \qquad (2)$$

$$PI = 1 \ if \ 0.2 mg/l < Cl \ \leq 0.5 mg/l$$

$$PI = 1 - 2.5 \times (Cl - 0.5) \ if \ 0.5 mg/l < Cl \leq 0.8 \ mg/l$$

$$PI = 0.25 \ if \ Cl > 0.8 mg/l$$

Later, Tamminen et al. (2008) proposed three water age performance curves for evaluation of water age (Figure 2.1). The functions differ in upper limits for water age, ranging from 30 h to 350 h. These limits were assumed by the authors in order to perform sensitivity analysis. The authors did not provide scientific evidence in which to base such assumptions.

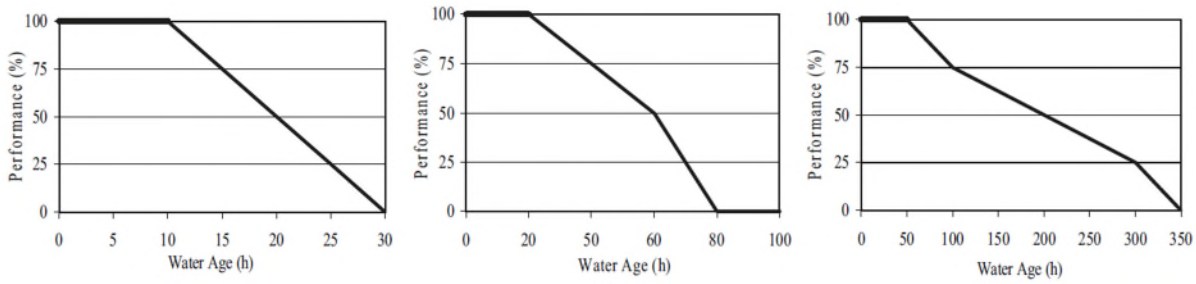


Figure 2.1 Water age penalty curves (Tamminen et al, 2008).

Shokoohi et al. 2017 proposed the following performance function formulated as in equation (3):

$$PI = 1 \; if \; water \; age \; \leq 8 \; hours$$
$$PI = -0{,}025 \times (WA - 8) + 1 \; if \; 8 \; hours < Water \; age < 48 \; hours \qquad (3)$$
$$PI = 0 \; if \; 48 \; hours \leq Water \; age$$

where PI is the performance index and WA is the water age (h). In the proposed performance curve, if the water age is equal to or less than 8 h the performance index is 1 and if the water age is equal or higher than 48 h, the performance index is null. If the water age is between 8 and 48 h, a number between zero and one will be dedicated for its performance considering a linear function. Eight and 48 h are specified based on the results of Srinivasan et al. (2008), who investigated the effects of chlorine and residence time on total bacteria in drinking WDS. Based on experiments carried out in a laboratory pipe looped system, the authors observed that the median percentage of bacteria present in bulk water increased to 7, 37, 58, and 88, as the residence times increased to 8.2, 12, 24, and 48 hours, respectively, in the presence of a 0.2 mg/L chlorine residual.

Recently, Nyirenda and Tanyimboh (2020) formulated a water quality index and relevant sub-indices and applied it to service reservoirs within a water distribution network. Among the sub-indices, chlorine, water age and THM are considered (Figure 2.2)

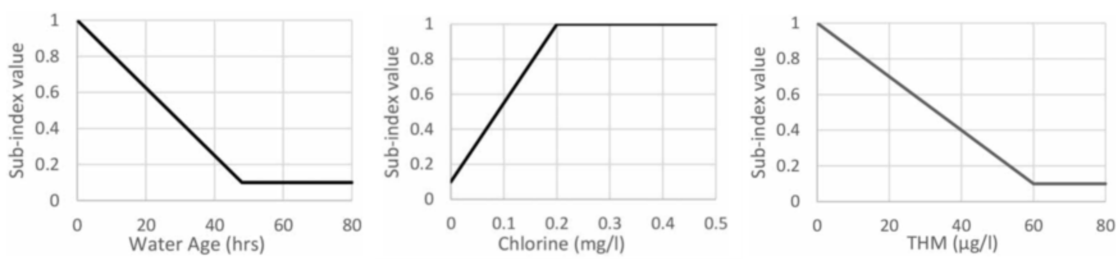


Figure 2.2 Water age, Chlorine and THM sub-index (Nyirenda and Tanyimboh, 2020)

Nyirenda and Tanyimboh (2020) proposed the following water age performance function formulated as in equation (4):

$$P = -0{,}0188 \times WA + 1;\ if\ Water\ age < 48\ h \qquad (4)$$

$$P = 0.1;\ \ if\ Water\ age \geq 48\ h$$

Both Shokoohi et al. (2017) and Nyirenda and Tanyimboh (2020) performance functions seem to converge to a minimum performance when the water age reaches 48 h, while Coelho (1996) suggested a much stricter value of 10 hours. On the other hand, for both Coelho (1996) and Shokoohi et al. (2017) the performance only starts decreasing after a given time (6 and 8 h, respectively) while for Nyirenda and Tanyimboh (2020) the performance is always decreasing until it reaches 0.1 (Figure 2.3).

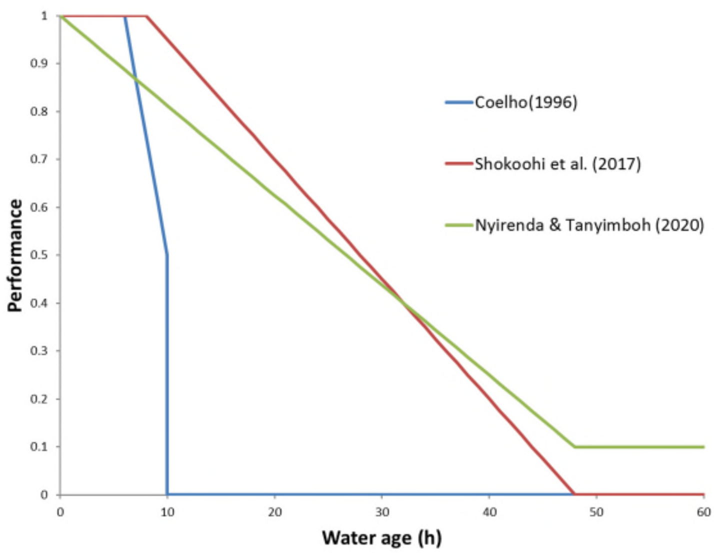


Figure 2.3 Comparison of existing water age performance functions

Regarding chlorine performance functions, the two functions proposed by Coelho (1996) and Nyirenda & Tanyimboh (2020) are very similar (Figure 2.4) with a linear growth from minimum chlorine concentrations until 0.2 mg/L, where the performance index assumes a unit value. However, the application domain of Nyirenda & Tanyimboh (2020) function is smaller (only chlorine concentrations under 0.5 mg/L).

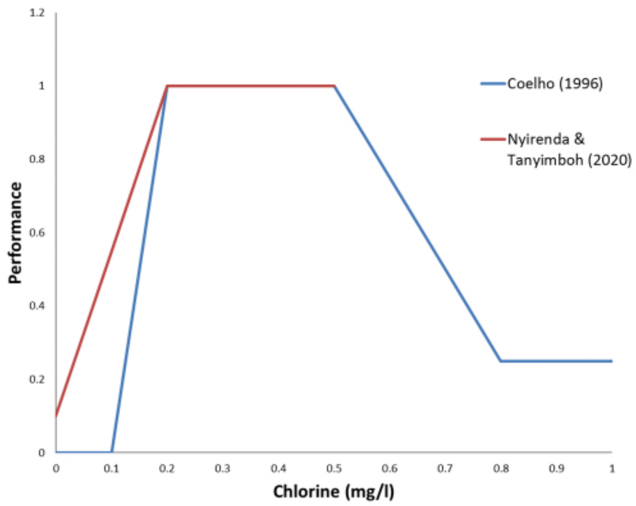


Figure 2.4 Chlorine Performance functions

High values of chlorine concentration have negative effects in water quality, such as increasing the formation of disinfection by-products. However, this has not been considered by Nyirenda & Tanyimboh (2020).

2.6 Gaps of knowledge

The literature review demonstrated that water age can vary widely in a WDS and that no consensus has been reached in specifying what a long or desirable water age range is. The reason for such is probably due to the limited evidence of the correlation between water age and overall water quality in WDS.Thus, the performance functions for water age are scarce and the upper and lower limits are frequently not based on solid scientific knowledge, but on case specific observations or limited results from laboratory experiments. Consequently, optimization problems that consider water quality by incorporating water age have focused on minimizing water age, not aiming at any particular goal. Hence, further studies are necessary on the relationship between water age and water quality that can be the base of water age performance functions.

3 METHODOLOGY

The methodology adopted in this thesis has five main steps (Table 3.1). It is based on full-scale systems data collection and analysis for the development of water age performance functions. The methodology was applied to two cases studies at two diferent conditions, namely winter and summer, given the variability of the water quality at different water temperatures (Blokker et al, 2016).

Table 3.1– Main steps of the adopted methodology

Step		Description
1	Data collection	Collection of existing water quality data and of the hydraulic model (or of data for assembling the model)
2	Data processing	Identify the water quality sampling locations in the hydraulic model. Determining water age at the nodes where water quality samples were taken. Identify which quality parameters can be further used to assess correlation with water age.
3	Correlate water quality and age	Analysis of the relationship between water age and identified water quality parameters
4	Develop chlorine and water age performance functions	Development of a general chlorine performance function and of specific water age performance functions for the case studies
5	Application and testing	Application of existing and developed performance functions to the case studies

3.1 Data Collection

Large datasets were collected from two different water utilities. While case study 1 is an urban system in a major city, including domestic and industrial uses of water, case study 2 is located in a touristic area where water consumption varies seasonaly.

For case study 1, the hydraulic model had to be assembled and calibrated. For that, the collected data included infrastructures inventory, monitoring data (flow and pressure) and billing data, for February and August 2020. For case study 2, the two hydraulic models were provided by the water utility, representative of the summer and winter months of 2018.

On the water quality side, data collected corresponds to the results of the utilities' water quality control program, no specific campaign was carried out for this thesis. The largest time span possible was considered so that it was possible to get a significant array of data, since there are parameters that are analyzed with a lower frequency than others. Collected data included the results of the analysis for non-conservative parameters such as free chlorine, trihalomethanes, *E. coli*, coliform bacteria, and heterotrophic plate counts (HPC) at 22ºC and at 36ºC.

3.2 Data processing

The water sampling locations in the provided datasets were identified by address, without georeference. In order to establish a link with the model, the closest node in the model had to be identified. The nodes where water sampling was carried out for quality monitoring were identified by matching the addresses in the provided water quality data sets and by making use of Google Earth features.

Upon the assembly and calibration of the hydraulic model, water age at the nodes was determined by running extended period simulations (EPS) using small time steps (1 min) The water age time series at the nodes where there is monitoring data were extracted from the model, bearing in mind that there are variations over time that need to be evaluated and that the results on the beginning of the EPS are meaningless, since the model is still balancing. The time series were analysed and the first hours of simulation were discarded since during these periods the hydraulic model is still reaching balance and water that entered the system has not yet reached every part of the network.

The water quality data provided by the water utilities was further analysed in order to identify for which non-conservative parameters there was enough data for a correlation analysis with water age in the next step. Chlorine was identified as the parameter for which more data was available, as it is monitored more frequently.

3.3 Correlation between water age and quality

The relation between the identified water quality parameter (chlorine) and water age at the nodes where chlorine was monitored was assessed by plotting the two variables. Linear regressions were applied and the correlation was assessed by means of the coefficient of determination (R^2). Equations for chlorine concentration prediction as a function of water age were determined.

3.4 Development of water age performance functions

For the development of water age performance functions for the studied systems, a general chlorine performance function was first developed, based on existing curves and current knowledge. The previously obtained correlations between chlorine and water age were used to predict water age at a given chlorine ratio. Then, predicted chlorine concentrations were converted to performance by making use of the chlorine performance function and transformed in water age performance functions.

Distinct performance functions were developed and analysed for the two case studies in Winter and Summer conditions.

3.5 Application of performance curves to assess WDS performance

Water quality performance in the two case studies was assessed by aplying existing and developed water age performance curves. Average water age at each consumption node was converted into a performance index (PI) from 0 to 1. Nodes in the network with no demand, for which water age increases linearly over time were not considered. Then, a global performance index was determined as the average of the indices of all the consumption nodes considered.

One of the developed performance curves was also applied to one of the case studies in two distinct situations comprising the actual operating conditions and an optimized valve status scenario. For each water quality monitoring node and for each situation, a performance index was computed according to the modelled water age. An average global WA index for the network was computed by averaging nodal WA indexes in all the network's nodes and compared for each situation.

4 CASE STUDY 1 | COSTEIRA

In this chapter, case study 1 is presented. It comprises a water distribution system in the centre of Portugal, divided into district metered areas, for which there was no complete and update hydraulic model. The characteristics of the system and the data available and collected for this case study are described herein. The system was studied in two diferent conditions, namely the winter and the summer conditions, in which water demand and water temperature are significantly diferent.

4.1 Case study description

The city of Castelo Branco is supplied gravitically by four tanks, namely Bela Vista, S. Gens, Castelo and Costeira tanks. Case study regards Costeira's subsystem which serves the South-Western part of Castelo Branco (Figure 4.1). The subsystem starts at Costeira's potable water tank, supplies an average of 5 900 clients and has an extension of 116 km, approximately 50 clients/km. Apart from supplying water to the South-Western part of Castelo Branco, this tank also serves two nearby villages (Taberna Seca and Cardosa).

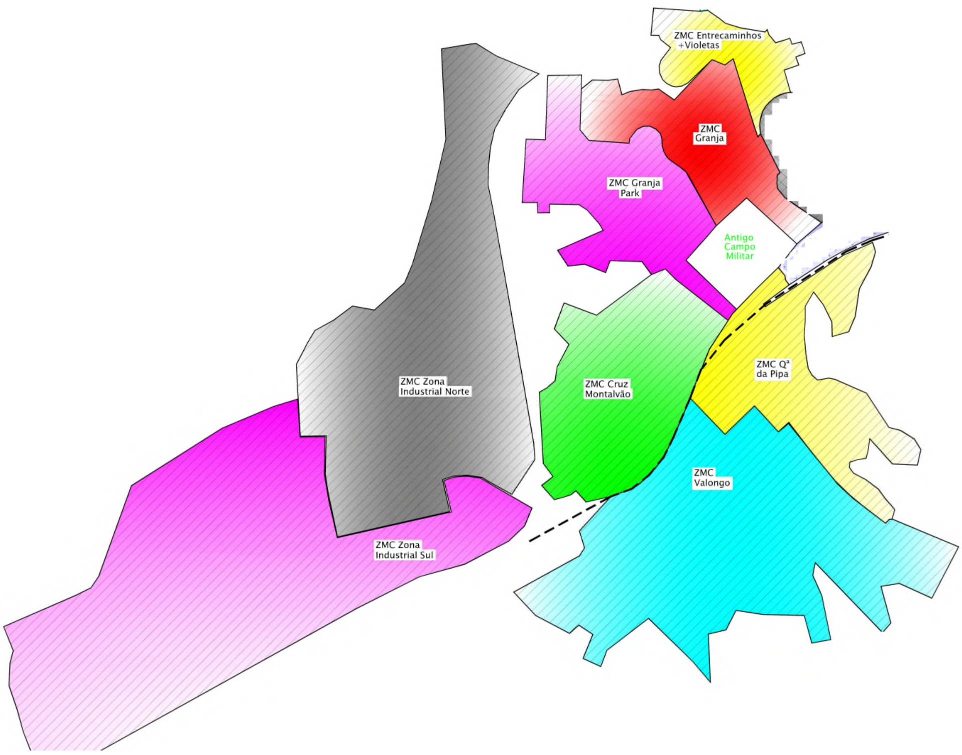


Figure 4.1 District metered areas (DMA) in Costeira's WDS

The tank itself is a double chamber tank with 2,500 m^3 each and the elevation of the bottom slab is placed at +428,0 mASL. The pipe network is composed of approximately 107 km of Polyvinyl Chloride (PVC) pipes (93%) and 9 km of Ductile Cast Iron (DCI) pipes (7%). The network is divided in 12 District Metered Areas (DMA). In Table 4.1 a brief description of the type of water demands in each DMA is presented.

Table 4.1– Demand type distribution by DMA

	Demand type distribution (%)				
DMA	**Household**	**Commercial**	**Public services**	**Industry**	**Green parks**
Entrecaminhos	75%	5%	5%		15%
Violetas	75%	5%	5%		15%
Granja	90%	5%			5%
Granja Park	65%		15%		20%
Cruz de Montalvão	100%				
Quinta da Pipa - Socorro	100%				
Valongo	100%				
Cardosa	100%				
Taberna seca	100%				
Southern Industrial Area				90%	10%
Northern Industrial Area				90%	10%

The yearly total demand supplied in Costeira's system in 2019 was 1 119 429 m^3, while the monthly demand supplied was 96 969 m^3 in February 2020 and 152 906 m^3 in August 2020. The demand in August was approximately 50% higher than in February (Table 4.2), partly because of urban irrigation uses that tend to be very moticeable during the night time.

Table 4.2– Demand distribution by DMA in February and August 2020

	Average daily demand (m^3/h)	
DMA	**February**	**August**
Cardosa	0.92	2.55
Taberna seca	1.31	3.11
Danone	20.55	21.98
Entrecaminhos	12.03	17.80
Granja	16.34	31.18
Granja Parque	13.66	40.56
Pipa Socorro	8.28	9.69
Cruz de montalvão	18.16	19.78
Valongo	6.69	13.69
Violetas	5.32	4.75
Northern Industrial Area	12.49	22.79
Southern Industrial Area	23.47	27.31
Hospital	5.81	5.81

In this system there are two noticeable large consumers, Danone's Plant and the Hospital. Danone is located inside the Southern Industrial Area though it has its own DMA and was treated as a regular DMA on the analysis. The Hospital on the other hand, does not belong to any DMA and, most probably, has a very particular flow pattern due to the existent water tank. Water is supplied at intervals to fill this tank. No records of flow pattern or water level in the hospital's tank are being recorded and for that reason a constant average flow was considered, according to the monthly average demand provided by Serviços Municipalizados de Castelo Branco. A deeper knowledge of the hospital's demand behaviour could lead to a small difference in results but, the fact that it is located directly in a water main close to the source makes its influence in the water age analysis of the rest of the system very small.

The difference in altimetry elevations of the case study 1 area varies between +428 mASL in the tank site and +310 mASL in the lowest point of the terrain in the southern area of the network (Figure 4.2).

Figure 4.2 Costeira's water supply network and elevations contour model (Satellite image source: Google Earth)

The two main distribution pipes consist of a northern PVC line with diameters from 160 to 250 mm and a southern line made of DCI pipes with diameters of 600 mm to 500 mm. The relatively large diameter of the latter one is due to its past use serving the parishes in the South of Castelo Branco's Municipality, a use that has been suspended. The secondary distribution pipes are mainly PVC with diameters from 90 mm to 250 mm (Figure 4.3).

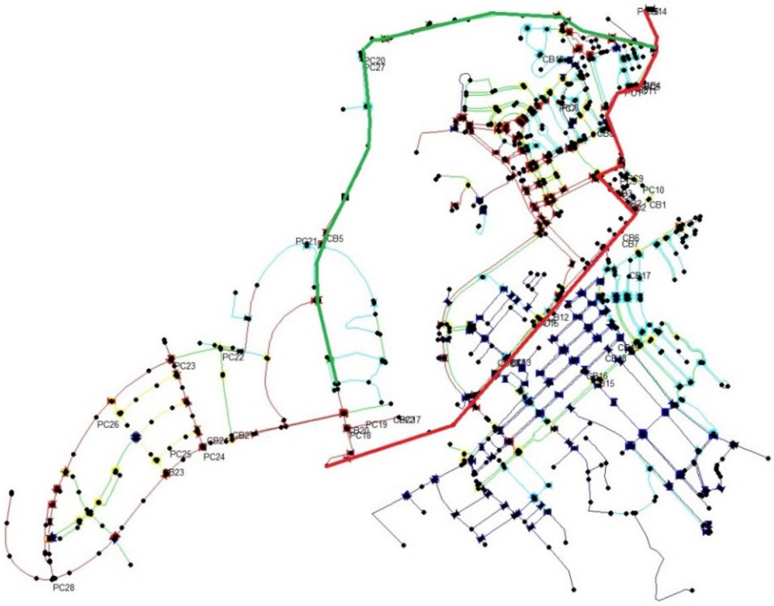


Figure 4.3 Costeira's water supply network mains –Northern line (green) / Southern line (red)

With the concession contract signed in 2007, with the multimunicipal company Águas do Centro, S.A, the Municipality ceased the responsibility for the water abstraction and treatment, keeping only the responsibility of the direct water distribution to consumers. Treated water is therefore supplied to the city's water tanks with a stipulated dose of chlorine.

4.2 Data collection and treatment

For building the hydraulic model and to study correlations between water age and water quality data, a large set of data was supplied by SMAS Castelo Branco, including flow and pressure time series for two distinct periods (winter and summer) and the results from the water quality control program over the last 5 years.

4.2.1 Data for hydraulic model assembling

The software used to build the model was EPANET, a free and open source computer program that performs extended period simulations of the hydraulic and water quality behaviour of pressurized pipe networks (Rossman, 2000).

The inventory of pipe network was supplied in a shape format (.shp) by Serviços Municipalizados de Castelo Branco. The shape format was then converted to CAD format and imported into EPANET (.inp). The resulting EPANET model was then subject to extensive review and processing, with the addition of flow control and pressure reduction valves and corrections to the geometrical definition of the model.

Flow and pressure records, measured every fifteen minutes at the entrance of the DMA's were made available for February and August 2020 by the water utility. The location of these metering installations can be viewed in Figure 4.4.

Figure 4.4 Costeira's subsystem DMA metering locations

At DMA Granja Parque the first two days of August had missing records. At DMA North Industrial Zone, on the 22nd and 23rd of August there was a burst and the entire Industrial Zone had to be supplied through DMA South Industrial Zone. In these cases, the gaps in the time series were filled with data from similar days in the same month.

Adimensional daily demand patterns were obtained for each of the twelve DMAs from flow time series and attributed to the model nodes according to their location. Figure 4.5 and Figure 4.6 present the demand patterns obtained for February and August respectively. There is a noticeable difference in the shape of the patterns comparing the Winter and Summer situation, even though the typical peaks around lunch and dinner occur in both situations in the DMAs where household consumption prevails. During Summer, irrigation demands at night time will have a favourable effect on water age.

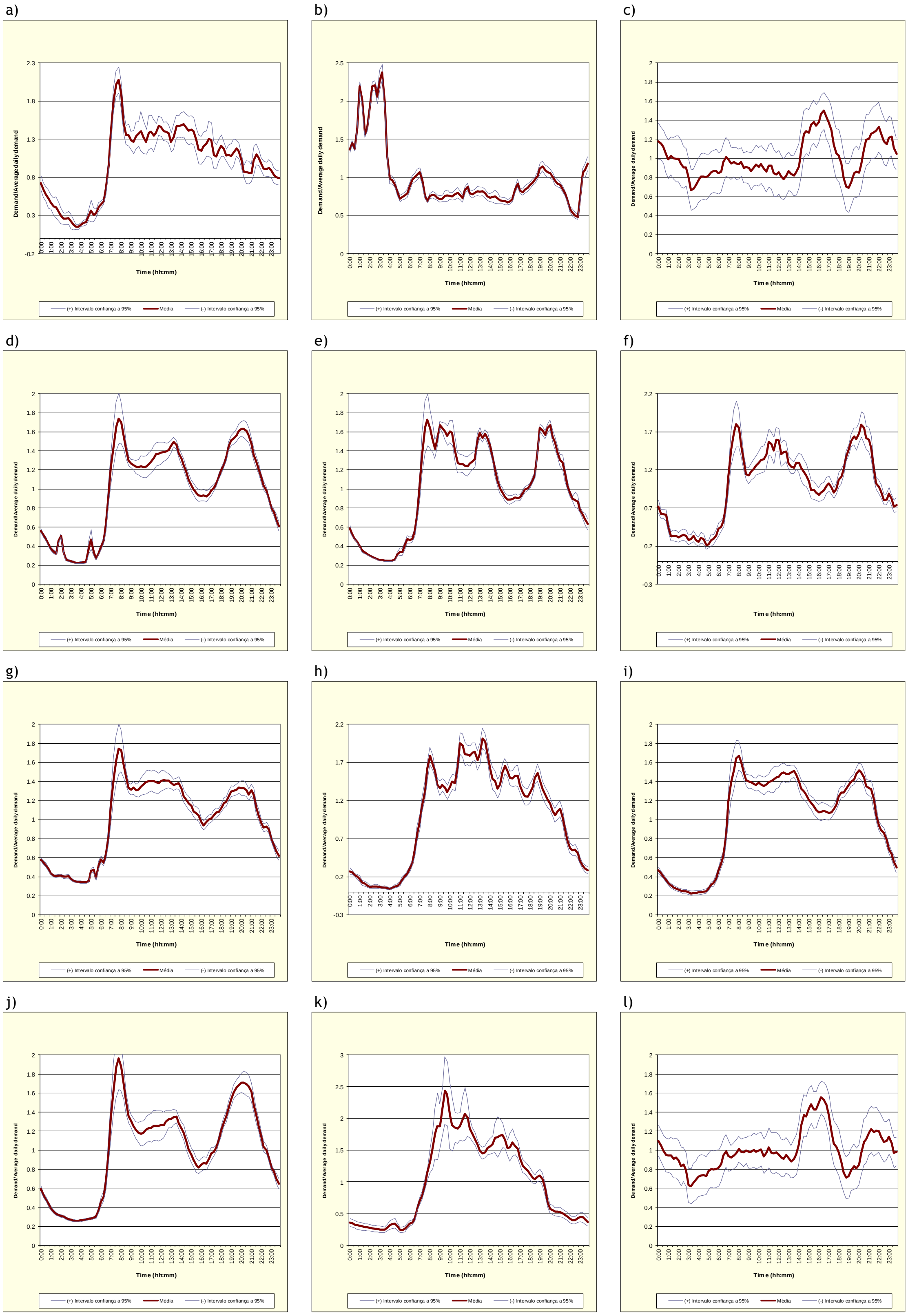


Figure 4.5 Costeira's adimensional (demand/daily average demand) daily demand pattern on February 2020 (red line – average/blue lines – confidence level 95%); a) Cardosas b) Cruz de montalvão c) Danone d) Entrecaminhos e) Granja f) Granja Parque g) Pipa Socorro h) Taberna Seca i) Valongo j) Violetas k) North Industrial Zone l) South Industrial Zone (red lines-average daily; blue lines-confidence level 95%)

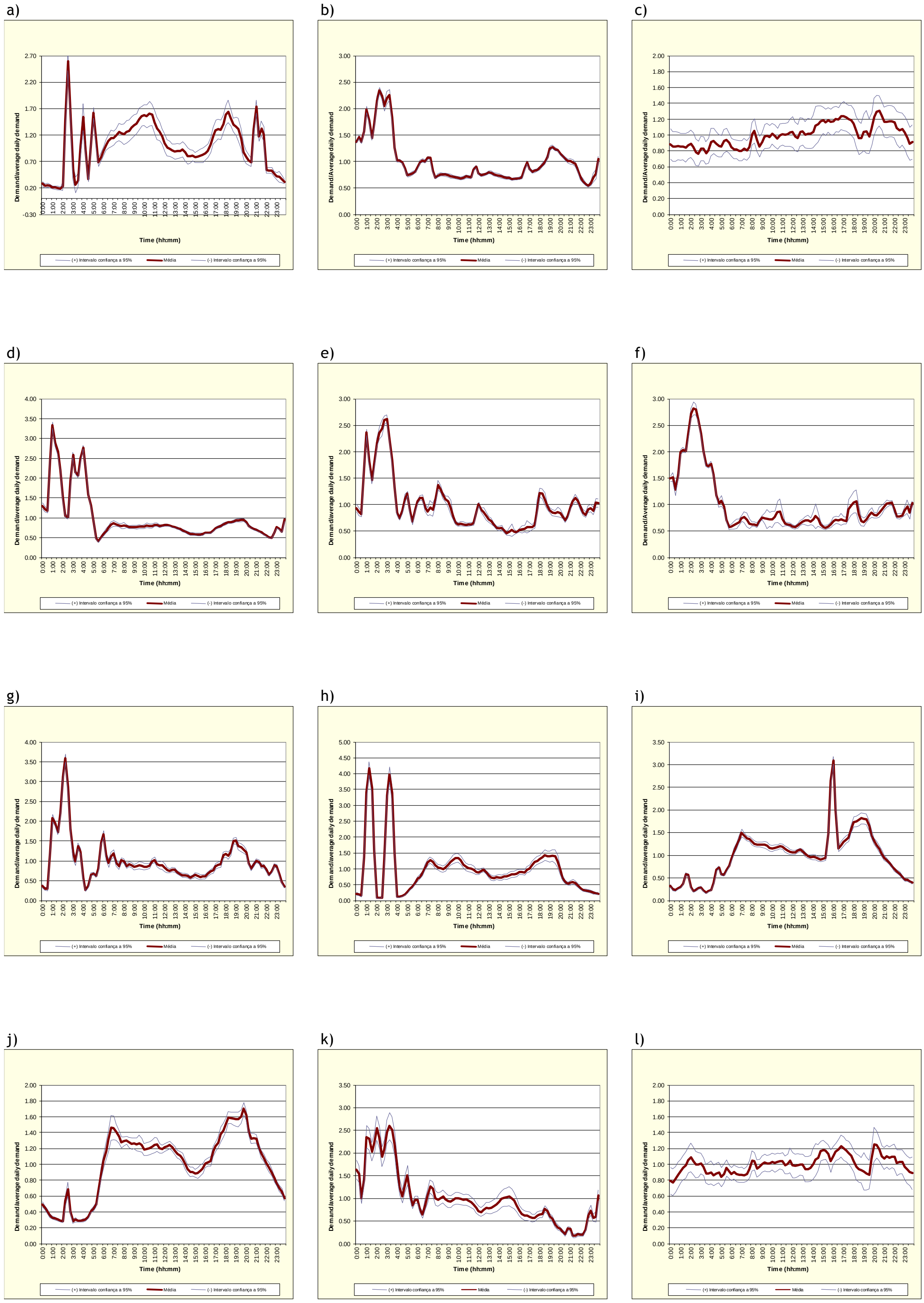


Figure 4.6 Costeira's adimensional (demand/daily average demand) daily demand pattern in August 2020 (red line – average/blue lines – confidence level 95%); a) Cardosas b) Cruz de montalvão c) Danone d) Entrecaminhos e) Granja f) Granja Parque g) Pipa Socorro h) Taberna Seca i) Valongo j) Violetas k) North Industrial Zone l) South Industrial Zone(red lines-average daily; blue lines-confidence level 95%)

In addition to the flow and pressure time series, measured at the entrance of each DMA a second dataset consisting of billing data of consumers from Costeira subsystem was also provided by the water utility. This was used to establish the distribution of the average daily flow inside each DMA. Nodal weights were computed by dividing the monthly bill by the total bill of each DMA. In the billing records some of the values were negative due to billing adjustments. For the purpose of nodal demand weight attribution these values were considered to be null. The adresses in the billing dataset were manualy linked to EPANET nodes.

Extended period simulations (EPS) were run for 696 h (29 days), which was enough for the water age to stabilize at every node after the initial ramp up. Since the same daily pattern is repeated throughout several days, after the initial hours the results start cycling in 24 h cycles. The hydraulic time steps and quality time steps used in the simulations was a one-minute interval. Figueiredo (2014) tested the time steps for sensitivity where it was verified that the values of one minute are the ones that produce a better compromise between computation time and calibrated results, producing an error around 1%.

The model results for flow and pressure at the entrance nodes of each DMA were compared with the initial records for calibration. A correction factor was then applied to each nodal demand according to its DMA in order to maximize the correlations between the results of pressure and flow of the model to the real measurements. Correlations of 99% and 98% were obtained for February and August, respectively, for both flow and pressure variables. The results of the calibration can be found in **Annex I**.

4.2.2 Water quality data

Raw datasets regarding water quality in the WDS were made available by Serviços Municipalizados de Castelo Branco and compiled for this thesis. These data sets contain the records of selected water quality parameters analysed for the mandatory water quality control program between the 1st of January 2015 and the 30th of April 2020. The chosen parameters were free chlorine, total chlorine, coliform bacteria, Enterococci, E. Coli, HPC at 22ºC, HPC at 36ºC and trialomethanes (bromoform, chloroform, dibromochloromethane and bromodichloromethane), as these are non-conservative substances and are likely to change over the water residence time in the system.

The data set was initially pre-processed in order to remove data regarding sampling locations outside Costeira subsystem. Then, only data regarding samples collected in February (Winter conditions) and August (Summer conditions) were considered. Because the resulting dataset was relatively small, the range of WQ data representative of the Winter conditions was extended from the 15^{th} of January to the 15^{th} of March, and in Summer from the 15^{th} of July to the 15^{th} of September, assuming the demand behaviours are very similar to those of February and August, respectively. In this process, thirty-nine (39) possible locations were identified as having useable data for this study, 35 of them regarding the Winter conditions and 11 in the Summer conditions. The final datasets considered herein are summarized in Table 4.3 and Table 4.4, and included in Annex II and Annex III, for the Winter and Summer conditions, respectively.

Table 4.3– WQ data – Winter conditions

Parameter	No. of samples	Year	Units	Minimum value observed	Average value observed	Maximum value observed
Coliform bacteria	30	2015-2020	UFC/ 100 ml	0	0	0
Bromodichloromethane	1	2017	µg/L	4	4	4
Bromoform	1	2017	µg/L	<3	<3	<3
Cloroform	1	2017	µg/L	15	15	15
Dibromochloromethane	1	2017	µg/L	<3	<3	<3
Free Chlorine	279	2015-2020	mg/L	0.00	0.96	1.96
Enterococci	6	2017-2020	UFC/100ml	0	0	0
E.coli	37	2015-2020	UFC/100ml	0	0	0
HPC at 22ºC	11	2017-2020	UFC/ml	Not detected	Not detected	Not detected
HPC at 36ºC	11	2017-2020	UFC/ml	Not detected	Not detected	Not detected

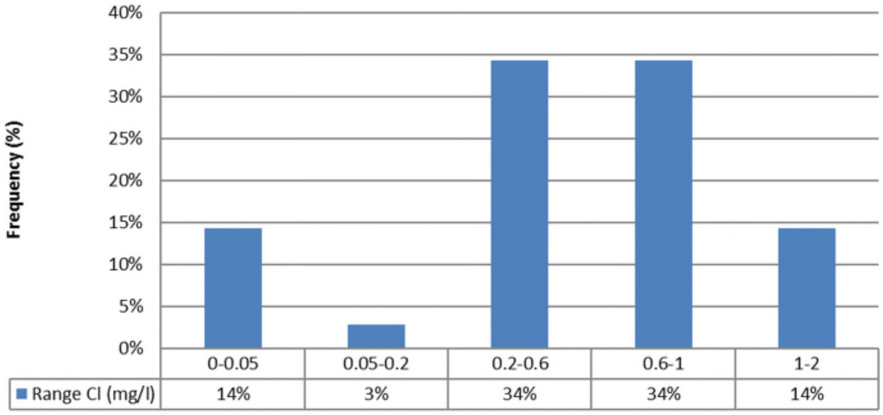
From Table 4.3 it is easily assessed that for the Winter conditions there is just one record for the parameters that comprise thrialomethanes, and the result is below the reference values in the drinking water law. The microbiological records are either null or non detectable. Thus, only the free chlorine records present sufficient data to attempt for a correlation analysis with water age. An analog situation may also be observed for the Summer conditions (Table 4.4).

Table 4.4– WQ data – Summer conditions

Parameter	No. of samples	Year	Units	Minimum value observed	Average value observed	Maximum value observed
Coliform bacteria	27	2015-2019	UFC/ 100 ml	0	0	0
Bromodichloromethane	1	2015	µg/L	6	6	6
Bromoform	1	2015	µg/L	<3	<3	<3
Cloroform	1	2015	µg/L	17	17	17
Dibromochloromethane	1	2015	µg/L	3	3	3
Free Chlorine	250	2015-2019	mg/L	0.00	0.88	1.68
Enterococci	3	2015-2019	UFC/100ml	0	0	0
E.coli	33	2015-2019	UFC/100ml	0	0	0
HPC at 22ºC	5	2015-2019	UFC/ml	Not detected	Not detected	Not detected
HPC at 36ºC	5	2015-2019	UFC/ml	Not detected	3	3
Total Organic Carbon	1	2015	mg C/L	3.8	3.8	3.8

Free chlorine concentration in Costeira subsystem varies from 1.96 mg/L to zero. The distribution of chlorine concentration values in the datasets for Winter and Summer can be found in Figure 4.7. Regarding free chlorine data, values below or equal to 0.05 mg/L were disregarded for further analysis with water age because of the precision limits of the measuring method. In the measurement of residual chlorine, a portable colorimeter is generally used (which uses the DPD method) in which the accuracy is ± 0.05 mg/L of free residual chlorine. This resulted in the elimination of a significant amount of records (14% in Winter data set and 36% in Summer data set), as can be observed in Figure 4.7.

a)



b)

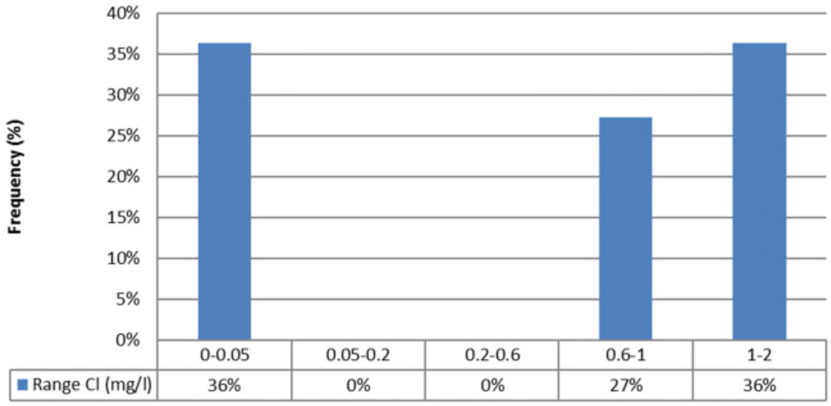


Figure 4.7 Histogram of average free chlorine at sampling locations; a) Winter conditions b) Summer conditions

Chlorine concentrations at sampling nodes in summer are, in general, too low or too high, as in the dataset there are no samples in the recomended range of 0.2 to 0.6 mg/L (Figure 4.7). This can either suggest that, in general, the consumers are not being supplied with the correct chlorine concentrations or that the sampling locations are not representattive of the Costeira system.

The water quality records were organized by address of the location where sample collection took place. A manual work had to be carried out in order to identify the closest node of each sampling locations in the network model for further comparison with the computed water age. The locations of the sampling nodes are presented in Figure 4.8.

Figure 4.8 Location of the water quality sampling nodes in Costeira subsystem.

5 CASE STUDY 2 | QUINTA DO LAGO

In this chapter, case study 2 is presented. It comprises a water distribution system in the south of Portugal, located in a touristic area, for which there is already a complete and updated hydraulic model. The characteristics of the system and the data available and collected for this case study are described herein. The system was studied in two diferent conditions, namely the winter and the summer conditions.

5.1 Case study description

Infraquinta is the company in charge of the water distribution networks in Quinta do Lago and surrounding villages in the parish of Almancil, municipality of Loulé, located in the South of Portugal.

The water distribution network supplies ca. 1.7 Mm^3/year to a population of approximately 2,000 inhabitants with a highly seasonal character, given the touristic use of the area (See Figure 5.1). The water demand in summer is approximately 4.5 times the demand in winter. It comprises 72.8 km of pipes, ranging from 63 to 400 mm diameter. Predominant pipe materials are PVC (53%) and asbestos cement (44%), mostly installed in the 1980's. Water flow is hourly measured at each of the 2000 clients. Pressure is measured every minute in seven locations within the distribution system. Water with guaranteed quantity and quality is provided by the upstream multimunicipal system managed by Águas do Algarve.

Figure 5.1 Satellite view of Quinta do Lago and skeletonization of the WDS (Satellite image source: Google Earth)

The distribution network is supplied by one tank (See Figure 5.2) from which the network splits in three main axis composed of PVC and Ductile Cast Iron pipes.

Figure 5.2 Infraquinta's Potable water tank

The difference in altimetry elevations of the case study 2 area varies between +37 mASL in the tank site and +5 mASL in the lowest point of the terrain (See Figure 5.3).

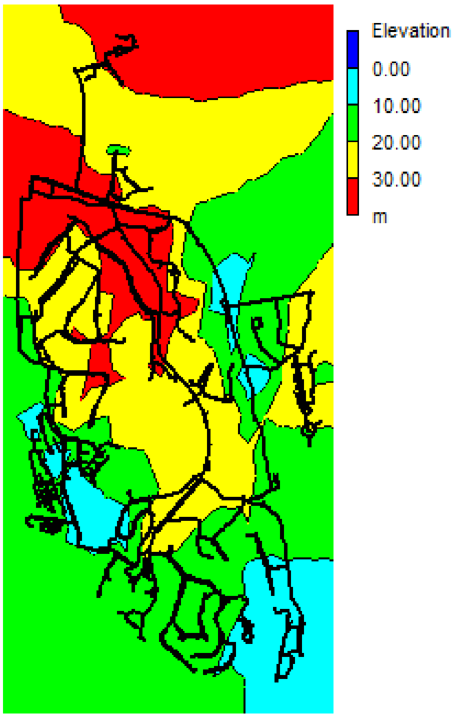


Figure 5.3 Infraquinta's water supply network elevations contour plot

The distribution pipes in the network vary from 50 mm to 400 mm. Two models were provided, calibrated with field data and representative of the winter and summer conditions in the year 2018. Extended period simulations of 264 h were carried out with 1 min time step, using EPANET.

5.2 Water quality data

Datasets regarding water quality in the WDS were made available by Infraquinta. These data sets contain the results of the analysis carried out for the mandatory water quality control program between the 28th of January 2008 and 21st of December 2015.

The datasets for Quinta do Lago system include the results for the following parameters: free chlorine, coliform bacteria, Enterococci, *Clostidrium perfringens*, *E. Coli*, HPC at 22ºC, HPC at 36ºC, trialomethanes (bromoform, chloroform, dibromochloromethane and bromodichloromethane), aluminium, calcium, copper, conductivity, manganese, magnesium, oxidability, total hardness, pH and turbidity.

For this case study, a slightly different approach regarding the time span for analysis was taken. The datasets were divided in two prevalent operating conditions, namely the Winter conditions, ranging from November to April, and the Summer conditions, from May to October. A brief of the sample data can be viewed in Table 5.1 and Table 5.2 for the Winter and Summer conditions, respectively. The complete datasets used herein are included in **Annex IV** and **Annex V**, for the Winter and Summer conditions, respectively.

Table 5.1– WQ data – Winter conditions

Parameter	No. of samples	Year	Units	Minimum value observed	Average value observed	Maximum value observed
Escherichia coli	78	*2008-2015*	#/100 mL	0.00	0.00	0.00
HPC at 22 ºC	45		N/mL	0.00	3.36	103.00
HPC at 36 ºC	45		N/mL	0.00	2.10	71.00
Enterococci	6		#/100 mL	0.00	0.00	0.00
Coliform bacteria	78		#/100 mL	0.00	0.00	0.00
Clostridium perfringens	45		N/100 mL	0.00	0.00	0.00
Free chlorine	63		mg/L	0.00	0.40	1.00
Cloroform	7		µg/L	2.10	52.37	90.00
Bromoform	7		µg/L	1.33	2.84	4.86
Dibromochloromethane	7		µg/L	7.49	13.04	19.50
Bromodichloromethane	7		µg/L	7.46	13.31	20.30
Conductivity	45		µS/cm	190.00	245.57	750.00
pH	45		pH units	7.30	7.80	8.80
Oxidability	33		mg/L O_2	0.50	1.34	4.50
Calcium	7		mg/L Ca	24.00	25.43	27.00
Total Hardness	7		mg/L $CaCO_3$	90.00	97.00	120.00
Magnesium	7		mg/L Mg	6.00	7.17	8.20
Copper	6		mg/L	0.01	0.03	0.07
Manganese	16		µg/L	0.70	5.48	16.00
Aluminium	21		µg/L	18.00	27.41	76.00
Turbidity	10		UNT	0.40	0.51	0.80

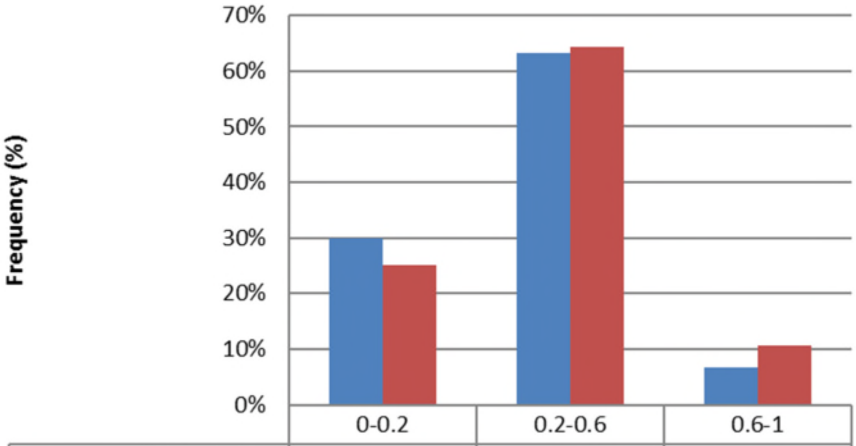
Table 5.2– WQ data – Summer conditions

Parameter	No. of samples	Year	Units	Minimum value observed	Average value observed	Maximum value observed
Escherichia coli	73	2008-2015	#/100 mL	0.00	0.00	0.00
HPC at 22 ºC	56		N/mL	0.00	17.47	300.00
HPC at 36 ºC	56		N/mL	0.00	14.42	300.00
Enterococci	10		#/100 mL	0.00	0.00	0.00
Coliform bacteria	73		#/100 mL	0.00	0.00	0.00
Clostridium perfringens	57		N/100 mL	0.00	0.00	0.00
Free chlorine	64		mg/L	0.10	0.36	0.87
Cloroform	10		µg/L	4.86	14.54	24.00
Bromoform	10		µg/L	1.19	2.12	3.93
Dibromochloromethane	10		µg/L	5.38	10.76	12.80
Bromodichloromethane	10		µg/L	6.69	11.82	14.00
Conductivity	57		µS/cm	200.00	227.25	270.00
pH	57		pH units	6.70	7.66	8.30
Oxidability	45		mg/L O_2	0.50	1.06	2.20
Calcium	10		mg/L Ca	23.00	28.38	32.00
Total Hardness	10		mg/L Ca CO_3	90.00	106.24	140.00
Magnesium	10		mg/L Mg	5.00	7.21	9.00
Copper	5		mg/L	0.01	0.04	0.12
Manganese	15		µg/L	3.36	12.30	32.00
Aluminium	28		µg/L	21.00	37.66	100.00
Turbidity	7		UNT	0.40	0.64	0.90

As in case study 1, the microbiological records are generally null and not correlatable to any parameter. The exception to this is the HPC results which, in some cases, has values different from zero. However, a closer look at the datasets reveal that in most sampling nodes only one sample was collected or, in some other cases, two readings varying from zero to an extremely high value exist, resulting in a poor dataset. The resulting number of points available for correlation with water age would be very strict and limiting to the consistency of the analysis. It is recommended that in future works dedicated campaigns are used instead of Quality Control Plan data to maximize the number of points to be correlated. The number and spatial distribution of the sampling locations should be at least enough to embark all network locations and be representative of all the situations found, including the least favourable ones.

On the chemical parameters side, and considering the non-conservative parameters only, chlorine is, by far, the parameter for which there are more data that can be used to find correlations with water age. For the other parameters, namely the ones that comprise THMs, there are very few results (7 in winter and 10 in summer). Hence, finding correlations between water age and water quality parameters will herein be based on the disinfectant residual concentration only.

The distribution of free chlorine values throughout the WDS in Winter and Summer conditions can be found in Figure 5.4. One can observe that a significant percentage, above 60% of the free chlorine values are within the range of 0.2 - 0.6 mg/L which is the recommendable range in the Portuguese regulations (DL 152/2017).



	0-0.2	0.2-0.6	0.6-1
Range Cl Summer(mg/l)	30%	63%	7%
Range Cl Winter (mg/l)	25%	64%	11%

Figure 5.4 Histogram of average free chlorine at nodes

As in case study 1, the sampling locations for water quality analysis are identified in the datasets by the address of the location, not georeferenced or identified by any tag that could be identified in the GIS data. The identification of the corresponding nodes in the EPANET model was manually carried out for further correlation analysis with the computed water age. In this process, 40 locations were identified as having usable data, 28 of them applicable to the Winter conditions and 30 in the Summer conditions. The locations of the sampling nodes are presented in Figure 5.5.

Figure 5.5 Location of water quality sampling nodes in Quinta do Lago system.

6 RESULTS

In this section, the main results obtained for the two case studies are presented and discussed. First, correlations between water age and disinfectant concentration at the nodes are investigated. Then, performance curves for chlorine and water age are developed. The obtained curves are applied to the case studies, as well as existing ones in literature for comparison.

6.1 Correlation of water age with chlorine concentration

As explained in the previous section, the water quality datasets provided by the water utilities contained only few results on chemical non-conservative water quality parameters. For that reason, the correlations between water age and water quality parameters presented in this section focus only on the relationship between water age and free chlorine in the systems.

6.1.1 Case study 1

With the demand distribution obtained with the methodology described in Chapter 4, the model ran an extenteded period simulation for 29 days (696 hours). This period was considered long enough for all the nodes of the model to stabilize and start repeating the daily water age pattern in order to evaluate average and extreme water age values. The effect of stabilization may be observed in Figure 6.1 where it is visible the initial growth of water age and foster stabilization with the repetition of the water age pattern.

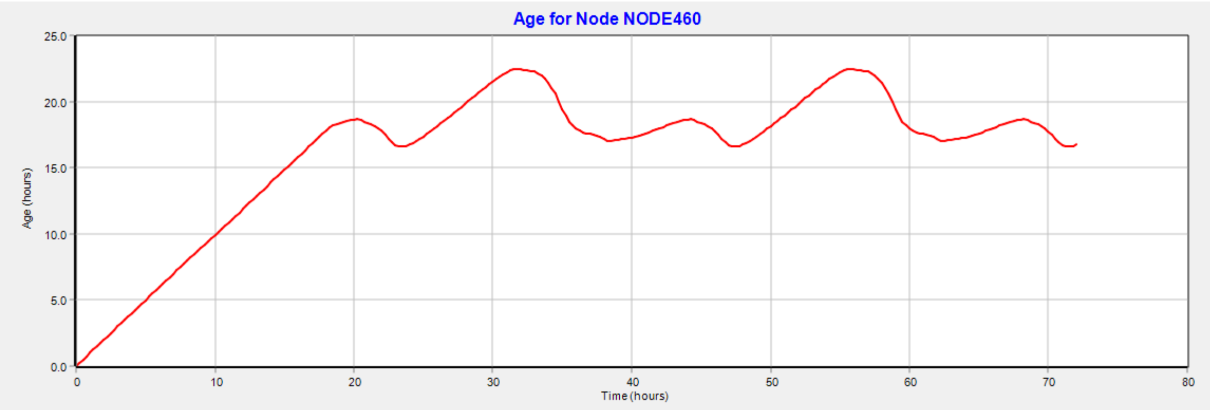


Figure 6.1 Variation of water age at Node 460 in February 2020.

This stabilization occurs at different times of the simulation for distinct locations, hence only the results for the last 24 hours of the EPS were considered for water age statistics. Figure 6.2 represents the frequency of occurrence of average nodal water age values (based on the data series of average nodal WA for the last 24 hours of simulation at each node ordered) in the consumption nodes for the February and August conditions. The results presented in this graphic, are based on the results obtained for all the nodes in the WDS model except nodes with maximum water age equal to the EPS total time of simulation, as these nodes are taken as modeling shortcomings and would deviate the analysis towards the higher water age values.

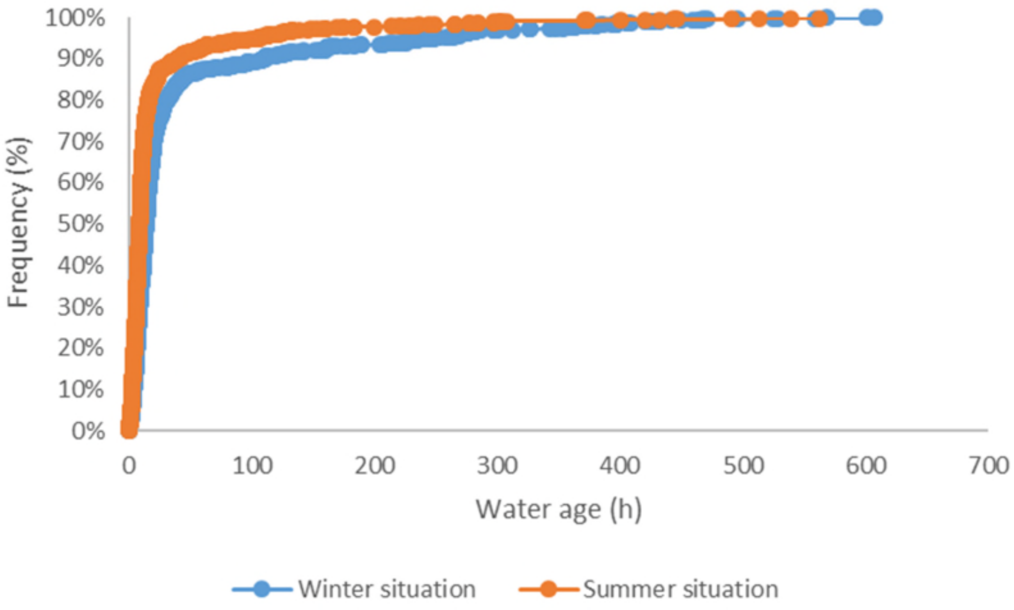


Figure 6.2 – Frequency of average water age values in Costeira

The relation of water age at nodes in the network for the Winter conditions reveals that the water age at approximately 75% of the nodes is less than 24 h and that 86% of the nodes receive water that entered the system in the last 48 hours. In the Summer conditions, the same percentages grow to 87% and 91% respectively for 24 and 48 hours. The demand distribution obtained in the model leaves some of the nodes in the extremity of the model without any demand associated, making that the water age in these nodes increases linearly over time, which is not representative of the reality. To avoid any artificial deviations in the results due to these nodes with maximum water age equal to the simulation time, these nodes were not included in the assessment of water age in the WDS.

Table 6.1 and Table 6.2 present the water age statistics in the nodes with water quality datasets available for the Winter and Summer conditions. Points 6 and 7, though corresponding to two separate addresses, are connected to the same node of the model, and are therefore treated together.

Table 6.1 – Water age at the nodes with WQ datasets - Winter conditions

	Water age (h)			
ID of sampling location	Minimum	Maximum	Average	Standard deviation
1	5.08	11.26	7.06	2.00
2	7.16	13.51	9.92	2.08
3	3.85	9.94	5.64	1.84
4	1.34	3.99	2.04	0.79
5	3.85	12.00	7.24	2.81
6 & 7	5.35	8.41	6.38	0.95
8	1.76	3.39	2.26	0.44
9	3.87	10.01	5.79	1.99

	Water age (h)			
ID of sampling location	Minimum	Maximum	Average	Standard deviation
10	4.84	10.57	6.69	1.59
11	6.79	8.78	7.57	0.63
12	6.86	8.92	7.70	0.64
13	7.32	10.01	8.69	0.80
14	0.03	0.04	0.03	0.00
15	14.98	21.58	17.71	1.90
16	16.52	22.41	18.84	1.85
17	8.15	8.15	1.59	13.40
18	9.01	13.89	10.67	1.46
19	7.71	12.56	9.25	1.43
20	17.34	20.84	18.91	0.98
21	299.90	312.58	312.02	1.29
22	17.57	21.06	19.14	0.97
23	154.02	164.34	159.55	3.36
24	86.02	89.49	87.76	1.09
25	5.60	11.76	7.68	2.03
26	1.76	6.22	2.97	1.41
27	35.36	35.36	1.19	40.07
28	1.40	5.22	2.46	1.25
29	12.22	17.64	14.46	1.47
30	17.72	17.72	1.75	22.89
31	12.65	12.65	1.89	18.07
32	8.43	8.43	1.62	13.63
33	94.33	94.33	0.91	97.55
34	245.11	272.86	268.64	2.35
35	7.85	18.26	12.94	3.46

Table 6.2 – Water age at the nodes with WQ datasets - Summer conditions

	Water age (h)			
ID of sampling location	Minimum	Maximum	Average	Standard deviation
1	1.36	4.47	3.00	0.74
4	0.65	3.19	1.49	0.49
6&7	3.55	7.13	5.52	0.92
14	0.03	0.03	0.03	0.00
22	12.25	15.07	13.27	0.84
24	97.18	99.74	98.68	0.63
30	10.72	10.72	2.06	18.59
36	0.87	0.87	0.35	2.37
37	4.35	4.35	2.37	12.70
38	8.17	8.17	2.76	16.72
39	1.53	1.53	0.83	4.74

Because of the limits of precision of the analysis equipment, records equal or under 0.05 mg/L of chlorine were eliminated from the dataset for comparison with water age. This resulted in the exclusion of points

21, 23 and 34 in the Winter conditions and point 24 in the Summer conditions. This first approach of relating water age with chlorine is presented in Figure 6.3.

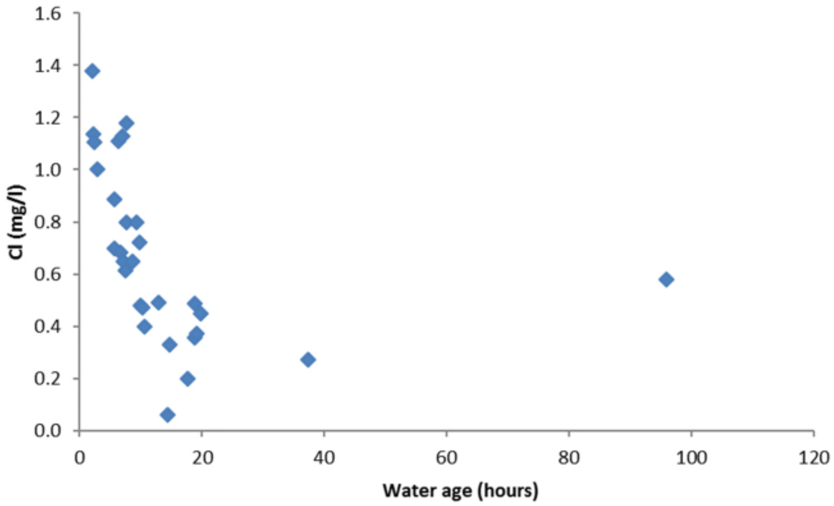


Figure 6.3 – Water age vs chlorine for the Winter conditions- First approach

The results show that, in general, the average chlorine concentration is lower at the nodes where the average water age is higher. However, the data points are somewhat scattered which does not allow to determine a chlorine function. In an effort to improve these results, the dataset used was analyzed in more detail. Considering that the operational conditions of the WDS could have been diferent in the past and that the developed model could not represent those conditions, only the most recent chlorine data (2019 and 2020) was considered in the next analysis. These considerations resulted in the elimination of points 5, 8, 9, 10, 14, 15, 17, 20, 22, 23, 25, 26, 27, 30 and 32 from both datasets (winter and Summer). In addition, daily water age variations at the nodes was considered: instead of using a daily average water age at the sampling nodes, the average water ages in the 10:00 a.m. to 12:00 a.m. period was used, as this is most probably the time when the samples were collected. Sampling location 33 was also excluded because there was only one single record of chlorine at that location that could not be validated by any other. Table 6.3 expresses the final data set obtained for the Winter conditions.

Table 6.3 – Dataset of water age and chlorine after processing - Winter conditions

ID of sampling node	Water age (hours) Minimum	Maximum	Average	Cl (mg/L)
1	5.08	11.26	5.69	0.39
3	3.85	9.94	4.02	0.61
4	1.34	3.99	1.45	1.05
6/7	5.35	8.41	6.38	0.30
11	6.79	8.78	8.74	0.80
12	6.79	8.92	8.87	0.65
13	7.32	10.01	9.85	0.80
16	16.52	22.41	19.71	0.00
18	9.01	13.89	10.58	0.49
19	7.71	12.56	9.31	0.72
28	1.40	5.22	1.61	1.00
29	12.22	17.64	13.76	0.33
31	12.65	18.07	16.47	0.20
35	7.85	18.26	15.86	0.06

The new relation obtained between average water age and free chlorine records improved significantly (Figure 6.4) but the coefficient of determination of the linear regression still shows a small correlation between the two variables. These results match the findings of Machel and Boxall (2012) in which mean age proved a limited association with general water quality, being necessary to consider mixing effects, and the maximum age component, to obtain some association. The fact that chlorine decay depends on a number of other factors besides residence time, like pipe materials, dosage (Tamminen et al, 2008) or temperature (AWWA, 2002), might justify a weaker relationship between water age and chlorine.

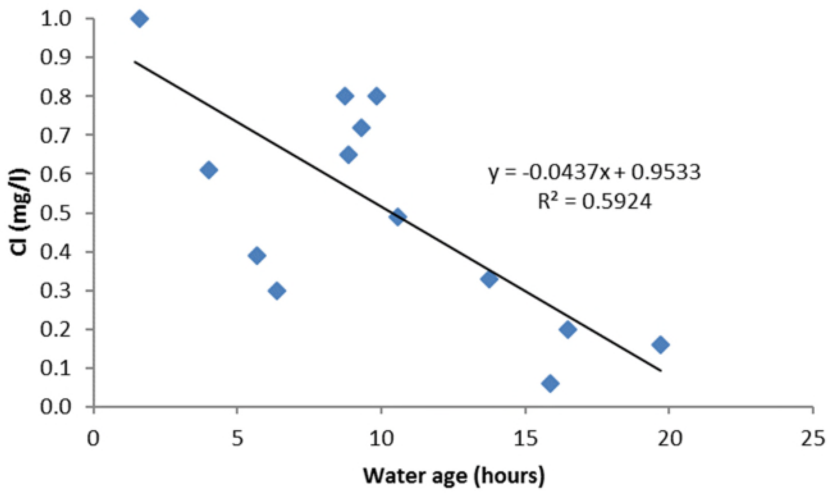


Figure 6.4 – Average water age (at 10:00-12:00) vs chlorine (samples 2019-2020)-Winter conditions

The chlorine values were then compared to the nodal maximum water age values taken from the model, obtaining a much better correlation than the one observed by using average water age values (Figure

6.5). The coefficient of determination of approximately 0.75 keeps providing evidence of a certain independency of the two variables.

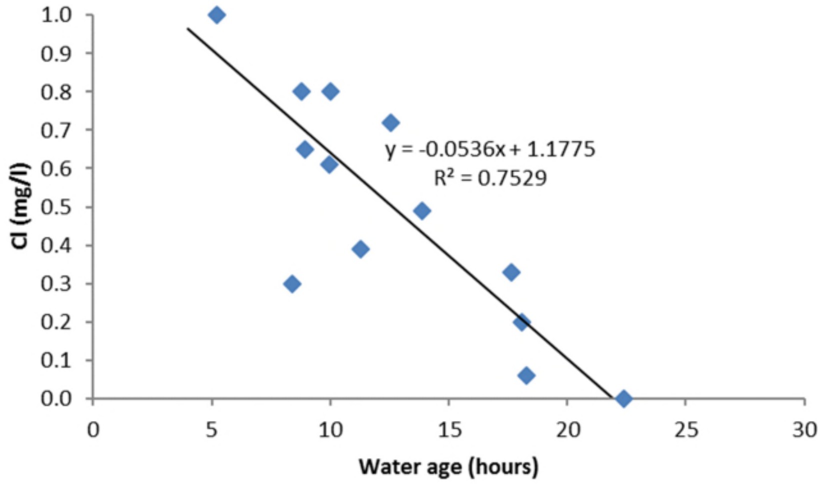


Figure 6.5 – Maximum water age vs chlorine (samples 2019-2020) - Winter conditions

A similar approach was then followed for the Summer conditions (August) resulting in the exclusion of points 24 and 30, the first for having records below the limits of detection and the latter for having only one old record. The resulting dataset can be observed in Table 6.4.

Table 6.4 – Dataset of water age and chlorine after processing - Summer conditions

	Water age (h)			
ID of sampling location	**Minimum**	**Maximum**	**Average**	**Cl (mg/L)**
1	1.36	4.47	3.23	1.20
4	0.65	3.19	1.23	1.12
6&7	3.55	7.13	5.87	0.84
14	0.03	0.03	0.03	1.30
22	12.25	15.07	14.90	0.12
36	0.87	2.37	1.96	0.93
37	4.35	12.7	7.43	0.06
38	8.17	16.72	9.38	0.08
39	1.53	4.74	3.03	0.72

Figure 6.6 and Figure 6.7 show the relation between the average water age and maximum water age with free chlorine. The conclusions follow closely the findings for the winter conditions, the coefficients of determination of the linear regression are close to one, indicating a certain independency of both variables but also a better correlation of free chlorine with the maximum water age values.

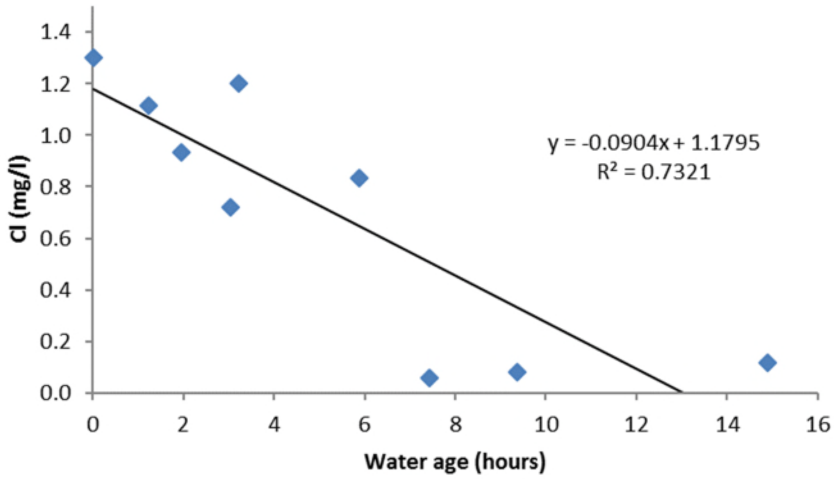


Figure 6.6 – Average water age (at 10:00-12:00) vs chlorine (samples 2019-2020) - Summer conditions

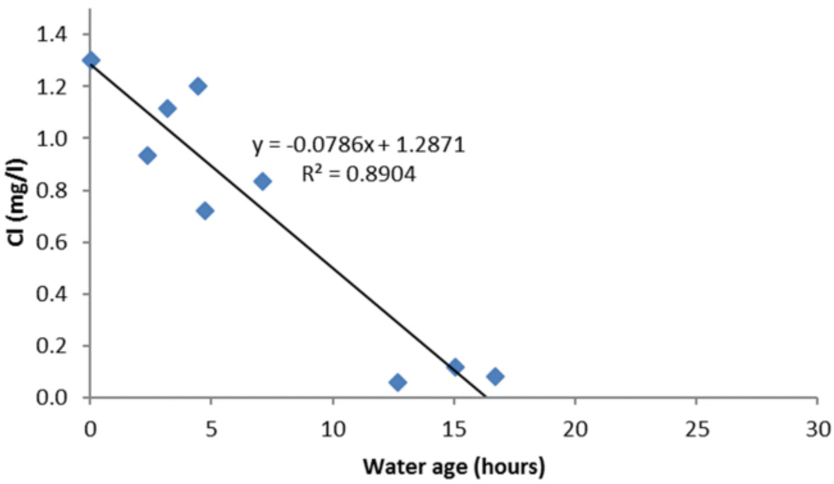


Figure 6.7 – Maximum water age vs chlorine (samples 2019-2020) - Summer conditions

Comparing the two functions obtained for winter and summer, considering maximum water age at the nodes, it can be observed that the slope of the curves is slightly higher in the summer than in the winter. Consequentely, chlorine decays faster and reaches close to zero values in about 16 h in Summer, while it takes 22 h in Winter. In conclusion, the water age can be related to chlorine concentration in Costeira system by the following expressions (5) and (6).

$$Cl = -0.0536\, WA + 1.1775\,;\;\; WA\; \leq 22\, h;\; Winter \qquad (5)$$

$$Cl = -0.0786\, WA + 1.2871\,;\;\; WA\; \leq 16\, h;\; Summer \qquad (6)$$

Where *Cl* is free chlorine concentration (mg/L) and *WA* is maximum water age (h).

6.1.2 Case study 2

The model was run for an extended period simulation for 11 days (264 hours), based on real demand patterns recorded by flow meters scattered throughout the network. The period of stabilization considered in this case was 48 h, before this moment of the simulation all water age results were discarded. Figure 6.8 represents the frequency of occurrence of water age values in the consumption nodes for the Winter and Summer conditions. The results presented were obtained for all consumption nodes in the WDS model, i.e., all nodes except those with maximum water age equal to the EPS total time of simulation, as these nodes would deviate the analysis towards the higher water age values.

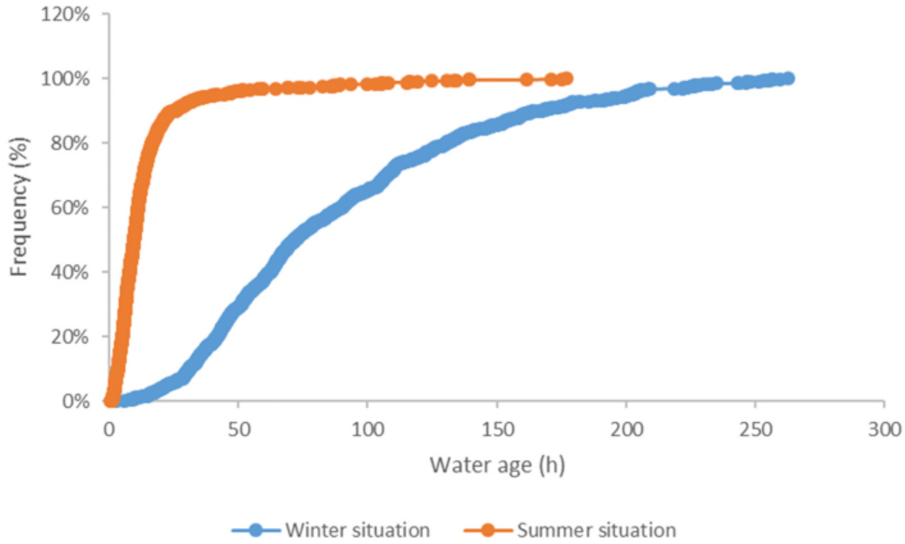


Figure 6.8 – Frequency of average water age values for Case study 2

The results show that, in Winter, the water age at approximately 18% of the nodes is equal or less than 24 h and that at 58% of the nodes it is equal or less than 48 h. While in the Summer conditions these percentages increase to 90% and 96% respectively for 24 h and 48 h. These differences between the Winter and Summer conditions reflect the seasonal fluctuations of the demand.

Nodes with no demand in the extremities of the model were deleted from the water age dataset to avoid any artificial deviations in the results induced by having maximum water age equal to the simulation time. In **Annex VI** the obtained water age at the nodes where water quality datasets are available are presented for the Winter and Summer conditions.

On the Winter conditions, sampling locations 7, 24 and 36 have been rejected because they correspond to old records of chlorine data and may not represent the actual satus of the WDS, while points 11, 17, 20 and 49 were excluded because of the large variation between the minimum and maximum water age which was probably caused by single events and for that reason the average values may not be representative. Table 6.5 expresses the final data set obtained for the Winter conditions.

Table 6.5 – Dataset of water age and chlorine after processing - Winter conditions

	Water age (hours)			
ID of sampling node	Minimum	Maximum	Average	Cl (mg/L)
3	5.34	17.85	10.00	0.47
5	29.88	63.51	43.84	0.42
10	23.29	119.71	79.99	0.20
11	7.73	37.19	21.56	0.40
13	25.91	67.39	39.81	0.40
15	12.91	35.97	23.13	0.45
16	13.98	41.36	25.94	0.46
20	48.00	218.81	135.15	0.10
25	1.04	6.55	3.23	0.42
27	6.12	26.04	14.13	0.50
29	22.07	44.26	30.74	0.37
30	0.00	8.46	1.14	0.60
33	17.94	129.20	76.51	0.20
35	12.63	107.47	36.71	0.38
38	0.40	2.74	1.24	0.61
39	2.81	11.84	7.73	0.46

The relations obtained between average and maximum water age and free chlorine for the Winter conditions are presented in Figure 6.9 and Figure 6.10. Good correlations between the two variables were obtained as the coefficient of determination of the linear regression is close to the unit, approximately 0.85 and 0.75 for the average and maximum water age, respectively. In this case, the correlation is better with the average water age than with the maximum water age, contrarily to what was observed in case study 1, this may be due to the longer residence times and lower flow velocities which make a better fit with EPANET's quality model considering complete mix in the nodes.

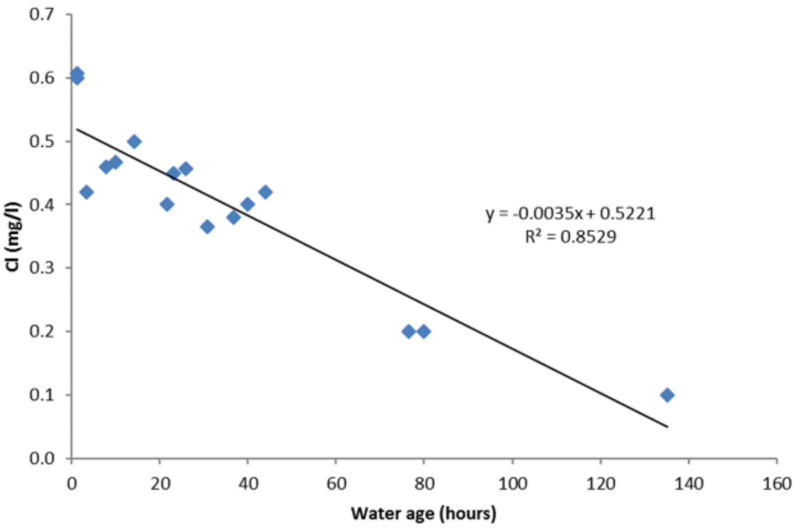


Figure 6.9 – Average water age vs chlorine - Winter conditions

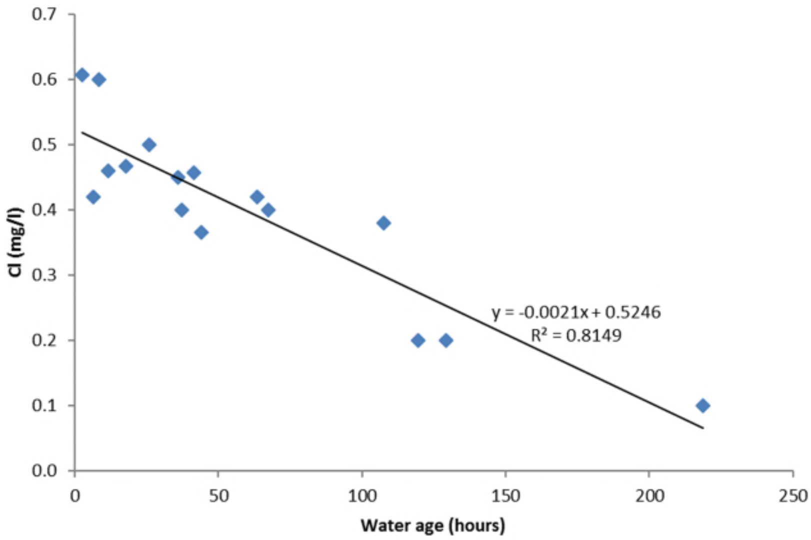


Figure 6.10 – Maximum water age vs chlorine - Winter conditions

In the Summer conditions, sampling points 2, 24, 30, 42 and 53 were discarded because the records of chlorine corresponded to old values. Points 9, 11, 27, 34, 37, 43 were excluded from the dataset because of the huge variation between maximum and minimum values of water age. The resulting dataset is presented in Table 6.6.

Table 6.6 – Dataset of water age and chlorine after processing - Summer conditions

	Water age (hours)			
ID of sampling node	Minimum	Maximum	Average	Cl (mg/L)
2	5.45	39.90	13.84	0.34
3	1.73	3.78	2.38	0.70
5	4.29	10.49	6.37	0.54
14	11.36	32.27	18.14	0.23
18	4.26	11.58	6.70	0.40
24	1.05	69.99	26.33	0.20
26	3.27	13.62	5.49	0.66
27	1.79	9.37	3.63	0.70
28	2.86	23.21	7.45	0.35
32	1.51	14.03	5.11	0.58
38	0.17	1.43	0.50	0.56

The relations obtained between average and maximum water age and free chlorine for the Summer conditions are presented in Figure 6.11 and Figure 6.12.

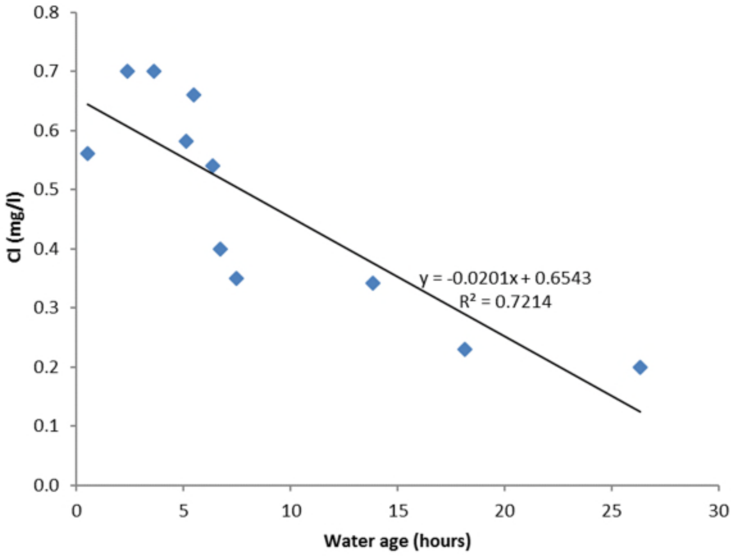


Figure 6.11 –Average water age vs chlorine - Summer conditions

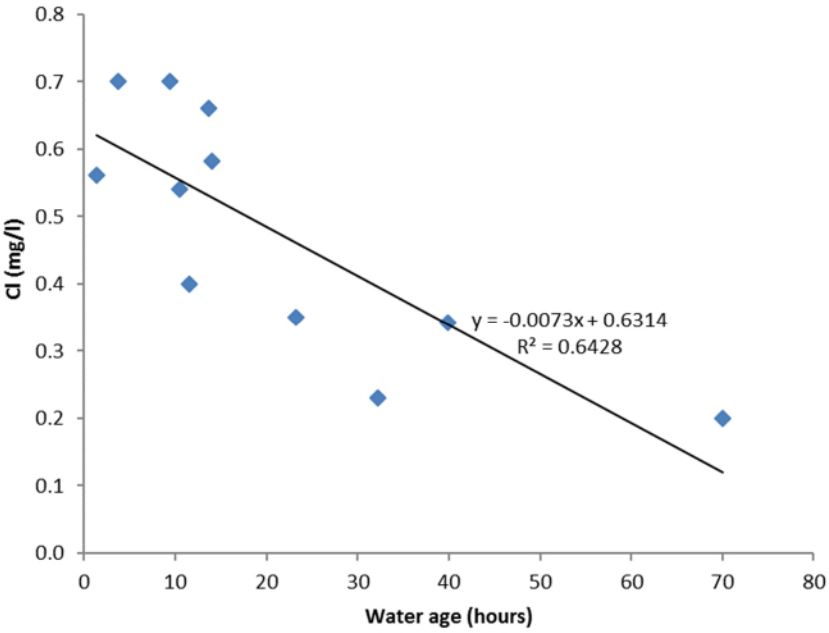


Figure 6.12 –Maximum water age vs chlorine - Summer conditions

Once again, a close to linear relashionship between water age and chlorine is obtained. As in the Winter conditions, the correlation is better with the average water age values, contrarily to the results for Case Study 1. This attests the particularity of the results to each WDS. Regarding this, it is advisable to test the better adjustment of water quality parameters both with average and maximum values of water age, to assess which one is better suited for the system under study.

Comparing the two functions obtained for winter and summer, considering average water age at the nodes, it can be observed that the slope of the curves is much higher in summer than in winter. Consequentely, chlorine decays faster and reaches close to zero values in about 32 h in Summer, while it takes 149 h in Winter. In conclusion, the water age can be related to chlorine concentration in Quinta do Lago system by the following expressions (7) and (8).

$$Cl = -0.0035\, WA + 0.5221\ ;\ \ WA\ \leq 149\, h;\ Winter \tag{7}$$

$$Cl = -0.0201\, WA + 0.6543\ ;\ \ WA\ \leq 32\, h;\ Summer \tag{8}$$

Where *Cl* is free chlorine concentration (mg/L) and *WA* is average water age (h).

6.2 Development of performance functions

Performance curves were developed for each case study and for each studied condition (winter and summer). The methodology adopted, as explained in Section 3, started by establishing a general chlorine performace function. Then, for each water age, a correspondent chlorine concentration is assigned, based on the equations obtained in the previous section. Chlorine concentrations were then converted to performance index by making use of the chlorine performance function.

6.2.1 Chlorine performance function

Despite the availability of chlorine performance functions in literature (See Chapter 2.5), a new curve was developed in this thesis. The criteria for setting the upper and lower limits and correspondent performance index was based on the concentration range recommended by the national law and on the WHO guidelines for drinking water quality. A value of 1 is proposed as the performance index (PI) when free chlorine ranges from 0.2 mg/L to 0.6 mg/L. Under 0.2 mg/L, the minimum required concentration for ensuring protection of the drinking water, the performance decreases linearly with decreasing chlorine levels. Above 0.6 mg/L, the chlorine concentration is higher than needed and may promote DBP formation and complaints due to taste and odour. Thus, the performance linearly decreases with increasing chlorine concentrations until 2.0 mg/L, which is the chlorine threshold for odour in distilled water (WHO, 2003). Performance is null in the range of 2.0 to 5.0 mg/L, which is the guideline value for free chlorine in drinking water (WHO, 2017). The resulting proposed performance function for free chlorine is presented in Figure 6.13.

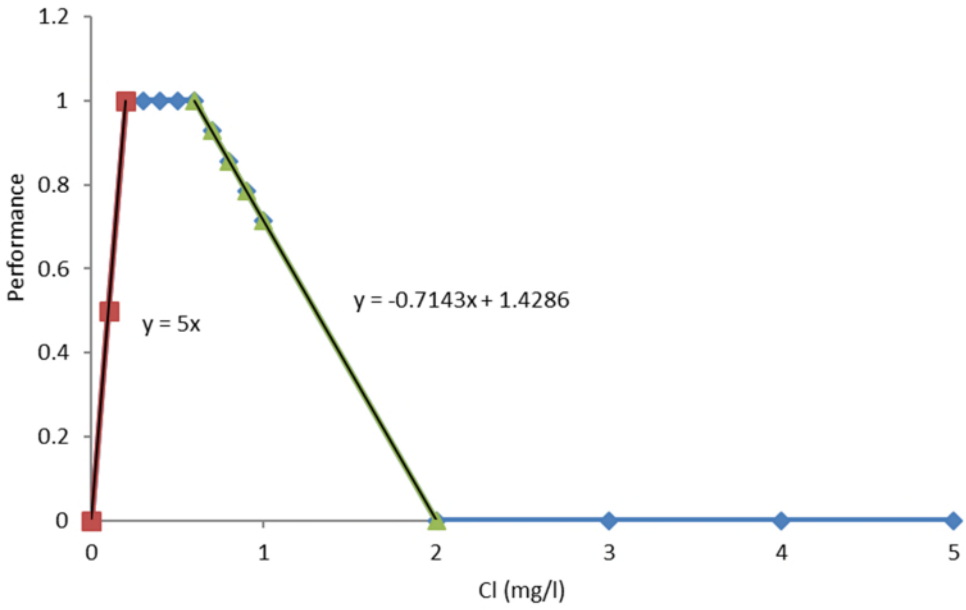


Figure 6.13 – General chlorine performance index

According to the developed function, the performance associated to a given node of a WDS where chlorine concentration is above 0.6 mg/L and up to 1 mg/L (which is quite common, especially near the treatment plants) is high (PI>0.7) but not optimum, as the upper limit of the recommended chlorine concentration range is exceeded.

6.2.2 Water age performance functions

Water age performance functions were developed for each case study at each studied conditions by making use of the observed correlations between water age and chlorine at the consumption nodes and of the general chlorine performance curve.

6.2.2.1 Case study 1

Based on Equation (5), the performance curve in equation (9) and in Figure 6.14 was developed for Costeira system in winter conditions.

$$PI = 0.0383\, WA + 0.6452 \; if \; WA \leq 11 \; hours$$

$$PI = 1 \; if \; 11 \; hours < WA \leq 18 \; hours \tag{9}$$

$$PI = -0.2536\, WA + 5.5873 \; if \; 18 \; hours < WA \leq 22 \; hours$$

$$PI = 0 \; if \; 22 \; hours < WA$$

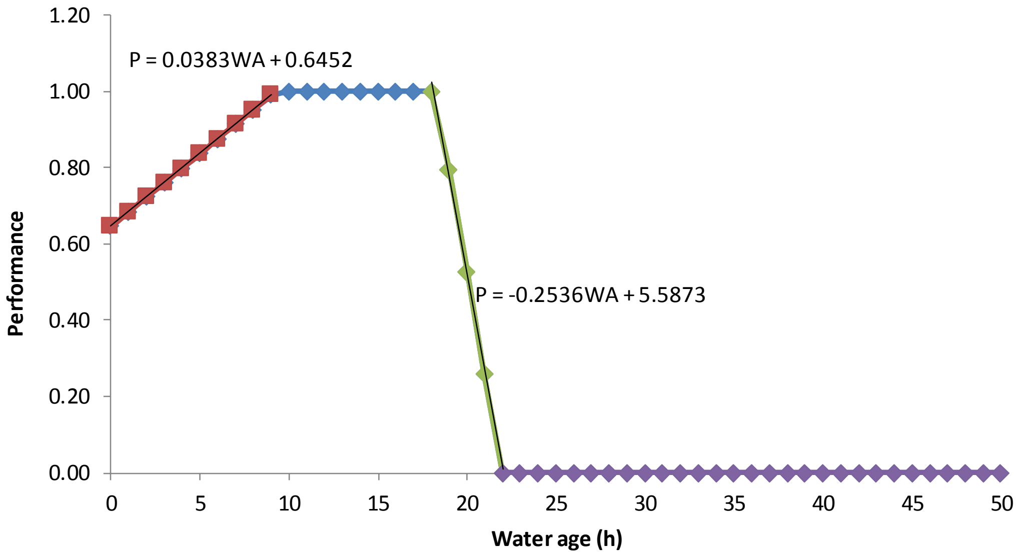


Figure 6.14 – Water age performance curve – Winter conditions/Case Study 1

A conventional grading has been adopted, whereby 1.0 is the optimum performance, 0.75 is good performance and 0.5 is the acceptability threshold. Below 0.5, performance is unacceptable, with 0 corresponding to a no-service situation.

For the summer conditions, the performance curve obtained is expressed in Equation 10 and presented in Figure 6.15.

$$PI = 0.0353\ WA + 0.723\ if\ WA \leq 9\ hours$$

$$PI = 1\ if\ 9\ hours < WA \leq 14\ hours \qquad (10)$$

$$PI = -0.393\ WA + 6.4355\ if\ 14\ hours < WA \leq 16\ hours$$

$$PI = 0\ if\ 16\ hours < WA$$

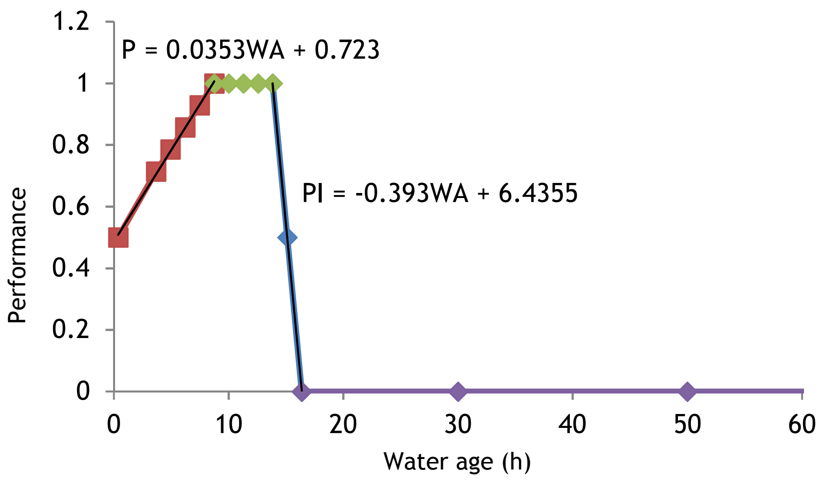


Figure 6.15 –Water age performance curve – Summer conditions/Case Study 1

Accordingly, optimum performance in the Costeira System is reached for residence times of eleven (11) hours to eighteen (18) hours during winter and nine (9) hours to fourteen (14) hours during the summer. As expected, performance reaches null values at shorter residence times in the summer than in winter due to increased chlorine decay rates at higher temperatures in summer. The two curves, developed for the two conditions, are very similar and mostly differ in the upper water age limits for acceptable performance.

Contrarily to the existing performance functions found in literature, the developed curves for Costeira system allow to penalize very short residence times, as these correspond to chlorine concentrations higher than the maximum recommended value. For higher residence times, the curves are very similar to those of Coelho (1996) and of Shokoohi et al. (2017), differing mostly in the duration of the maximum performance.

6.2.2.2 Case study 2

Based on Equation (7), the performance curve in equation (11) and in Figure 6.16 was developed for Quinta do Lago system in winter conditions.

$$PI = 1 \; if \; WA \; \leq 92 \; hours \qquad (11)$$

$$PI = -0.0175 \; WA + 2.6105 \; if \; 92 \; hours < WA \; \leq 149 \; hours$$

$$PI = 0 \; if \; 149 \; hours < WA$$

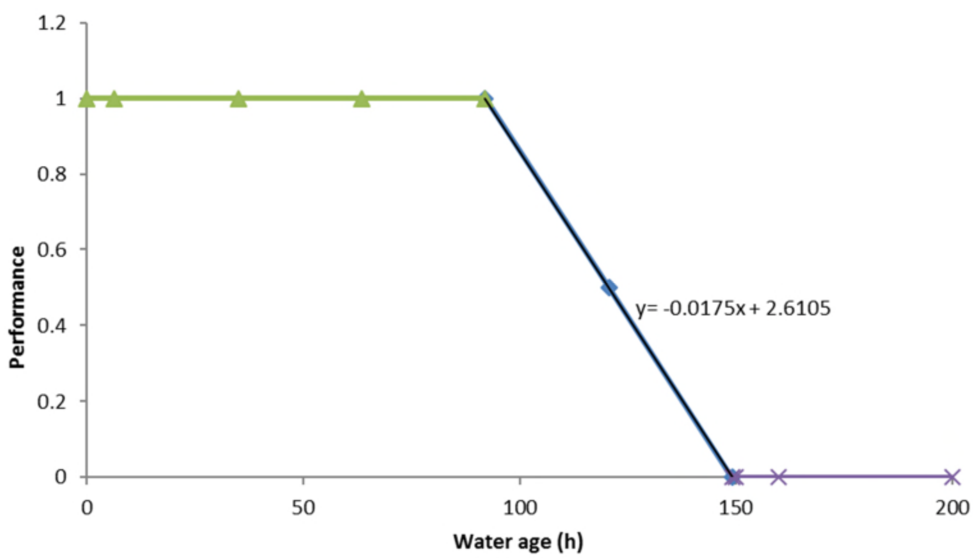


Figure 6.16 – Water age performance curve – Winter Conditions/Case Study 2

For the summer conditions, the performance curve obtained is expressed in Equation (12) and presented in Figure 6.17.

$$PI = 0.0264\,WA + 0.9286\; if\; WA \le 0.4\; hours$$

$$PI = 1\; if\; 0.4\; hours < WA \le 23\; hours \qquad (12)$$

$$PI = -0.1005\,WA + 3.2715\; if\; 23\; hours < WA \le 33\; hours$$

$$PI = 0\; if\; 33\; hours < WA$$

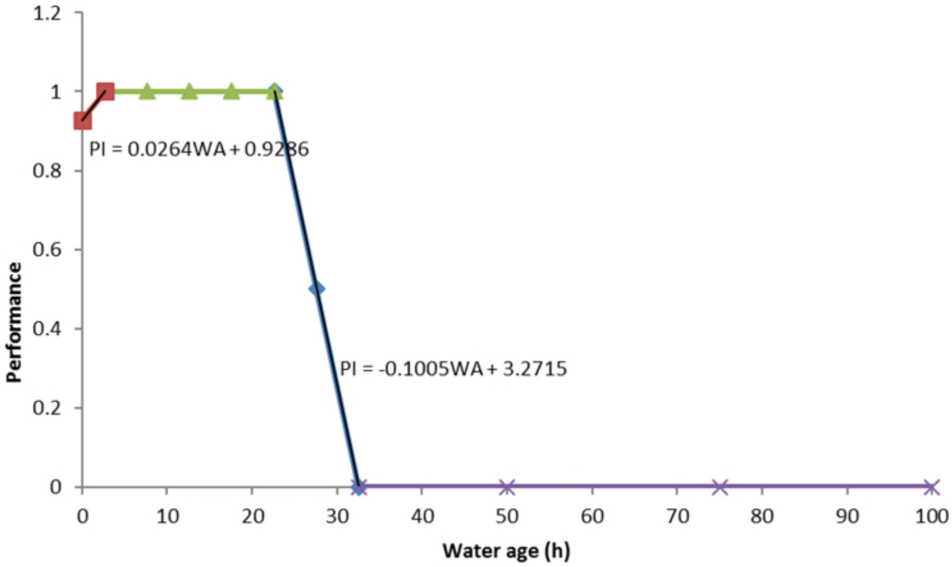


Figure 6.17 – Water age performance curve – Summer conditions/Case Study 2

Optimum performance in Infraquinta's system is reached for residence times of zero (0) hours to ninety-two (92) hours during the winter and three (3) hours to twenty-three (23) hours during the summer. Shorter residence times are found for the summer conditions due to the much higher water demand in this touristic area.

The two curves obtained for Quinta do Lago system are very different, as the longer residence times in Winter, at lower temperatures, do not seem to be a problem for the water quality and the performance remains optimum for much higher water ages in winter (up to 92h) than in summer (up to 23 h). Thus, the two curves differ mostly in water age upper limits. In summer, chlorine concentrations at the nodes closer to the storage tank, where water age is low, are often higher than the recommended and, thus, the performance is slightly penalized.

These curves are quite different from the ones obtained for Costeira system, suggesting that the performance of different systems regarding water age should not be based on a single, universal performance function.

6.3 Performance Assessment

6.3.1 Water quality assessment using water age performance curves

Water quality performance in the two case studies was assessed by applying existing and developed water age performance curves. Average water age at each consumption node was converted into a performance index (PI) from 0 to 1 by using equations 1, 3, 4, 9 and 10. Nodes in the network with no demand, for which water age increases linearly over time were not considered. Then, a global performance index was determined as the average of the indexes of all the consumption nodes. The results for Costeira system in Winter (1698 nodes) and in Summer (1688 nodes) are presented in Table 6.7.

Table 6.7 – Water age global performance index - Case Study 1

	Average Water age (h)	Global Water age Performance Index			
		Costeira	Coelho (1996)	Shokoohi et al (2017)	Nyirenda & Tanyimboh (2020)
Winter Conditions	41.16	0.64	0.32	0.72	0.62
Summer Conditions	21.55	0.74	0.55	0.84	0.74

The global water age performance index obtained ranges from 0.32 to 0.72 for Winter conditions and from 0.55 to 0.84 for Summer conditions. The results demonstrate that the WDS may be evaluated regarding water age as performing well (PI of 0.74) or performing in an unacceptable way (PI of 0.32), depending on the performance function used. In general, Shokoohi et al (2017) function gives the highest performance index, because it considers that water quality problems only occur when water age is higher than 48h, which is higher than the average water age in the network in both Winter and Sumer. On the opposite, Coelho (1996) function is the most penalyzing to water age performance due to the low upper limit for water age (10 h). Surprisingly, Nyirenda & Tanyimboh (2020) function, developed for storage tanks, gives PI values much similar to the ones obtained with the developed performance curves. This is likely due to a balance between not penalizing nodes where water age is in the 22 - 48h (winter) or 16 – 48h (summer), which have null performance in the developed functions, and linearly penalizing the nodes where water age is in the range of 11 - 18h (Winter) or 9 – 14 h (Summer), which have maximum performance in the developed functions.

In general, the global performance index determined by the new performance functions suggest that Costeira system behaves better in summer (PI of 0.74) than in Winter (PI of 0.64), that is, the decrease in water demand in winter has a greater effect on water quality, by increasing stagnation, than the temperature increase in summer. By using the performance functions, applied to all the consumption nodes, one can have a better idea of the global water age in the system than by evaluating only the results of water quality analyses obtained for a small set of samples, which can hardly be representative of the whole system.

The results for Quinta do Lago system in winter (1057 nodes) and in summer (1175 nodes) are presented in Table 6.8.

Table 6.8 – Water age performance - Case Study 2

	Average Water age (h)	Global Water age Performance Index			
		Quinta do Lago	Coelho (1996)	Shokoohi et al (2017)	Nyirenda & Tanyimboh (2020)
Winter Conditions	52.63	0.93	0.02	0.27	0.22
Summer Conditions	14.44	0.91	0.46	0.86	0.74

The global water age performance index obtained ranges from 0.02 to 0.93 for Winter conditions and from 0.46 to 0.91 for Summer conditions. Again, the results show that very diferent results are obtained depending on the used performance function and that the existing functions in literature are specific for a given system in certain conditions and can not be universaly applied.

Once again, Coelho (1996) function is the most penalizing one, due to the very low upper limit of 10 h and Shokoohi et al (2017) functions give the highest PI of all functions in literature. Nyirenda &Tanyimboh (2020) function results are not similar to those obtained with the new functions, as observed in case study 1. Particularly for the Winter conditions, the existing curves presented in the literature do not seem to be usable to assess water quality, as water age, in Quinta do Lago system.

The functions developed for Quinta do Lago show that the performance of the system regarding water age is very good and similar in both Winter and Summer, which is in agreement with the water quality control analysis.

On the face of this varying results it is advisable to develop PI curves independently for each system and limiting the time span, considering different environmental conditions, for the applicability of these curves.

6.3.2 Water quality assessment in current and optimized conditions

In this section, Costeira system operational conditions were optimized for improving water age while supplying water with the adequate pressure (25 m). A particle swarm optimization algorithm was used to determine the status of the shut-off valves in the network so that water flow was re-routed. Instead of minimizing water age at all nodes, the objective function was to keep water age at the consumption nodes under 22 h whenever possible, given the existing water demand and infrastructure, according to the developed performance function (Equation 9).

Nodal water age for the last 24 hours of the simulation was extracted from EPANET’s results report and the average nodal water age was computed for each node. The results were then put side by side with the ones extracted from the winter simulation for comparison (Figure 6.18).

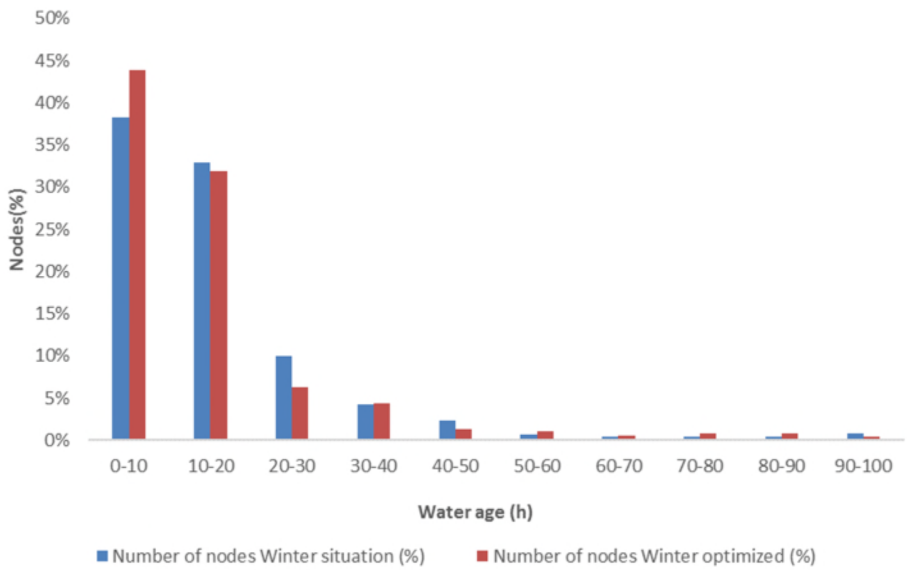
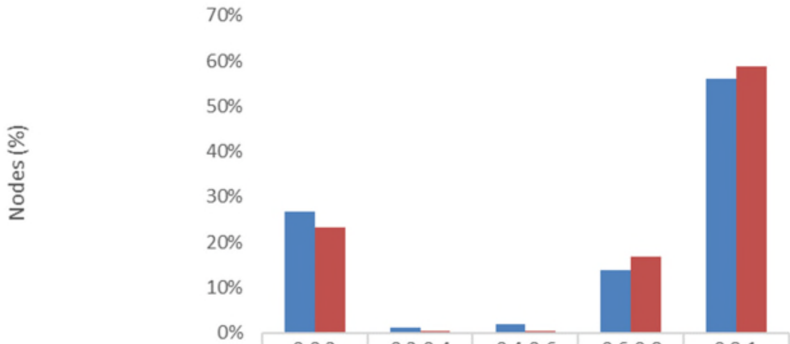


Figure 6.18 – Distribution of the average water age at the nodes in current and optimized conditions

After optimizing the system, the number of nodes where water age is higher than 22 h decreases from 26% to 23%. Consequently, the number of nodes where water age is low (lower than 10 hours) increases by 6%. The percentage of nodes with water age from 10 to 20 hours only shows a slight decrease. In this case study, a small percentage of nodes has average water age higher than 30 h, in both current and optimized conditions. However, in those nodes the water age can be as high as 100 h. In these nodes the performance index will be null according to the WDS performance curve obtained for this case.

In addition to helping in setting water age goals in the optimization problem, the developed performance function was also used to assess the optimization results (See Figure 6.19). By distributing the nodal water age in performance intervals, it is clear that the optimization reduced the number of nodes where performance index in the current conditions is within 0.0 to 0.2. However, the improvement is rather small and, most probably, reducing water age at those nodes requires other measures than simply opening or closing existing valves.



	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1
Performance Base Winter situation	26.78%	1.25%	1.95%	13.89%	56.13%
Performance optimized Winter scenario	23.38%	0.57%	0.50%	16.72%	58.83%

Figure 6.19 – Distribution of nodes according to PI intervals in current and optimized conditions

The performance indexes obtained for the nodes in the two conditions were averaged to determine the global system PI. The improvement achieved for the global PI was from 0.65 in the current winter conditions to 0.69 in the optimized situation. While this is not a huge improvement, these results demonstrate it is possible to minimize water age and reduce the potential number of clients affected by the adverse effects related with a high water age by operating valves to re-route the flows in the network and improve water age and the performance of the system. In addition, it demonstrates the usefulness of the developed performance function in assessing performance of an operation scenario.

7 CONCLUSIONS

7.1 Summary and general conclusions

In this thesis, water age performance functions were developed for two WDS in two different seasons. The performance functions are based on observed correlations between water age and chlorine concentrations in the system. The whole work was based on the analysis of existing water quality datasets gathered by the water utilities for the water quality control programs, and on determined water age by hydraulic simulation of the systems in real conditions.

Despite the water utilities provided data for many water quality parameters, the only one with sufficient data to be correlated with water age was free chlorine. Even so, these chlorine data series suffered from lack of records in some ranges, especially the lower ones, below 0.2 mg/L.

Close to linear relationships between water age and chlorine were observed in both case studies, particularly in Costeira system, where the water follows two well defined routes in the water mains and most sampling locations were found to be close to the connections of the DMAs and the water mains.

A general chlorine performance function was developed. The criteria for setting the upper and lower limits and correspondent performance index was based on the concentration range recommended by the national law and on the WHO guidelines for drinking water quality. This function was used in this thesis to convert chlorine concentrations in water to performance indexes.

The developed water age performance functions for the two WDS are diferent in shape and in upper limits. This is probably due to the diferent water quality, water temperature and the pipes materials and conditions, which determine the time the water can remain in the systems without water quality degradation. Hence, the application of these functions and of the existing ones to the case studies lead to very diferent results. As such it is recommended that performance curves be developed for each individual system as opposed to using generalized performance curves. This procedure should be revised and updated periodically or in the event, large consumers or configuration changes are introduced to the WDS.

One performance function and its upper limit was used to assess water age improvement in Costeira system in an idealized scenario where check-valves status would be optimized improving water quality. The performance function proved to be usefull in setting water age goals and for analysing the results obtained. The methodology used in this thesis can also be used by the water utilities to establish particularized performance functions and water age goals.

7.2 Recommendations for future work

The methodology for determining water age performance functions could be further developed by incorporating water quality datasets from samples collected specificaly for this purpose in several locations throughout the system, including the network far extremities. The samples should be analysed for residual chlorine and other parameters that obey to a specific standard or recommendations, such as THM.

The influence of the time span the water spends inside the head reservoir before entering the network should also be assessed.

Ideally, the developed models in which to further test the methodology would be throughoutly calibrated and validated and built on hydraulic simulators in which mixing at the nodes would be accurately modelled. The use of EPANET and all the existing simulators that consider complete mixing at the junctions might lead to errors in estimating water age, especially in smaller WDS or in pipes' extremities.

In addition to average or maximum water age, further analysis should look for relationships between water quality parameters and the retention time the water spends along the system while in high or low flow conditions.

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ANNEXES

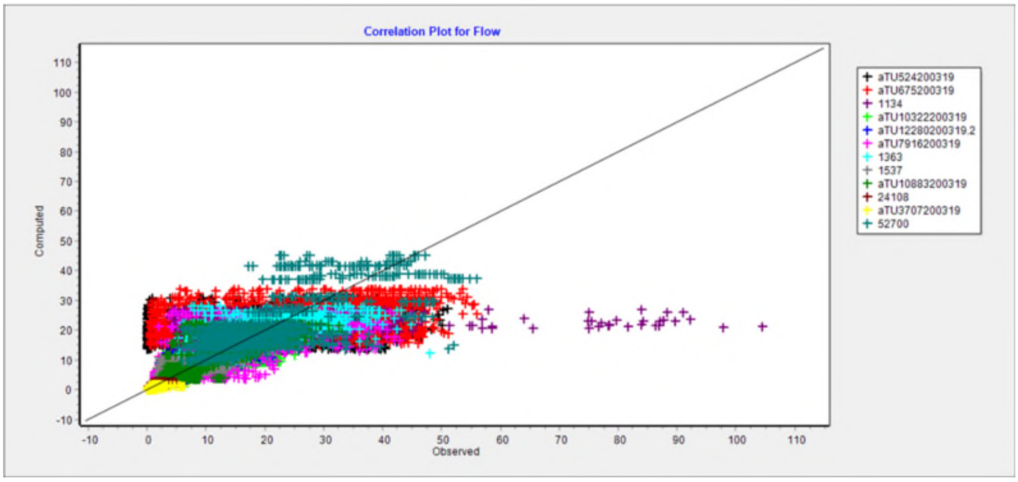
ANNEX I – Calibration of Case Study I

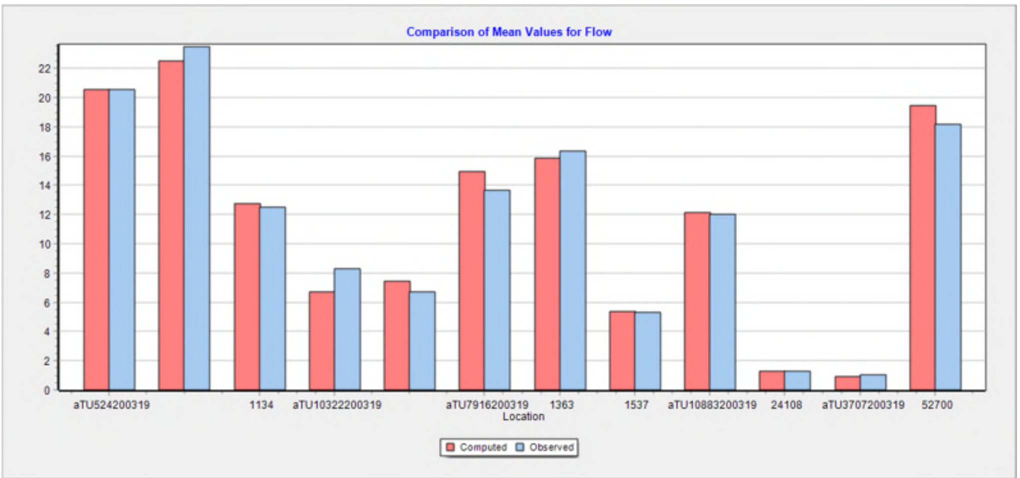
Demand calibration - February

Calibration Statistics for Flow

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
aTU524200319	2784	20.56	20.55	11.57	13.464
aTU675200319	2784	23.47	22.48	11.841	13.765
1134	2784	12.49	12.75	5.502	8.855
aTU10322200319	2784	8.28	6.71	2.478	3.285
aTU12280200319.2	2784	6.69	7.47	2.07	2.697
aTU7916200319	2784	13.66	14.92	4.567	6.037
1363	2784	16.34	15.86	2.925	4.415
1537	2784	5.32	5.36	1.161	1.704
aTU10883200319	2784	12.03	12.12	2.301	3.277
24108	2784	1.3	1.31	0.337	0.482
aTU3707200319	2784	1.01	0.92	0.325	0.52
52700	2784	18.16	19.45	4.204	5.999
Network	33408	11.61	11.66	4.107	6.912

Correlation Between Means: 0.994



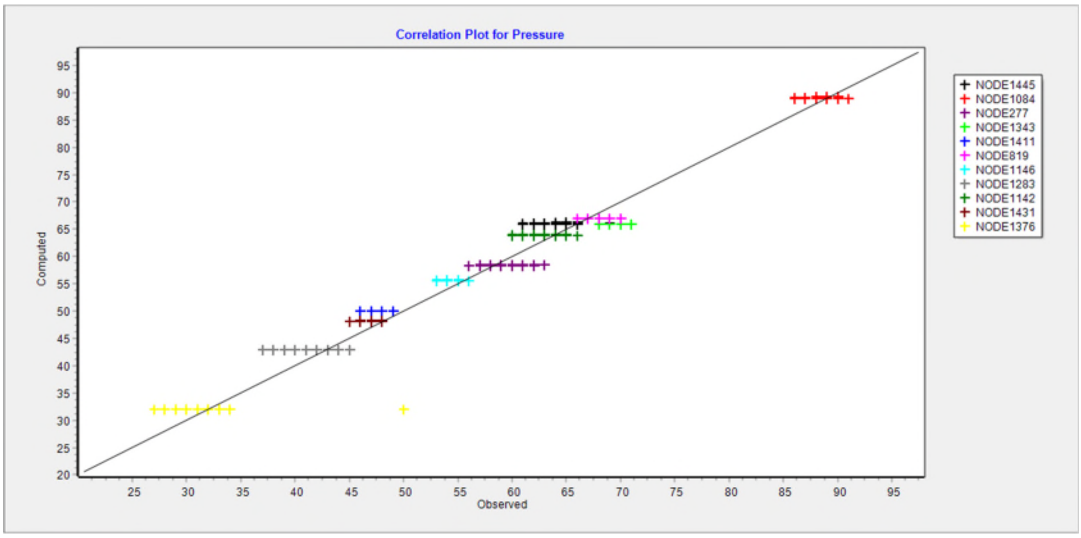


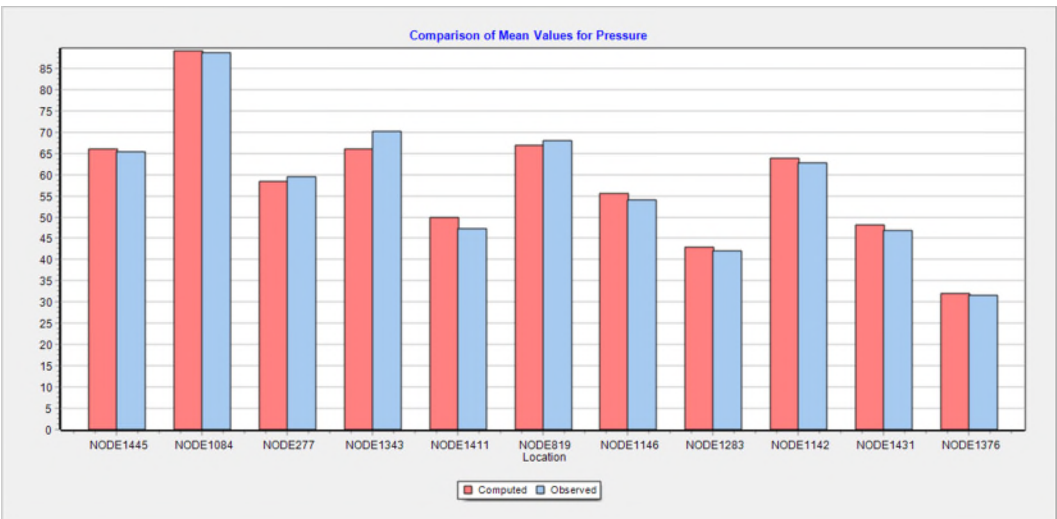
Pressure calibration - February

Calibration Statistics for Pressure

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
NODE1445	2784	65.31	66.13	0.821	1.09
NODE1084	2784	88.58	89.13	0.607	0.807
NODE277	2784	59.42	58.41	1.093	1.24
NODE1343	2784	70.13	66	4.128	4.158
NODE1411	2784	47.21	49.96	2.754	2.792
NODE819	2784	68.07	66.96	1.109	1.21
NODE1146	2784	54.11	55.62	1.503	1.544
NODE1283	2784	42.1	42.96	0.98	1.611
NODE1142	2784	62.73	63.92	1.206	1.347
NODE1431	2784	46.79	48.14	1.353	1.418
NODE1376	2784	31.68	32	0.407	0.813
Network	30624	57.83	58.11	1.451	1.892

Correlation Between Means: 0.994





Demand calibration - August

Calibration Statistics for Flow

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
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aTU524200319	2784	22.48	22.8	9.968	11.911
aTU675200319	2784	27.65	35.2	11.903	15.154
1134	2784	22.72	22.23	10.03	12.904
aTU1032220031	92784	9.72	10.72	3.559	4.936
aTU1228020031	9.22784	13.66	13.91	3.312	5.353
aTU7916200319	2784	40.46	46.89	12.532	18.171
1363	2784	31.55	31.07	7.748	12.142
1537	2784	4.73	4.77	0.877	1.18
aTU1088320031	92784	17.83	18.88	5.875	8.295
24108	2784	3.1	3.2	1.486	2.675
aTU3707200319	2784	2.58	2.76	1.388	1.907
52700	2784	19.73	19.93	3.548	5.2
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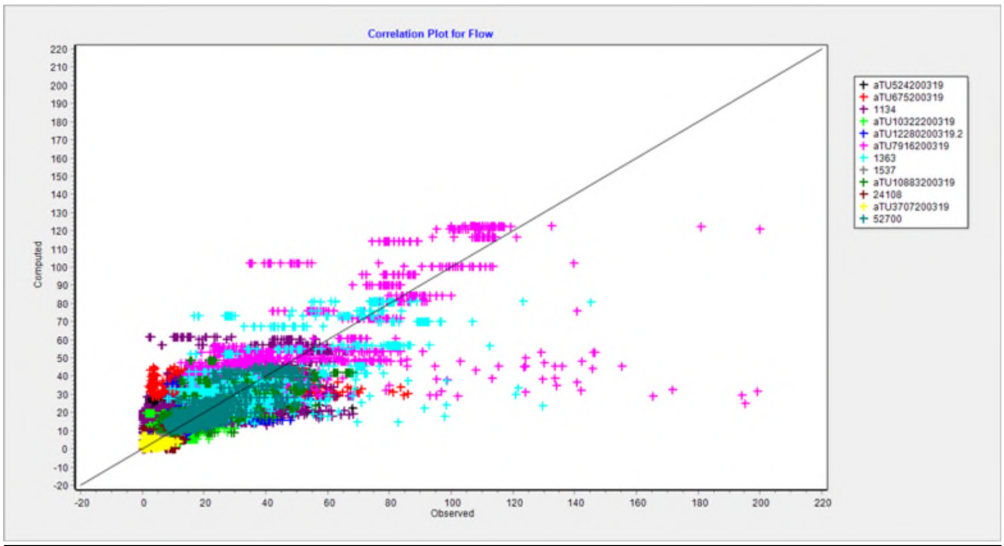
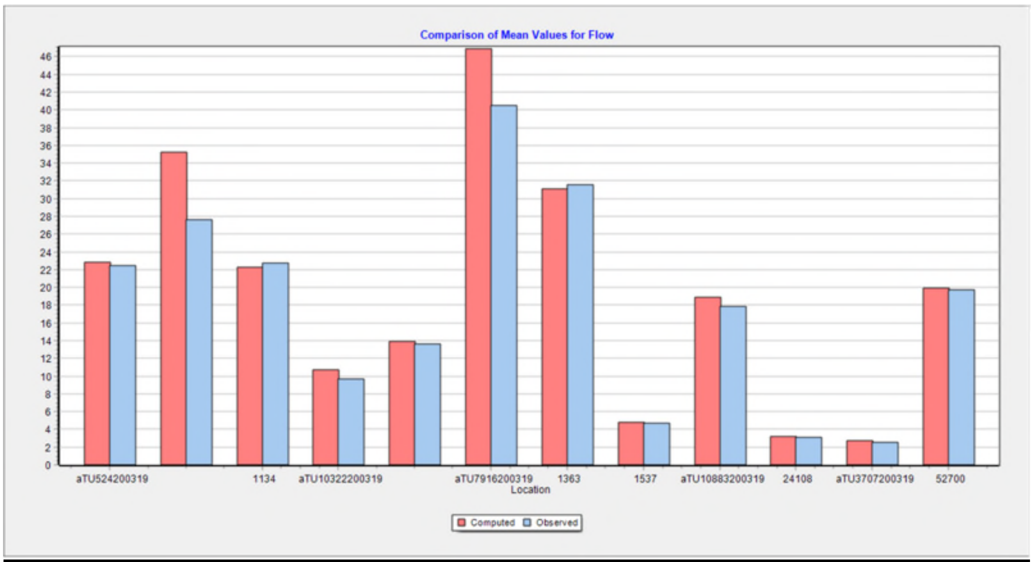
Network	33408	18.02	19.36	6.019	9.902

Correlation Between Means: 0.986





ANNEX II – Case Study I – Water quality data. Winter Conditions

Sample ID	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
1	Coliform bacteria	UFC/ 100 ml	2	2016-2020	0.00	0.00	0.00
	Free chlorine	mg/L Cl	6	2016-2020	0.39	0.65	0.97
	Escherichia Coli	UFC/100ml	2	2016-2020	0.00	0.00	0.00
2	Free chlorine	mg/L Cl	2	2015	0.43	0.47	0.51
3	Coliform bacteria	UFC/ 100 ml	2	2015-2019	0.00	0.00	0.00
	Free chlorine	mg/L Cl	11	2017-2020	0.55	0.88	1.18
	Escherichia Coli	UFC/100ml	2	2015-2019	0.00	0.00	0.00
4	Coliform bacteria	UFC/ 100 ml	0	2017-2020	0.00	0.00	0.00
	Free chlorine	mg/L Cl	168	2015-2020	0.60	1.14	1.96
	Escherichia Coli	UFC/100ml	13	2016-2020	0.00	0.00	0.00
	Bromodichloromethane	µg/L	1	2017	4.00	4.00	4.00
	Bromoform	µg/L	1	2017	<3	<3	<3
	Chloroform		1	2017	15.00	15.00	15.00
	Dibromochloromethane	µg/L	1	2017	<3	<3	<3
	Enterococci	UFC/100ml	5	2017-2020	0.00	0.00	0.00
	HPC 22°C	UFC/ mL	8	2017-2020	Não Detectado	Não Detectado	Não Detectado
	HPC 36 ºC	UFC/1 ml	8	2017-2020	Não Detectado	Não Detectado	Não Detectado
5	Free chlorine	mg/L Cl	2	2015	0.49	0.62	0.74
6	Free chlorine	mg/L Cl	3	2016-2018	0.82	0.91	0.96
7	Free chlorine	mg/L Cl	32	2015-2020	0.21	0.66	1.16
	Coliform bacteria	UFC/ 100 ml	6	2015-2020	0.00	0.00	0.00
	Escherichia Coli	UFC/100ml	6	2015-2020	0.00	0.00	0.00
	Enterococci	UFC/100ml	1	2019	0.00	0.00	0.00
	HPC 22°C	ufc/ mL	1	2019	Não Detectado	Não Detectado	Não Detectado
	HPC 36 ºC	UFC/1 ml	1	2019	Não Detectado	Não Detectado	Não Detectado
8	Coliform bacteria	UFC/ 100 ml	2	2017-2018	0.00	0.00	0.00

Sample ID	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Free chlorine	mg/L Cl	10	2016-2018	0.91	1.11	1.40
	Escherichia Coli	UFC/100ml	2	2017-2018	0.00	0.00	0.00
9	Coliform bacteria	UFC/ 100 ml	2	2016-2018	0.00	0.00	0.00
	Free chlorine	mg/L Cl	8	2016-2020	0.05	0.98	1.35
	Escherichia Coli	UFC/100ml	2	2016-2018	0.00	0.00	0.00
	HPC 22°C	UFC/ mL	1	2018	Não Detectado	Não Detectado	Não Detectado
	HPC 36 ºC	UFC/1 ml	1	2018	Não Detectado	Não Detectado	Não Detectado
10	Free chlorine	mg/L Cl	2	2017-2018	1.06	1.13	1.12
11	Free chlorine	mg/L Cl	1	2019	0.80	0.80	0.80
12	Free chlorine	mg/L Cl	1	2019	0.65	0.65	0.65
13	Coliform bacteria	UFC/ 100 ml	1	2019	0.00	0.00	0.00
	Free chlorine	mg/L Cl	1	2019	0.80	0.80	0.80
	Escherichia Coli	UFC/100ml	1	2019	0.00	0.00	0.00
14	Free chlorine	mg/L Cl	2	2017	1.27	1.38	1.49
15	Free chlorine	mg/L Cl	2	2015	0.41	0.49	0.56
16	Free chlorine	mg/L Cl	2	2015-2020	0.16	0.36	0.55
17	Coliform bacteria	UFC/ 100 ml	1	2015	0.00	0.00	0.00
	Free chlorine	mg/L Cl	3	2015	0.29	0.48	0.59
	Escherichia Coli	UFC/100ml	1	2015	0.00	0.00	0.00
18	Free chlorine	mg/L Cl	1	2020	0.49	0.49	0.49
19	Free chlorine	mg/L Cl	1	2020	0.72	0.72	0.72
20	Coliform bacteria	UFC/ 100 ml	1	2015	0.00	0.00	0.00
	Free chlorine	mg/L Cl	2	2015	0.22	0.37	0.52
	Escherichia Coli	UFC/100ml	1	2015	0.00	0.00	0.00
21	Free chlorine	mg/L Cl	1	2016	0.00	0.00	0.00
22	Coliform bacteria	UFC/ 100 ml	2	2015	0.00	0.00	0.00
	Free chlorine	mg/L Cl	2	2015	0.29	0.45	0.61
	Escherichia Coli	UFC/100ml	2	2015	0.00	0.00	0.00
23	Free chlorine	mg/L Cl	2	2019	0.01	0.03	0.05
24	Free chlorine	mg/L Cl	2	2015	0.38	0.43	0.47
25	Coliform bacteria	UFC/ 100 ml	1	2017	0.00	0.00	0.00
	Free chlorine	mg/L Cl	1	2017	1.18	1.18	1.18

Sample ID	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Escherichia Coli	UFC/100ml	1	2017	0.00	0.00	0.00
	HPC 22°C	ufc/ mL	1	2017	Não Detectado	Não Detectado	Não Detectado
	HPC 36 ºC	UFC/1 ml	1	2017	Não Detectado	Não Detectado	Não Detectado
26	Free chlorine	mg/L Cl	1	2015	0.70	0.70	0.70
27	Free chlorine	mg/L Cl	1	2015	0.58	0.58	0.58
28	Free chlorine	mg/L Cl	1	2018	1.00	1.00	1.00
29	Free chlorine	mg/L Cl	1	2019	0.33	0.33	0.33
30	Free chlorine	mg/L Cl	1	2015	0.27	0.27	0.27
31	Free chlorine	mg/L Cl	1	2020	0.20	0.20	0.20
32	Free chlorine	mg/L Cl	1	2015	0.40	0.40	0.40
33	Coliform bacteria	UFC/ 100 ml	2	2020	0.00	0.00	0.00
	Free chlorine	mg/L Cl	2	2020	0.01	0.05	0.08
	Escherichia Coli	UFC/100ml	2	2020	0.00	0.00	0.00
34	Coliform bacteria	UFC/ 100 ml	1	2020	0.00	0.00	0.00
	Free chlorine	mg/L Cl	1	2020	0.01	0.01	0.01
	Escherichia Coli	UFC/100ml	1	2020	0.00	0.00	0.00
35	Coliform bacteria	UFC/ 100 ml	1	2020	0.00	0.00	0.00
	Free chlorine	mg/L Cl	1	2020	0.06	0.06	0.06
	Escherichia Coli	UFC/100ml	1	2020	0.00	0.00	0.00

ANNEX III – Case Study I – Water quality data. Summer Conditions

Sample ID	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
1	Free Chlorine	mg/L Cl	1	2017	1.20	1.20	1.20
	Total Residual Chlorine	mg/L Cl	1	2017	1.53	1.53	1.53
4	Coliform bacteria	UFC/ 100 ml	6	2015 2019	0.00	0.00	0.00
	Free Chlorine	mg/L Cl	71	2015-2019	0.75	1.12	1.68
	Total Residual Chlorine	mg/L Cl	72	2015-2019	0.94	1.36	1.65
	Escherichia Coli	UFC/100ml	6	2015-2019	0.00	0.00	0.00
	Bromodichloromethane	µg/L	1	2015	6.00	6.00	6.00
	Bromoform	µg/L	1	2015	<3	<3	<3
	Cloroform	µg/L	1	2015	17.00	17.00	17.00
	Dibromochloromethane	µg/L	1	2015	3.00	3.00	3.00
	Total Organic Carbon	mg C/L	1	2015	3.80	3.80	3.80
	Enterococci	UFC/100ml	2	2015-2019	0.00	0.00	0.00
	Oxidability	UFC/ 100 ml	2	2015-2019	2.60	3.15	3.70
	HPC at 22°C	ufc/ mL	2	2015-2019	Não Detectado	Não Detectado	Não Detectado
	HPC at 36 ºC	UFC/1ml	2	2015-2019	Não Detectado	Não Detectado	Não Detectado
7	Free Chlorine	mg/L Cl	20	2015-2019	0.41	0.84	1.19
	Coliform bacteria	UFC/ 100 ml	4	2018-2019	0.00	0.00	0.00
	Total Residual Chlorine	mg/L Cl	16	2015-2019	0.51	1.03	1.44
	Escherichia Coli	UFC/100ml	4	2018-2019	0.00	0.00	0.00
	Oxidability	UFC/ 100 ml	2	2015-2019	2.60	2.60	2.60
	HPC at 22°C	ufc/ mL	1	2018	Não Detectado	Não Detectado	Não Detectado
	HPC at 36 ºC	UFC/1ml	1	2019	3.00	3.00	3.00
14	Free Chlorine	mg/L Cl	3	2016	1.20	1.30	1.38
	Total Residual Chlorine	mg/L Cl	3	2016	1.37	1.50	1.64
22	Free Chlorine	mg/L Cl	4	2019	0.03	0.05	0.07
	Total Residual Chlorine	mg/L Cl	4	2019	0.21	0.23	0.26
24	Free Chlorine	mg/L Cl	10	2019	0.00	0.03	0.06
	Total Residual Chlorine	mg/L Cl	10	2019	0.03	0.07	0.10
30	Free Chlorine	mg/L Cl	1	2016	1.12	1.12	1.12
	Total Residual Chlorine	mg/L Cl	1	2016	1.33	1.33	1.33
36	Free Chlorine	mg/L Cl	6	2015-2017	0.47	0.93	1.12
	Total Residual Chlorine	mg/L Cl	5	2015-2017	0.71	1.12	1.42

Sample ID	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Coliform bacteria	UFC/ 100 ml	3	2015-2017	0.00	0.00	0.00
	Escherichia Coli	UFC/100ml	3	2015-2017	0.00	0.00	0.00
37	Free Chlorine	mg/L Cl	10	2019	0.01	0.03	0.06
	Total Residual Chlorine	mg/L Cl	10	2019	0.03	0.08	0.15
38	Free Chlorine	mg/L Cl	10	2019	0.00	0.04	0.08
	Total Residual Chlorine	mg/L Cl	10	2019	0.06	0.11	0.17
39	Free Chlorine	mg/L Cl	2	2019	0.72	0.72	0.72
	Total Residual Chlorine	mg/L Cl	1	2019	1.01	1.01	1.01
	Coliform bacteria	UFC/ 100 ml	1	2019	0.00	0.00	0.00
	Escherichia Coli	UFC/100ml	1	2019	0.00	0.00	0.00

ANNEX IV – Case Study 2 – Water quality data. Winter Conditions

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
1	Free chlorine	mg/L	1	2014	0.00	0.20	0.20
	Escherichia coli	#/100 mL	2	2009 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2009 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2009 2014	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	2	2009 2014	0.00	0.00	0.00
	Conductivity	µS/cm	2	2009 2014	210.00	229.00	248.00
	Clostridium perfringens	N/100 mL	2	2009 2014	0.00	0.00	0.00
	pH	Units pH	2	2009 2014	7.70	7.70	7.70
	Oxidability	mg/L O2	1	2009	4.50	4.50	4.50
3	Free chlorine	mg/L	3	2012 2014	0.40	0.47	0.60
	Escherichia coli	#/100 mL	3	2012 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2012 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2012	0.00	0.00	0.00
	Conductivity	µS/cm	1	2012	220.00	220.00	220.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	Units pH	1	2012	7.80	7.80	7.80
	Oxidability	mg/L O2	1	2012	1.50	1.50	1.50
	Manganese	mg/L	1	2012	7.00	7.00	7.00
	Aluminium	µg/L	1	2012	20.00	20.00	20.00
5	Free chlorine	mg/L	5	2008 2015	0.25	0.42	0.60
	Escherichia coli	#/100 mL	5	2008 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	5	2008 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2014	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	2	2008 2014	0.00	0.00	0.00
	Conductivity	µS/cm	2	2008 2014	210.00	225.00	240.00
	Clostridium perfringens	N/100 mL	2	2008 2014	0.00	0.00	0.00
	pH	Units pH	2	2008 2014	7.90	7.95	8.00
	Oxidability	mg/L O2	1	2008	1.30	1.30	1.30
	Manganese	mg/L	1	2014	5.00	5.00	5.00
	Aluminium	µg/L	1	2014	26.00	26.00	26.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
6	Free chlorine	mg/L	1	2009	0.24	0.24	0.24
	Escherichia coli	#/100 mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2009	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2009	6.00	6.00	6.00
	Conductivity	µS/cm	1	2009	231.00	231.00	231.00
	Clostridium perfringens	N/100 mL	1	2009	0.00	0.00	0.00
	pH	Units pH	1	2009	7.50	7.50	7.50
	Oxidability	mg/L O2	1	2009	0.70	0.70	0.70
7	Free chlorine	mg/L	1	2008	0.40	0.40	0.40
	Escherichia coli	#/100 mL	1	2008	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2008	0.00	0.00	0.00
8	Free chlorine	mg/L	2	2008 2009	0.37	0.69	1.00
	Escherichia coli	#/100 mL	2	2008 2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2008 2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2009	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2009	0.00	0.00	0.00
	Conductivity	µS/cm	1	2009	240.00	240.00	240.00
	Clostridium perfringens	N/100 mL	1	2009	0.00	0.00	0.00
	pH	Units pH	1	2009	7.90	7.90	7.90
	Oxidability	mg/L O2	1	2009	0.70	0.70	0.70
9	Free chlorine	mg/L	1	2009	0.28	0.28	0.28
	Escherichia coli	#/100 mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2009	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2009	0.00	0.00	0.00
	Conductivity	µS/cm	1	2009	248.00	248.00	248.00
	Clostridium perfringens	N/100 mL	1	2009	0.00	0.00	0.00
	pH	Units pH	1	2009	7.80	7.80	7.80
10	Free chlorine	mg/L	1	2014	0.20	0.20	0.20
	Escherichia coli	#/100 mL	3	2013 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2013 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	3	2013 2015	0.00	34.33	103.00
	HPC at 36 ºC	N/mL	3	2013 2015	0.00	24.00	71.00
	Conductivity	µS/cm	3	2013 2015	220.00	220.00	220.00
	Clostridium perfringens	N/100 mL	3	2013 2015	0.00	0.00	0.00
	pH	Units pH	3	2013 2015	8.20	8.50	8.80

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Oxidability	mg/L O2	2	2013 2015	1.20	1.40	1.60
	Calcium	mg/L Ca	1	2014	25.00	25.00	25.00
	Total hardness	mg/L Ca CO3	1	2014	93.00	93.00	93.00
	Enterococci	#/100 mL	1	2014	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2014	7.00	7.00	7.00
	Cloroform	µg/L	1	2014	9.38	9.38	9.38
	Bromoform	µg/L	1	2014	3.52	3.52	3.52
	Dibromochloromethane	µg/L	1	2014	11.30	11.30	11.30
	Bromodichloromethane	µg/L	1	2014	10.50	10.50	10.50
	Turbidity	UNT	2	2013 2015	0.40	0.45	0.50
	Copper	mg/L	1	2014	0.02	0.02	0.02
	Manganese	mg/L	1	2015	2.61	2.61	2.61
	Aluminium	µg/L	2	2014 2015	28.00	52.00	76.00
11	Free chlorine	mg/L	1	2014	0.40	0.40	0.40
	Escherichia coli	#/100 mL	1	2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2014	2.00	2.00	2.00
	HPC at 36 ºC	N/mL	1	2014	2.00	2.00	2.00
	Conductivity	µS/cm	1	2014	210.00	210.00	210.00
	Clostridium perfringens	N/100 mL	1	2014	0.00	0.00	0.00
	pH	Units pH	1	2014	7.90	7.90	7.90
	Turbidity	UNT	1	2014	0.40	0.40	0.40
	Manganese	mg/L	1	2014	6.00	6.00	6.00
	Aluminium	µg/L	1	2014	20.00	20.00	20.00
13	Free chlorine	mg/L	1	2012	0.40	0.40	0.40
	Escherichia coli	#/100 mL	2	2010 2012	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2010 2012	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2012	0.00	0.00	0.00
	Conductivity	µS/cm	1	2012	210.00	210.00	210.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	Units pH	1	2012	7.80	7.80	7.80
	Oxidability	mg/L O2	1	2012	1.50	1.50	1.50
	Manganese	mg/L	1	2012	9.00	9.00	9.00
	Aluminium	µg/L	1	2012	24.00	24.00	24.00
15	Free chlorine	mg/L	2	2014 2015	0.30	0.45	0.60
	Escherichia coli	#/100 mL	2	2014 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2014 2015	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	HPC at 22 ºC	N/mL	1	2015	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2015	0.00	0.00	0.00
	Conductivity	µS/cm	1	2015	230.00	230.00	230.00
	Clostridium perfringens	N/100 mL	1	2015	0.00	0.00	0.00
	pH	Units pH	1	2015	7.70	7.70	7.70
	Oxidability	mg/L O2	1	2015	1.00	1.00	1.00
	Manganese	mg/L	1	2015	2.53	2.53	2.53
	Aluminium	µg/L	1	2015	18.00	18.00	18.00
16	Free chlorine	mg/L	3	2010 2015	0.40	0.46	0.49
	Escherichia coli	#/100 mL	3	2010 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2010 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2010 2015	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	2	2010 2015	0.00	0.00	0.00
	Conductivity	µS/cm	2	2010 2015	215.00	222.50	230.00
	Clostridium perfringens	N/100 mL	2	2010 2015	0.00	0.00	0.00
	pH	Units pH	2	2010 2015	7.80	7.90	8.00
	Oxidability	mg/L O2	1	2010	0.80	0.80	0.80
	Calcium	mg/L Ca	1	2015	25.00	25.00	25.00
	Total hardness	mg/L Ca CO3	1	2015	93.00	93.00	93.00
	Enterococci	#/100 mL	1	2015	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2015	7.00	7.00	7.00
	Cloroform	µg/L	1	2015	8.04	8.04	8.04
	Bromoform	µg/L	1	2015	4.86	4.86	4.86
	Dibromochloromethane	µg/L	1	2015	19.50	19.50	19.50
	Bromodichloromethane	µg/L	1	2015	10.50	10.50	10.50
	Turbidity	UNT	1	2015	0.50	0.50	0.50
	Copper	mg/L	1	2015	0.01	0.01	0.01
	Iron	µg/L	1	2015	2.10	2.10	2.10
	Manganese	mg/L	1	2015	0.83	0.83	0.83
	Aluminium	µg/L	1	2015	26.00	26.00	26.00
19	Free chlorine	mg/L	1	2012	0.60	0.60	0.60
	Escherichia coli	#/100 mL	1	2012	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2012	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2012	0.00	0.00	0.00
	Conductivity	µS/cm	1	2012	190.00	190.00	190.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	Units pH	1	2012	7.90	7.90	7.90

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Oxidability	mg/L O2	1	2012	1.50	1.50	1.50
	Aluminium	µg/L	1	2012	23.00	23.00	23.00
20	Free chlorine	mg/L	1	2008	0.10	0.10	0.10
	Escherichia coli	#/100 mL	4	2008 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	4	2008 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	4	2008 2014	0.00	1.50	5.00
	HPC at 36 ºC	N/mL	4	2008 2014	0.00	0.00	0.00
	Conductivity	µS/cm	4	2008 2014	210.00	221.00	240.00
	Clostridium perfringens	N/100 mL	4	2008 2014	0.00	0.00	0.00
	pH	Units pH	4	2008 2014	7.60	7.95	8.40
	Oxidability	mg/L O2	4	2008 2014	0.70	1.13	1.60
	Turbidity	UNT	1	2013	0.40	0.40	0.40
	Manganese	mg/L	1	2013	8.00	8.00	8.00
	Amonia	mg/L	1	2008	0.21	0.21	0.21
	Aluminium	µg/L	2	2008 2014	26.00	43.00	60.00
24	Free chlorine	mg/L	2	2010 2013	0.19	0.20	0.20
	Escherichia coli	#/100 mL	3	2010 2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2010 2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2010 2013	0.00	5.00	10.00
	HPC at 36 ºC	N/mL	2	2010 2013	0.00	2.00	4.00
	Conductivity	µS/cm	2	2010 2013	200.00	208.00	216.00
	Clostridium perfringens	N/100 mL	2	2010 2013	0.00	0.00	0.00
	pH	Units pH	2	2010 2013	7.40	7.55	7.70
	Oxidability	mg/L O2	2	2010 2013	1.00	1.45	1.90
	Calcium	mg/L Ca	1	2010	27.00	27.00	27.00
	Total hardness	mg/L Ca CO3	1	2010	92.00	92.00	92.00
	Enterococci	#/100 mL	1	2010	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2010	6.00	6.00	6.00
	Cloroform	µg/L	1	2010	21.60	21.60	21.60
	Bromoform	µg/L	1	2010	1.33	1.33	1.33
	Dibromochloromethane	µg/L	1	2010	11.10	11.10	11.10
	Bromodichloromethane	µg/L	1	2010	13.60	13.60	13.60
	Turbidity	UNT	1	2013	0.50	0.50	0.50

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Copper	mg/L	1	2010	0.03	0.03	0.03
	Iron	µg/L	1	2010	90.00	90.00	90.00
	Manganese	mg/L	2	2010 2013	8.00	12.00	16.00
	Aluminium	µg/L	1	2013	31.00	31.00	31.00
27	Free chlorine	mg/L	1	2013	0.50	0.50	0.50
	Escherichia coli	#/100 mL	1	2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2013	0.00	0.00	0.00
25	Free chlorine	mg/L	6	2009 2015	0.20	0.42	0.60
	Escherichia coli	#/100 mL	6	2009 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	6	2009 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	4	2009 2015	0.00	1.75	4.00
	HPC at 36 ºC	N/mL	4	2009 2015	0.00	0.00	0.00
	Conductivity	µS/cm	4	2009 2015	200.00	212.00	238.00
	Clostridium perfringens	N/100 mL	4	2009 2015	0.00	0.00	0.00
	pH	Units pH	4	2009 2015	7.40	7.50	7.70
	Oxidability	mg/L O2	3	2009 2015	0.50	0.97	1.40
	Calcium	mg/L Ca	1	2013	26.00	26.00	26.00
	Total hardness	mg/L Ca CO3	1	2013	120.00	120.00	120.00
	Magnesium	mg/L Mg	1	2013	7.00	7.00	7.00
	Cloroform	µg/L	1	2013	15.00	15.00	15.00
	Bromoform	µg/L	1	2013	1.63	1.63	1.63
	Dibromochloromethane	µg/L	1	2013	10.00	10.00	10.00
	Bromodichloromethane	µg/L	1	2013	11.80	11.80	11.80
	Copper	mg/L	1	2013	0.07	0.07	0.07
	Manganese	µg/L	1	2015	0.70	0.70	0.70
	Aluminium	µg/L	2	2012 2015	22.00	22.00	22.00
29	Free chlorine	mg/L	2	2008 2010	0.20	0.37	0.53
	Escherichia coli	#/100 mL	2	2008 2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2008 2010	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2010	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2010	0.00	0.00	0.00
	Conductivity	µS/cm	1	2010	209.00	209.00	209.00
	Clostridium perfringens	N/100 mL	1	2010	0.00	0.00	0.00
	pH	Units pH	1	2010	7.80	7.80	7.80
	Oxidability	mg/L O2	1	2010	0.70	0.70	0.70

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
30	Free chlorine	mg/L	1	2008	0.60	0.60	0.60
	Escherichia coli	#/100 mL	3	2008 2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2008 2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2013	0.00	2.00	4.00
	HPC at 36 ºC	N/mL	2	2008 2013	0.00	9.00	18.00
	Conductivity	µS/cm	2	2008 2013	450.00	515.00	580.00
	Clostridium perfringens	N/100 mL	2	2008 2013	0.00	0.00	0.00
	pH	Units pH	2	2008 2013	7.70	7.75	7.80
31	Free chlorine	mg/L	2	2009 2012	0.20	0.30	0.40
	Escherichia coli	#/100 mL	3	2009 2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2009 2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	6.00	6.00	6.00
	HPC at 36 ºC	N/mL	1	2012	3.00	3.00	3.00
	Conductivity	µS/cm	1	2012	210.00	210.00	210.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	Units pH	1	2012	7.80	7.80	7.80
	Oxidability	mg/L O2	1	2012	1.10	1.10	1.10
	Calcium	mg/L Ca	1	2012	25.00	25.00	25.00
	Total hardness	mg/L Ca CO3	1	2012	90.00	90.00	90.00
	Enterococci	#/100 mL	1	2012	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2012	7.00	7.00	7.00
	Cloroform	µg/L	1	2012	10.90	10.90	10.90
	Bromoform	µg/L	1	2012	1.93	1.93	1.93
	Dibromochloromethane	µg/L	1	2012	7.49	7.49	7.49
	Bromodichloromethane	µg/L	1	2012	7.46	7.46	7.46
	Turbidity	UNT	1	2012	0.50	0.50	0.50
	Copper	mg/L	1	2012	0.02	0.02	0.02
	Iron	µg/L	1	2012	65.00	65.00	65.00
32	Free chlorine	mg/L	1	2010	0.68	0.68	0.68
	Escherichia coli	#/100 mL	1	2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2010	0.00	0.00	0.00
33	Free chlorine	mg/L	1	2014	0.20	0.20	0.20
	Escherichia coli	#/100 mL	2	2014 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2014 2015	0.00	0.00	0.00
34	Free chlorine	mg/L	2	2008 2015	0.70	0.80	0.90

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Escherichia coli	#/100 mL	2	2008 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2008 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2015	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	2	2008 2015	0.00	0.00	0.00
	Conductivity	µS/cm	2	2008 2015	210.00	480.00	750.00
	Clostridium perfringens	N/100 mL	2	2008 2015	0.00	0.00	0.00
	pH	Units pH	2	2008 2015	7.30	7.50	7.70
	Oxidability	mg/L O2	1	2015	1.40	1.40	1.40
	Turbidity	UNT	2	2008 2015	0.49	0.50	0.50
	Manganese	mg/L	1	2015	2.27	2.27	2.27
	Aluminium	µg/L	1	2015	31.00	31.00	31.00
35	Free chlorine	mg/L	5	2009 2015	0.10	0.38	0.60
	Escherichia coli	#/100 mL	7	2008 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	7	2008 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	5	2008 2014	0.00	21.40	99.00
	HPC at 36 ºC	N/mL	5	2008 2014	0.00	0.00	0.00
	Conductivity	µS/cm	5	2008 2014	210.00	229.80	260.00
	Clostridium perfringens	N/100 mL	5	2008 2014	0.00	0.00	0.00
	pH	Units pH	5	2008 2014	7.70	8.16	8.70
	Oxidability	mg/L O2	5	2008 2014	0.90	1.18	1.40
	Turbidity	UNT	1	2012	0.80	0.80	0.80
	Manganese	mg/L	2	2012 2014	3.54	6.27	9.00
	Aluminium	µg/L	4	2008 2014	21.00	26.25	29.00
36	Free chlorine	mg/L	1	2009	0.20	0.20	0.20
	Escherichia coli	#/100 mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00
38	Free chlorine	mg/L	6	2008 2015	0.50	0.61	0.70
	Escherichia coli	#/100 mL	6	2008 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	6	2008 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2010	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	HPC at 36 ºC	N/mL	2	2008 2010	0.00	0.00	0.00
	Conductivity	µS/cm	2	2008 2010	212.00	221.00	230.00
	Clostridium perfringens	N/100 mL	2	2008 2010	0.00	0.00	0.00
	pH	Units pH	2	2008 2010	7.40	7.65	7.90
	Oxidability	mg/L O2	1	2008	1.60	1.60	1.60
	Calcium	mg/L Ca	1	2008	24.00	24.00	24.00
	Total hardness	mg/L Ca CO3	1	2008	92.00	92.00	92.00
	Enterococci	#/100 mL	1	2008	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2008	8.20	8.20	8.20
	Cloroform	µg/L	1	2008	21.00	21.00	21.00
	Bromoform	µg/L	1	2008	3.90	3.90	3.90
	Dibromochloromethane	µg/L	1	2008	16.00	16.00	16.00
	Bromodichloromethane	µg/L	1	2008	19.00	19.00	19.00
39	Free chlorine	mg/L	8	2008 2015	0.13	0.46	0.60
	Escherichia coli	#/100 mL	9	2008 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	9	2008 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	5	2008 2015	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	5	2008 2015	0.00	0.20	1.00
	Conductivity	µS/cm	5	2008 2015	210.00	221.20	235.00
	Clostridium perfringens	N/100 mL	5	2008 2015	0.00	0.00	0.00
	pH	Units pH	5	2008 2015	7.30	7.48	7.80
	Oxidability	mg/L O2	4	2008 2013	0.50	1.05	1.40
	Calcium	mg/L Ca	1	2009	26.00	26.00	26.00
	Total hardness	mg/L Ca CO3	1	2009	99.00	99.00	99.00
	Enterococci	#/100 mL	1	2009	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2009	8.00	8.00	8.00
	Cloroform	µg/L	1	2009	29.80	29.80	29.80
	Bromoform	µg/L	1	2009	2.70	2.70	2.70
	Dibromochloromethane	µg/L	1	2009	15.90	15.90	15.90
	Bromodichloromethane	µg/L	1	2009	20.30	20.30	20.30
	Copper	mg/L	1	2009	0.01	0.01	0.01
	Manganese	mg/L	2	2013 2015	3.44	9.07	14.70
	Aluminium	µg/L	2	2013 2015	19.00	21.50	24.00
40	Free chlorine	mg/L	1	2009	0.10	0.10	0.10

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Escherichia coli	#/100 mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00

ANNEX V – Case Study II – Water quality data. Summer Conditions

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
1	Free Chlorine	mg/L	2	2012 2013	0.20	0.35	0.50
	Escherichia coli	#/100mL	4	2010 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	4	2010 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	4	2010 2015	0.00	0.50	2.00
	HPC at 36 ºC	N/mL	4	2010 2015	0.00	0.00	0.00
	Conductivity	µS/cm	4	2010 2015	210.00	220.75	233.00
	Clostridium perfringens	N/100 mL	4	2010 2015	0.00	0.00	0.00
	pH	pH Units	4	2010 2015	7.50	7.80	8.00
	Oxidability	mg/L O2	2	2010 2013	1.00	1.20	1.40
	Calcium	mg/L Ca	1	2012	30.00	30.00	30.00
	Total hardness	mg/L Ca CO3	1	2012	140.00	140.00	140.00
	Enterococci	#/100mL	1	2012	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2012	7.00	7.00	7.00
	Cloroform	µg/L	1	2012	9.30	9.30	9.30
	Bromoform	µg/L	1	2012	1.94	1.94	1.94
	Dibromochloromethane	µg/L	1	2012	8.34	8.34	8.34
	Bromodichloromethane	µg/L	1	2012	9.12	9.12	9.12
	Manganese	µg/L	2	2013 2015	3.36	5.18	7.00
2	Free Chlorine	mg/L	5	2009 2015	0.22	0.39	0.60
	Escherichia coli	#/100mL	7	2008 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	7	2008 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	7	2008 2015	0.00	3.57	12.00
	HPC at 36 ºC	N/mL	7	2008 2015	0.00	1.43	10.00
	Conductivity	µS/cm	7	2008 2015	200.00	228.29	270.00
	Clostridium perfringens	N/100 mL	7	2008 2015	0.00	0.00	0.00
	pH	pH Units	7	2008 2015	7.50	7.74	7.90
	Oxidability	mg/L O_2	5	2008 2015	0.50	0.98	1.20
	Calcium	mg/L Ca	1	2013	27.00	27.00	27.00
	Total hardness	mg/L $CaCO_3$	1	2013	96.00	96.00	96.00
	Enterococci	#/100mL	1	2013	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Magnesium	mg/L Mg	1	2013	7.00	7.00	7.00
	Cloroform	µg/L	1	2013	19.70	19.70	19.70
	Bromoform	µg/L	1	2013	2.38	2.38	2.38
	Dibromochloromethane	µg/L	1	2013	10.10	10.10	10.10
	Bromodichloromethane	µg/L	1	2013	12.50	12.50	12.50
	Copper	mg/L	1	2013	0.01	0.01	0.01
	Manganese	mg/L	2	2013 2015	9.00	9.90	10.80
	Aluminium	µg/L	5	2008 2015	22.00	34.20	67.00
3	Free Chlorine	mg/L	2	2012 2015	0.60	0.65	0.70
	Escherichia coli	#/100mL	2	2012 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2012 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2012 2015	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	2	2012 2015	0.00	0.00	0.00
	Conductivity	µS/cm	2	2012 2015	210.00	215.00	220.00
	Clostridium perfringens	N/100 mL	2	2012 2015	0.00	0.00	0.00
	pH	pH Units	2	2012 2015	7.80	7.80	7.80
	Aluminium	µg/L	2	2012 2015	21.00	23.50	26.00
4	Free Chlorine	mg/L	5	2008 2013	0.10	0.31	0.44
	Escherichia coli	#/100mL	5	2008 2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	5	2008 2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	4	2008 2013	0.00	1.25	5.00
	HPC at 36 ºC	N/mL	4	2008 2013	0.00	0.00	0.00
	Conductivity	µS/cm	4	2008 2013	210.00	218.75	230.00
	Clostridium perfringens	N/100 mL	4	2008 2013	0.00	0.00	0.00
	pH	pH Units	4	2008 2013	7.50	7.58	7.60
	Oxidability	mg/L O2	3	2008 2012	0.50	0.97	1.20
	Turbidity	UNT	1	2012	0.90	0.90	0.90
	Manganese	µg/L	2	2008 2012	5.90	7.95	10.00
	Aluminium	µg/L	2	2008 2012	23.00	23.50	24.00
5	Free Chlorine	mg/L	2	2010	0.21	0.54	0.87
	Escherichia coli	#/100mL	2	2010	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Coliform bacteria	N/100 mL	2	2010	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2010	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2010	0.00	0.00	0.00
	Conductivity	µS/cm	1	2010	228.00	228.00	228.00
	Clostridium perfringens	N/100 mL	1	2010	0.00	0.00	0.00
	pH	pH Units	1	2010	7.80	7.80	7.80
	Oxidability	mg/L O2	1	2010	0.90	0.90	0.90
6	Free Chlorine	mg/L	1	2008	0.20	0.20	0.20
	Escherichia coli	#/100mL	2	2008 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2008 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2008	2.00	2.00	2.00
	HPC at 36 ºC	N/mL	1	2008	0.00	0.00	0.00
	Conductivity	µS/cm	1	2008	240.00	240.00	240.00
	Clostridium perfringens	N/100 mL	1	2008	0.00	0.00	0.00
	pH	pH Units	1	2008	7.60	7.60	7.60
	Oxidability	mg/L O2	1	2008	1.30	1.30	1.30
	Aluminium	µg/L	1	2008	32.00	32.00	32.00
7	Free Chlorine	mg/L	1	2012	0.60	0.60	0.60
	Escherichia coli	#/100mL	1	2012	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2012	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2012	2.00	2.00	2.00
	Conductivity	µS/cm	1	2012	210.00	210.00	210.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	pH Units	1	2012	7.70	7.70	7.70
	Oxidability	mg/L O2	1	2012	1.50	1.50	1.50
	Aluminium	µg/L	1	2012	23.00	23.00	23.00
10	Free Chlorine	mg/L	1	2012	0.50	0.50	0.50
	Escherichia coli	#/100mL	1	2012	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2012	0.00	0.00	0.00
12	Free Chlorine	mg/L	1	2008	0.20	0.20	0.20
	Escherichia coli	#/100mL	1	2008	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2008	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2008	1.00	1.00	1.00
	HPC at 36 ºC	N/mL	1	2008	1.00	1.00	1.00
	Conductivity	µS/cm	1	2008	230.00	230.00	230.00
	Clostridium perfringens	N/100 mL	1	2008	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	pH	pH Units	1	2008	7.40	7.40	7.40
	Oxidability	mg/L O2	1	2008	1.20	1.20	1.20
	Calcium	mg/L Ca	1	2008	28.00	28.00	28.00
	Total hardness	mg/L Ca CO3	1	2008	100.00	100.00	100.00
	Enterococci	#/100mL	1	2008	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2008	8.00	8.00	8.00
	Cloroform	µg/L	1	2008	18.00	18.00	18.00
	Bromoform	µg/L	1	2008	2.10	2.10	2.10
	Dibromochloromethane	µg/L	1	2008	12.00	12.00	12.00
	Bromodichloromethane	µg/L	1	2008	14.00	14.00	14.00
14	Free Chlorine	mg/L	1	2009	0.23	0.23	0.23
	Escherichia coli	#/100mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2009	50.00	50.00	50.00
	HPC at 36 ºC	N/mL	1	2009	20.00	20.00	20.00
	Conductivity	µS/cm	1	2009	232.00	232.00	232.00
	Clostridium perfringens	N/100 mL	1	2009	0.00	0.00	0.00
	pH	pH Units	1	2009	7.70	7.70	7.70
	Oxidability	mg/L O2	1	2009	0.80	0.80	0.80
17	Free Chlorine	mg/L	1	2009	0.12	0.12	0.12
	Escherichia coli	#/100mL	2	2008 2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2008 2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2009	9.00	38.50	68.00
	HPC at 36 ºC	N/mL	2	2008 2009	6.00	6.50	7.00
	Conductivity	µS/cm	2	2008 2009	248.00	249.00	250.00
	Clostridium perfringens	N/100 mL	2	2008 2009	0.00	0.00	0.00
	pH	pH Units	2	2008 2009	7.40	7.65	7.90
	Oxidability	mg/L O2	2	2008 2009	1.20	1.35	1.50
	Calcium	mg/L Ca	1	2009	28.00	28.00	28.00
	Total hardness	mg/L Ca CO3	1	2009	100.00	100.00	100.00
	Enterococci	#/100mL	1	2009	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2009	8.00	8.00	8.00
	Cloroform	µg/L	1	2009	12.40	12.40	12.40
	Bromoform	µg/L	1	2009	2.40	2.40	2.40
	Dibromochloromethane	µg/L	1	2009	12.80	12.80	12.80
	Bromodichloromethane	µg/L	1	2009	13.10	13.10	13.10

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Copper	mg/L	1	2009	0.01	0.01	0.01
	Aluminium	µg/L	1	2008	100.00	100.00	100.00
18	Free Chlorine	mg/L	3	2012 2015	0.30	0.47	0.60
	Escherichia coli	#/100mL	3	2012 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2012 2015	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	3	2012 2015	0.00	1.00	2.00
	HPC at 36 ºC	N/mL	3	2012 2015	0.00	0.00	0.00
	Conductivity	µS/cm	3	2012 2015	210.00	216.67	220.00
	Clostridium perfringens	N/100 mL	3	2012 2015	0.00	0.00	0.00
	pH	pH Units	3	2012 2015	7.90	8.03	8.20
	Oxidability	mg/L O2	2	2012 2015	1.10	1.15	1.20
	Calcium	mg/L Ca	3	2012 2015	23.00	26.67	30.00
	Total hardness	mg/L Ca CO3	3	2012 2015	90.00	108.67	140.00
	Enterococci	#/100mL	3	2012 2015	0.00	0.00	0.00
	Magnesium	mg/L Mg	3	2012 2015	6.00	7.00	8.00
	Cloroform	µg/L	3	2012 2015	4.86	8.61	12.20
	Bromoform	µg/L	3	2012 2015	1.19	2.29	3.93
	Dibromochloromethane	µg/L	3	2012 2015	5.38	9.46	12.20
	Bromodichloromethane	µg/L	3	2012 2015	6.69	9.10	12.00
	Turbidity	UNT	1	2013	0.40	0.40	0.40
	Copper	mg/L	2	2013 2015	0.01	0.01	0.02
	Manganese	µg/L	2	2013 2015	7.20	15.10	23.00
	Aluminium	µg/L	3	2012 2015	23.00	34.67	46.00
19	Free Chlorine	mg/L	2	2010 2013	0.30	0.38	0.45
	Escherichia coli	#/100mL	2	2010 2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2010 2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2010	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2010	0.00	0.00	0.00
	Conductivity	µS/cm	1	2010	222.00	222.00	222.00
	Clostridium perfringens	N/100 mL	1	2010	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	pH	pH Units	1	2010	7.70	7.70	7.70
	Oxidability	mg/L O2	1	2010	0.50	0.50	0.50
20	Free Chlorine	mg/L	3	2012 2015	0.40	0.53	0.70
	Escherichia coli	#/100mL	3	2012 2015	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2012 2015	0.00	0.00	0.00
21	Free Chlorine	mg/L	1	2012	0.20	0.20	0.20
	Escherichia coli	#/100mL	1	2012	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2012	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	8.00	8.00	8.00
	HPC at 36 ºC	N/mL	1	2012	9.00	9.00	9.00
	Conductivity	µS/cm	1	2012	210.00	210.00	210.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	pH Units	1	2012	8.10	8.10	8.10
	Aluminium	µg/L	1	2012	24.00	24.00	24.00
22	Free Chlorine	mg/L	1	2010	0.13	0.13	0.13
	Escherichia coli	#/100mL	1	2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2010	0.00	0.00	0.00
	Conductivity	µS/cm	1	2010	216.00	216.00	216.00
	Clostridium perfringens	N/100 mL	1	2010	0.00	0.00	0.00
	pH	pH Units	1	2010	7.20	7.20	7.20
	Oxidability	mg/L O2	1	2010	1.10	1.10	1.10
23	Free Chlorine	mg/L	1	2009	0.10	0.10	0.10
	Escherichia coli	#/100mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2009	300.00	300.00	300.00
	HPC at 36 ºC	N/mL	1	2009	300.00	300.00	300.00
	Conductivity	µS/cm	1	2009	246.00	246.00	246.00
	Clostridium perfringens	N/100 mL	1	2009	0.00	0.00	0.00
	pH	pH Units	1	2009	7.60	7.60	7.60
24	Free Chlorine	mg/L	1	2008	0.20	0.20	0.20
	Escherichia coli	#/100mL	1	2008	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2008	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2008	18.00	18.00	18.00
	HPC at 36 ºC	N/mL	1	2008	11.00	11.00	11.00
	Conductivity	µS/cm	1	2008	250.00	250.00	250.00
	Clostridium perfringens	N/100 mL	1	2008	0.00	0.00	0.00
	pH	pH Units	1	2008	7.50	7.50	7.50

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Oxidability	mg/L O2	1	2008	1.50	1.50	1.50
	Turbidity	UNT	1	2008	0.57	0.57	0.57
	Manganese	mg/L	1	2008	9.00	9.00	9.00
	Aluminium	µg/L	1	2008	31.00	31.00	31.00
26	Free Chlorine	mg/L	1	2010	0.66	0.66	0.66
	Escherichia coli	#/100mL	1	2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2010	0.00	0.00	0.00
27	Free Chlorine	mg/L	2	2012 2014	0.40	0.55	0.70
	Escherichia coli	#/100mL	2	2012 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2012 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2012	11.00	11.00	11.00
	HPC at 36 ºC	N/mL	1	2012	7.00	7.00	7.00
	Conductivity	µS/cm	1	2012	220.00	220.00	220.00
	Clostridium perfringens	N/100 mL	1	2012	0.00	0.00	0.00
	pH	pH Units	1	2012	7.80	7.80	7.80
	Oxidability	mg/L O2	1	2012	1.00	1.00	1.00
	Aluminium	µg/L	1	2012	39.00	39.00	39.00
28	Free Chlorine	mg/L	4	2008 2012	0.10	0.35	0.50
	Escherichia coli	#/100mL	6	2008 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	6	2008 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	6	2008 2014	0.00	1.00	4.00
	HPC at 36 ºC	N/mL	6	2008 2014	0.00	4.50	14.00
	Conductivity	µS/cm	6	2008 2014	200.00	228.17	262.00
	Clostridium perfringens	N/100 mL	6	2008 2014	0.00	0.00	0.00
	pH	pH Units	6	2008 2014	7.20	7.78	8.30
	Oxidability	mg/L O2	6	2008 2014	0.60	1.08	1.40
	Turbidity	UNT	1	2010	0.70	0.70	0.70
	Aluminium	µg/L	4	2008 2014	27.00	35.25	41.00
29	Free Chlorine	mg/L	1	2013	0.20	0.20	0.20
	Escherichia coli	#/100mL	1	2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2013	0.00	0.00	0.00
31	Free Chlorine	mg/L	1	2010	0.21	0.21	0.21
	Escherichia coli	#/100mL	1	2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2010	0.00	0.00	0.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	HPC at 22 ºC	N/mL	1	2010	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2010	0.00	0.00	0.00
	Conductivity	µS/cm	1	2010	219.00	219.00	219.00
	Clostridium perfringens	N/100 mL	1	2010	0.00	0.00	0.00
	pH	pH Units	1	2010	7.50	7.50	7.50
	Oxidability	mg/L O2	1	2010	0.50	0.50	0.50
32	Free Chlorine	mg/L	4	2008 2013	0.50	0.58	0.70
	Escherichia coli	#/100mL	4	2008 2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	4	2008 2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2009	0.00	0.50	1.00
	HPC at 36 ºC	N/mL	2	2008 2009	0.00	1.00	2.00
	Conductivity	µS/cm	2	2008 2009	240.00	251.00	262.00
	Clostridium perfringens	N/100 mL	2	2008 2009	0.00	0.00	0.00
	pH	pH Units	2	2008 2009	7.40	7.55	7.70
	Oxidability	mg/L O2	2	2008 2009	0.90	1.10	1.30
	Manganese	mg/L	1	2009	11.00	11.00	11.00
34	Free Chlorine	mg/L	1	2009	0.24	0.24	0.24
	Escherichia coli	#/100mL	1	2009	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2009	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2009	12.00	12.00	12.00
	HPC at 36 ºC	N/mL	1	2009	2.00	2.00	2.00
	Conductivity	µS/cm	1	2009	238.00	238.00	238.00
	Clostridium perfringens	N/100 mL	1	2009	0.00	0.00	0.00
	pH	pH Units	1	2009	7.50	7.50	7.50
	Oxidability	mg/L O2	1	2009	1.00	1.00	1.00
35	Free Chlorine	mg/L	1	2009	0.36	0.36	0.36
	Escherichia coli	#/100mL	2	2009 2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2009 2010	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2009 2010	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	2	2009 2010	0.00	0.00	0.00
	Conductivity	µS/cm	2	2009 2010	221.00	239.50	258.00
	Clostridium perfringens	N/100 mL	2	2009 2010	0.00	0.00	0.00
	pH	pH Units	2	2009 2010	7.60	7.70	7.80

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
	Oxidability	mg/L O2	2	2009 2010	0.50	0.65	0.80
	Calcium	mg/L Ca	1	2010	32.00	32.00	32.00
	Total hardness	mg/L Ca CO3	1	2010	99.00	99.00	99.00
	Enterococci	#/100mL	1	2010	0.00	0.00	0.00
	Magnesium	mg/L Mg	1	2010	5.00	5.00	5.00
	Cloroform	µg/L	1	2010	15.70	15.70	15.70
	Bromoform	µg/L	1	2010	1.41	1.41	1.41
	Dibromochloromethane	µg/L	1	2010	10.70	10.70	10.70
	Bromodichloromethane	µg/L	1	2010	11.70	11.70	11.70
	Turbidity	UNT	1	2010	0.70	0.70	0.70
	Aluminium	µg/L	1	2009	65.00	65.00	65.00
36	Free Chlorine	mg/L	3	2008 2010	0.10	0.24	0.31
	Escherichia coli	#/100mL	3	2008 2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	3	2008 2010	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	3	2008 2010	0.00	1.33	4.00
	HPC at 36 ºC	N/mL	3	2008 2010	0.00	7.00	21.00
	Conductivity	µS/cm	3	2008 2010	213.00	237.00	250.00
	Clostridium perfringens	N/100 mL	3	2008 2010	0.00	0.00	0.00
	pH	pH Units	3	2008 2010	7.60	7.77	8.00
	Oxidability	mg/L O2	3	2008 2010	0.50	1.00	1.40
	Calcium	mg/L Ca	2	2008 2009	26.00	27.00	28.00
	Total hardness	mg/L Ca CO3	2	2008 2009	100.00	100.00	100.00
	Enterococci	#/100mL	2	2008 2009	0.00	0.00	0.00
	Magnesium	mg/L Mg	2	2008 2009	8.00	8.50	9.00
	Cloroform	µg/L	2	2008 2009	12.10	18.05	24.00
	Bromoform	µg/L	2	2008 2009	1.77	2.29	2.80
	Dibromochloromethane	µg/L	2	2008 2009	11.00	11.90	12.80
	Bromodichloromethane	µg/L	2	2008 2009	12.40	13.20	14.00
	Turbidity	UNT	1	2008	0.60	0.60	0.60
	Copper	mg/L	1	2009	0.12	0.12	0.12
	Iron	µg/L	1	2008	27.00	27.00	27.00
	Manganese	mg/L	1	2008	32.00	32.00	32.00
	Aluminium	µg/L	1	2008	41.00	41.00	41.00

Sample Location	Parameter	Units	# samples	Period	Minimum observed value	Average observed value	Maximum observed value
37	Free Chlorine	mg/L	1	2013	0.20	0.20	0.20
	Escherichia coli	#/100mL	1	2013	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	1	2013	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	1	2013	0.00	0.00	0.00
	HPC at 36 ºC	N/mL	1	2013	0.00	0.00	0.00
	Conductivity	µS/cm	1	2013	210.00	210.00	210.00
	Clostridium perfringens	N/100 mL	1	2013	0.00	0.00	0.00
	pH	pH Units	1	2013	7.90	7.90	7.90
	Oxidability	mg/L O2	1	2013	1.60	1.60	1.60
	Aluminium	µg/L	1	2013	28.00	28.00	28.00
38	Free Chlorine	mg/L	7	2009 2014	0.30	0.52	0.80
	Escherichia coli	#/100mL	7	2009 2014	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	7	2009 2014	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	5	2009 2013	0.00	4.00	19.00
	HPC at 36 ºC	N/mL	5	2009 2013	0.00	2.40	10.00
	Conductivity	µS/cm	5	2009 2013	200.00	218.20	258.00
	Clostridium perfringens	N/100 mL	5	2009 2013	0.00	0.00	0.00
	pH	pH Units	5	2009 2013	7.20	7.56	7.80
	Oxidability	mg/L O2	4	2009 2013	0.60	1.43	2.20
	Turbidity	UNT	1	2012	0.60	0.60	0.60
	Manganese	mg/L	4	2009 2013	6.00	8.25	11.00
	Aluminium	µg/L	2	2012 2013	27.00	28.50	30.00
39	Free Chlorine	mg/L	2	2008 2010	0.44	0.52	0.60
	Escherichia coli	#/100mL	2	2008 2010	0.00	0.00	0.00
	Coliform bacteria	N/100 mL	2	2008 2010	0.00	0.00	0.00
	HPC at 22 ºC	N/mL	2	2008 2010	0.00	0.50	1.00
	HPC at 36 ºC	N/mL	2	2008 2010	0.00	0.00	0.00
	Conductivity	µS/cm	2	2008 2010	209.00	214.50	220.00
	Clostridium perfringens	N/100 mL	2	2008 2010	0.00	0.00	0.00
	pH	pH Units	2	2008 2010	6.70	7.05	7.40
	Oxidability	mg/L O2	1	2010	0.80	0.80	0.80
	Aluminium	µg/L	1	2008	40.00	40.00	40.00

ANNEX VI – Case Study II – Water age at nodes with WQ datasets

Water age statistics for Winter conditions

	Water age (h)			
ID of sampling location	Minimum	Maximum	Average	Standard deviation
1	5.34	17.85	10.00	2.84
2	2.81	11.84	7.73	2.21
7	4.52	19.92	10.78	3.42
9	23.29	119.71	79.99	28.70
11	15.68	47.59	25.91	6.54
14	29.88	63.51	43.84	7.24
17	0.76	51.83	8.89	12.96
18	1.04	6.55	3.23	1.27
20	5.26	51.33	17.07	9.33
22	13.98	41.36	25.94	5.57
23	17.94	129.20	76.51	29.49
24	21.74	46.07	34.01	5.64
25	0.40	2.74	1.24	0.68
27	48.00	218.81	135.15	45.84
30	7.73	37.19	21.56	5.99
33	12.63	107.47	36.71	18.20
34	12.91	35.97	23.13	4.83
36	14.74	36.05	24.92	3.89
37	6.12	26.04	14.13	4.74
39	0.00	8.46	1.14	2.21
42	22.07	44.26	30.74	4.66
44	25.91	67.39	39.81	10.37
49	16.88	96.04	38.36	19.37

Water age statistics for Summer conditions

	Water age (h)			
ID of sampling location	Minimum	Maximum	Average	Standard deviation
1	1.73	3.78	2.38	0.39
2	0.64	6.00	2.45	0.97
8	3.27	13.62	5.49	1.65
9	2.14	47.46	19.52	9.39
11	5.02	32.51	17.89	6.09
14	4.29	10.49	6.37	1.22
16	5.45	39.90	13.84	8.99
17	1.05	69.99	26.33	17.11
20	1.51	14.03	5.11	3.59
21	2.86	23.21	7.45	2.25
24	3.26	15.27	8.45	2.75
25	0.17	1.43	0.50	0.36
27	4.72	12.84	7.65	1.59
30	1.64	3.89	2.29	0.40
32	4.26	11.58	6.70	1.48
34	2.07	114.19	10.92	6.56

	Water age (h)			
ID of sampling location	Minimum	Maximum	Average	Standard deviation
37	4.82	46.12	12.43	5.60
38	1.79	9.37	3.63	1.96
42	3.09	14.07	5.97	1.90
43	5.30	51.61	10.35	6.86
48	4.18	9.87	6.28	1.21
49	11.36	32.27	18.14	3.91
53	2.61	10.10	4.64	1.19