Water age performance functions for water supply systems

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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 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 performance curves that allows to assess the age of the water in distribution systems. In this sense, two water distribution systems were analysed, 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.

1 INTRODUCTION

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 (e.g., trihalomethanes) 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.

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). Tracer tests have also been carried out to validate hydraulic models (Monteiro et al, 2016).

The Portuguese regulations (Decreto Regulamentar 23/95), demands the use of minimum size pipes to comply with the firefighting requirements which leads to an oversizing of pipes regarding the demand and consequently higher water ages in the WDS. The water quality issues related with water age 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. Water age influence 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 (Prasad and Walters, 2006).

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.

Some performance curves for water age and water quality already exist and were collected from the literature review (Figure 1) but the limit values present in them have little sustain. This has hindered the determination of reference values and of performance functions.

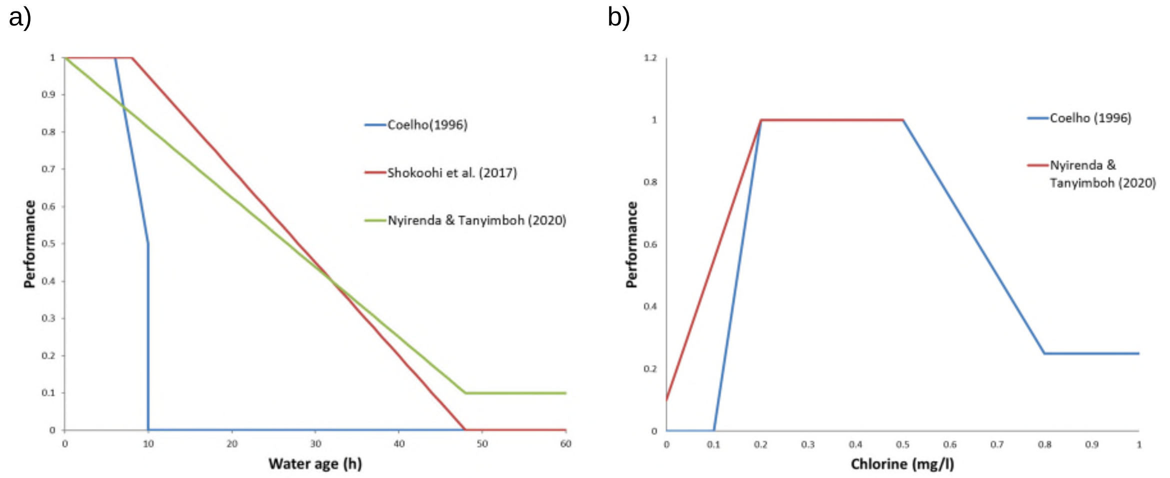


Figure 1 – Existing performance curves – a) water age b) chlorine

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.

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.

2 METHODOLOGY

This work was 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).

The first step of the methodology adopted was the collection of existing water quality data corresponding to the results of the utilities' water quality control program over a period of five years between 2015 and 2020 and of the hydraulic model in EPANET (or of data for assembling the model). The second step of the methodology was the data processing, which included the assembling of the hydraulic models and the identification of the water quality sampling locations in the hydraulic model. Then, water age at the nodes where water quality samples were taken was determined. The water quality data was evaluated regarding the parameters variability over time and the amount of results available in order to identify which quality parameters could be further used to assess correlation with water age.

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.

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.

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. 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 WA index for the network was computed and compared for each situation.

3 CASE STUDIES

Case study 1 comprises a water distribution system in Castelo Branco, a city in the centre of Portugal, divided into district metered areas, for which there was no complete and updated hydraulic model. This case study regards Costeira's subsystem which serves the South-Western part of Castelo Branco. 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), (Maricato, 2015).

Case study 2 comprises a water distribution system in Quinta do Lago in the south of Portugal, located in a touristic area, for which there is already a complete and updated hydraulic model. 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. 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.

4 RESULTS

The chlorine values were compared to the nodal average and maximum water age values obtained for Case study 1 for winter conditions, returning a much better correlation with maximum water age than the one observed by using average water age values (Figure 2 a). The coefficient of determination of approximately 0.75 keeps providing evidence of a certain correlation of the two variables.

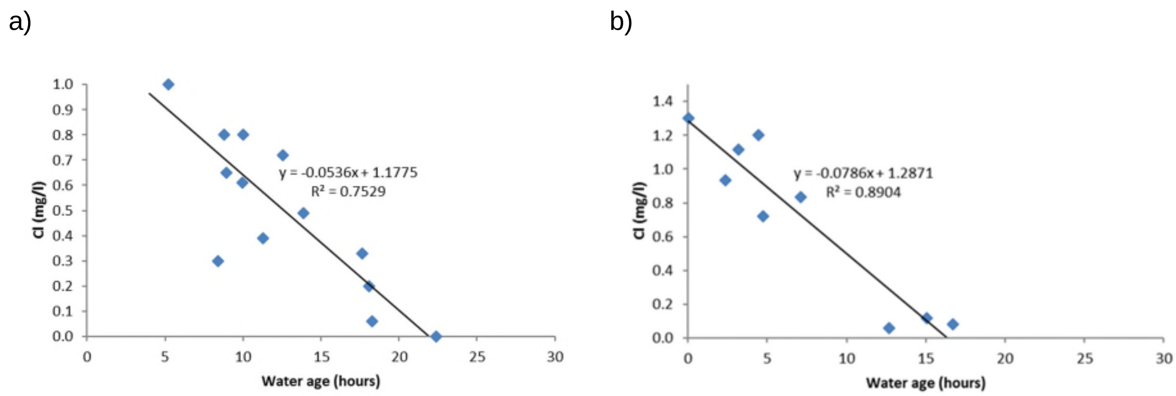


Figure 2 – Maximum water age vs chlorine (samples 2019-2020) |Case study 1 – a) winter conditions b) summer conditions

A similar approach was then followed for the Summer conditions (August). Figure 2 b) shows 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 (R^2) 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.

Accordingly, the water age in this system can be related to chlorine concentration by the following expressions (1) and (2).

$$Cl = -0.0536\,WA + 1.1775\,;\ \ WA\ \leq 22\,h;\ Winter \quad (1)$$

$$Cl = -0.0786\,WA + 1.2871\,;\ \ WA\ \leq 16\,h;\ Summer \quad (2)$$

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

A similar approach was followed for case study 2, but in this case the results shown a better correlation with the average water age nodal values (Figure 3 a) & b)).

a) b)

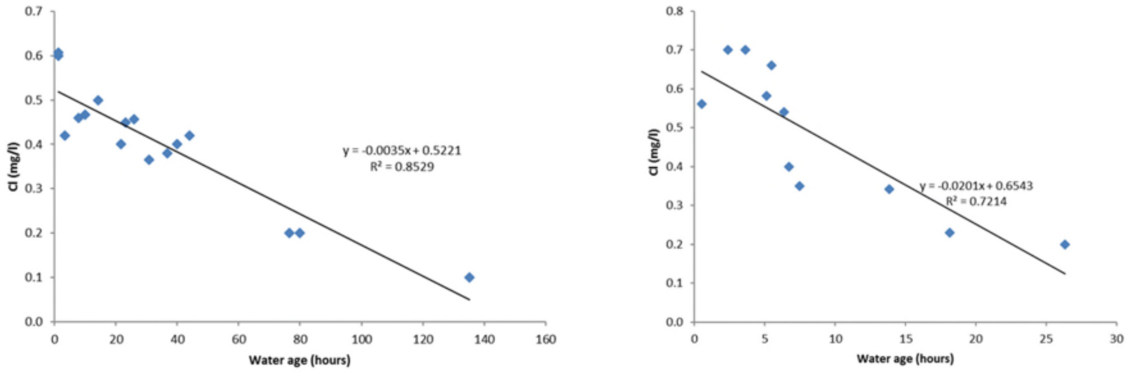


Figure 3 – Average water age vs chlorine |Case study 2 – a) winter conditions b) summer conditions

Accordingly, in case study 2, water age can be related to chlorine concentration by the following expressions (3) and (4).

$$Cl = -0.0035\,WA + 0.5221\,;\ \ WA\ \leq 149\,h;\ Winter \quad (3)$$

$$Cl = -0.0201\,WA + 0.6543\,;\ \ WA\ \leq 32\,h;\ Summer \quad (4)$$

5 PERFORMANCE FUNCTIONS DEVELOPMENT

Despite the availability of chlorine performance functions in literature, a new curve was developed in this work respecting the current law landmarks and World Health Organization (WHO) guidelines for drinking water quality. The resulting proposed performance function for free chlorine is presented in Figure 4.

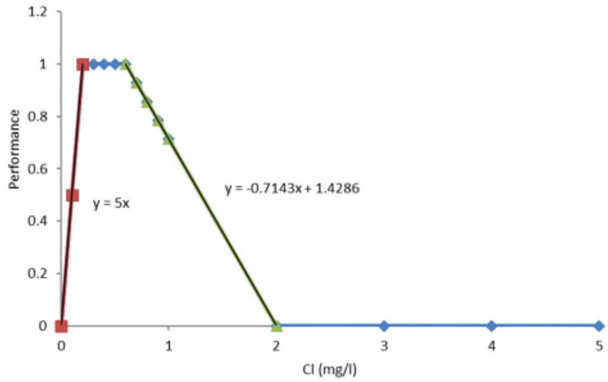


Figure 4 – General chlorine performance index

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.

Based on Equation (1), the performance function in equation (5) was developed for Costeira system in winter conditions.

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

$$PI = 1 \; if \; 11 \; hours < WA \leq 18 \; hours \tag{5}$$

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

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

For the summer conditions in case study 1, the performance curve obtained based in equation (2) is expressed in Equation (6).

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

$$PI = 1 \; if \; 9 \; hours < WA \leq 14 \; hours \tag{6}$$

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

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

Based on Equation (3), the performance curve in equation (7) was developed for Quinta do Lago system in winter conditions.

$$PI = 1 \; if \; WA \; \leq 92 \; hours \qquad (7)$$

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

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

For the summer conditions in case study 2, the performance curve obtained based on equation (4) is expressed in Equation (8).

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

$$PI = 1 \; if \; 0.4 \; hours < WA \leq 23 \; hours \qquad (8)$$

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

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

The graphical representation of the performance curves for case study 1 and case study 2 are presented in Figure 5.

a) b)

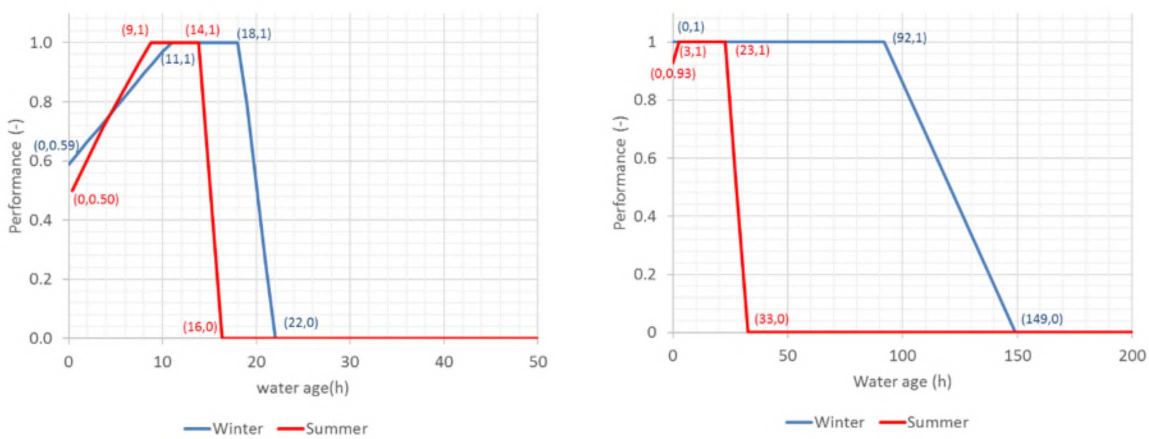


Figure 5 – Water age performance curves: a)Case study1 b)Case study 2

Water quality performance was assessed in the two case studies by applying existing and newly 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 5, 6, 7 and 8. A global performance index was determined as the average of the indexes of all the consumption nodes. The results for Costeira system and Quinta do Lago system are presented in Table 1 and Table 2 and compared to other three performance functions found in the literature.

Table 1 – 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	41.16	0.64	0.32	0.72	0.62
Summer	21.55	0.74	0.55	0.84	0.74

Table 2 – Water age performance - Case Study 2

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

These performance functions all have quite different shapes and return very different results in both case studies and for the two situations considered, suggesting that the performance of different systems regarding water age should not be based on a single, universal performance function as suggested in the studies found in the literature review.

Costeira system operational conditions further undergone an optimization algorithm 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. 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.

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 compared to the winter simulation for comparison (Figure 6).

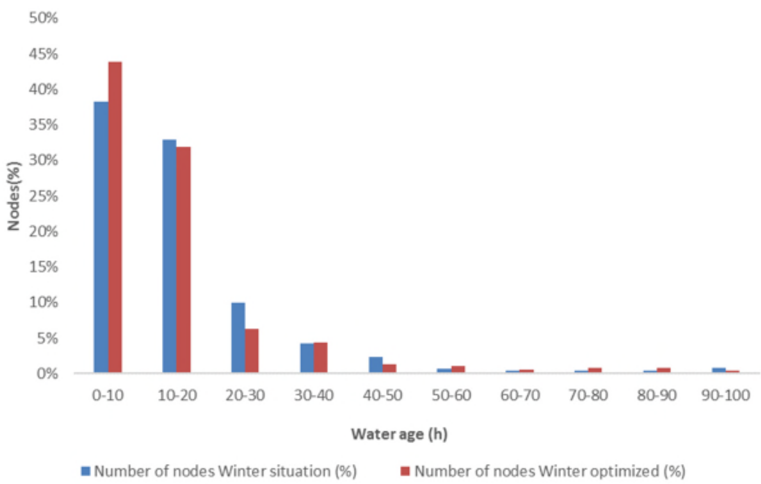
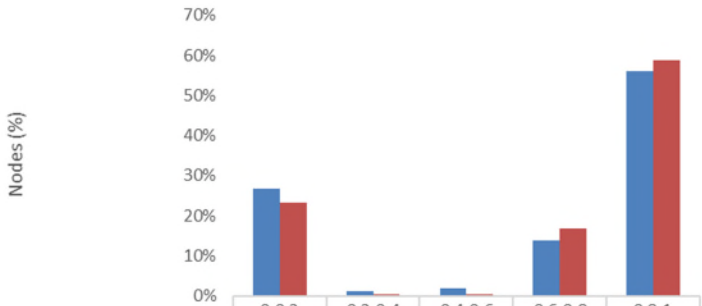


Figure 6 – Distribution of the average water age at the nodes in current and optimized conditions

After optimizing the system, the number of nodes where water age is higher than 22 h decreased from 26% to 23%. Consequently, the number of nodes where water age is low (lower than 10 hours) increased by 6%.

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 7) by distributing the nodal water age in performance intervals. The improvement was rather small and, most probably, reducing water age at those nodes requires other measures than simply operating 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 7 – 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 Performance Index. The improvement achieved for the global PI was from 0.65 in the current winter conditions to 0.69 in the optimized situation. 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.

6 CONCLUSIONS

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 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.

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 laws and on the WHO guidelines for drinking water quality. This function was used to convert chlorine concentrations in water to performance indexes.

The developed water age performance functions for the two WDS are different in shape and in upper limits. As such, recommendation that performance curves be developed for each individual system as opposed to using generalized performance curves is made.

The performance function proved to be useful in setting water age goals and for analysing the results obtained. The methodology followed in this work can also be used by the water utilities to establish particularized performance functions and water age goals.

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