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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Validation of KAPTA^{TM} 3000 AC4 and KAPTA^{TM} 3000 OT3 monitoring probes

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Mémoire

Présenté en vue de l'obtention du diplôme de Maîtrise ès sciences appliquées

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Ce mémoire intitulé:

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Présenté par

Mehrdad FALSAFIOUN

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

a été dûment accepté par le jury d'examen constitué de :

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Benoit BARBEAU, membre
Alicia BANNIER, membre externe

DEDICATION

I am dedicating this thesis to every member of my family, the only ones I can rely on…

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RÉSUMÉ

La surveillance de la qualité de l'eau potable de la source au robinet est essentielle en gestion du risque en eau potable pour la protection de la santé publique. Dans une approche multi-barrières de gestion du risque, le réseau de distribution représente la dernière barrière de protection avant le consommateur. La détection d’une éventuelle dégradation de la qualité de l’eau (intentionnelle ou non) sur le réseau de distribution est par conséquent critique et nécessite des actions rapides pour protéger la population. La surveillance en continu de la qualité de l’eau à l’aide de sondes intelligentes représente une solution prometteuse et innovante pour mieux appréhender les changements de qualité de l’eau sur le réseau de distribution et agir en prévention plutôt qu’en réaction à ces événements. De telles sondes permettent par ailleurs le suivi de la qualité de l’eau dans des zones critiques du réseau de distribution souvent peu appropriées pour l’application des méthodes conventionnelles de surveillance du réseau.

Cette recherche se concentre sur l’évaluation et la validation de deux types de sondes de surveillance développées pour mesurer en continu certains paramètres critiques indicateurs de la qualité de l’eau sur le réseau de distribution. Les sondes KAPTA^{TM} 3000 AC4 (mesure de la pression, de la conductivité, du chlore et de la température) et KAPTA^{TM} 3000 OT3 (mesure de la turbidité, de la matières organique et de la température) ont été testées à l'aide d'un pilote dans des conditions contrôlées au laboratoire, et sur le réseau de distribution municipal dans des conditions non contrôlées.

Les tests sur le pilote ont été effectués en eau chaude et en eau froide (21±1 °C et 8±1 °C respectivement), pour quatre niveaux de turbidités (eau du robinet, 2, 5 et 8 UTN) créés par l’ajout de kaolin (grade laboratoire) et de poudre de dépôts de fer issus du réseau de distribution, à des vitesses de 0,11 et 0,36 m/s. Les tests sur le réseau de distribution municipal ont été réalisés à une vitesse de 0,1 m/s. Les lectures des sondes ont été comparées aux mesures de référence conventionnelles utilisées par les municipalités pour mesurer la qualité de l’eau sur le réseau de distribution. Dans l'ensemble, les résultats à l'échelle pilote indiquent que les mesures des sondes sont précises et reproductibles. Néanmoins, une déviation du signal de turbidité a été observée avec une des deux sondes OT3 testées, ce qui met en évidence le besoin de développer une méthodologie pour détecter une telle déviation rapidement et la corriger. Les résultats des essais terrain ont

montré que les sondes KAPAT OT3 et AC4 étaient capables de détecter un événement d'eau rouge et la demande en chlore créée par un tel événement. Néanmoins, les deux sortes de sonde KAPTA ont systématiquement mesuré des valeurs de turbidité et de chlore plus élevées, ce qui peut être un problème pour les services publics car cela peut donner une fausse perception de faible risque (surestimation du chlore résiduel) ou au contraire, cela peut générer le déploiement d'interventions coûteuses sur le DS par les municipalités et non justifiées (surestimation de la turbidité). Enfin, les essais terrain et pilote ont révélé que le pas de temps de mesure de 6 secondes des KAPTA augmente la probabilité de détecter des pics de turbidité élevés. Une telle observation indique la nécessité de développer des méthodologies pour traiter les données mesurer par les sondes de manière adéquate afin de trouver le bon équilibre entre la prévention des risques et les dépenses des municipalités.

ABSTRACT

Monitoring drinking water quality from the source to the tap is essential in drinking water risk management and ultimately for public health protection. In a multi-barrier risk management approach, the distribution system represents the last barrier before reaching the consumers tap. The detection of any degradation of the drinking water quality (intentional or not) in the distribution system is therefore a critical issue which requires rapid actions to protect the public. Continuous monitoring of water quality using smart probes represents a promising and innovative solution for utilities to better understand changes in drinking water quality in the distribution system and to act in prevention rather than in reaction to these events. Such probes also allow the monitoring of water quality in critical areas of the distribution system, which are often not suitable for the application of conventional methods used by utilities to monitor the distribution system.

This research focuses on the evaluation and validation of two types of online monitoring probes developed to measure critical parameters indicative of water quality deterioration in the distribution network. The KAPTA^{TM} 3000 AC4 (measurement of pressure, conductivity, chlorine and temperature) and KAPTA^{TM} 3000 OT3 (measurement of turbidity, organic matter and temperature) probes were tested using a pilot under controlled conditions in the laboratory, and in the municipal distribution system under uncontrolled conditions.

For pilot experiments, the probes were tested in warm and cold water (21 ± 1 °C and 8 ± 1 °C respectively), at four levels of turbidity (tap water, 2, 5 and 8 NTU) created by adding to water kaolin (laboratory grade) and powder of iron deposits from the distribution network, at speeds of 0.11 and 0.36 m/s. Field experiments (municipal distribution system) were carried out at a speed of 0.1 m/s. The probe readings were compared to measures from conventional approaches used by utilities to measure drinking water quality in the distribution system. Overall, the pilot scale results indicate that the probes measurements are accurate and repeatable. Nonetheless, a drift in turbidity reading was observed with one of the OT3 probes which indicate that some methodology may be needed to detect such a drift rapidly and correct it. The field scale results showed that both the OT3 and the AC4 were able to detect a red water event and the chlorine decay associated with such an event. Nonetheless, the KAPTA systematically measured higher turbidity and chlorine values, which can be an issue for utilities as it can provide a false perception of low risk (overestimation

of the chlorine residual) or it can cause the deployment of costly interventions on the DS by utilities which may not be justified (overestimation of turbidity). Finally, both field and pilot scale experiments revealed that the short 6-second time step measurement of the KAPTA increases the probability to measure high turbidity spikes. Such an observation evidences the need to develop methodologies to process the probes data adequately to find the right balance between risk prevention and costs.

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LIST OF SYMBOLS AND ABBREVIATIONS

^{O}C	Degree Celsius
DO	Dissolved oxygen
DPD	N, N-diethyl-p-phenylenediamine
DS	Distribution system
E. coli	*Escherichia coli*
HOCl	Hypochlorous acid
mg/L	Milligram per litre
NTU	Nephelometric Turbidity Unit
OM	Organic Matter
ppm	Parts per million
SCADA	Supervisory Control and Data Acquisition
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
USEPA	United States Environmental Protection Agency

CHAPTER 1 INTRODUCTION

Waterborne disease outbreaks due to the presence of pathogens in the distribution system represent the main threat for drinking water facilities. These outbreaks have been related to different causes (combined or not), including among others human error, sudden and unexpected change in raw water quality, deficiencies in the drinking water treatment chain or in the distribution system design for example (Hrudey, et al. 2003). Distribution systems deficiencies leading to contaminant intrusion, including cross-connections, contamination during storage, and corrosion among others, would be related to 3% of waterborne outbreaks, and would typically impact the distribution system and its drinking water users at large (Beer, et al. 2015a; Craun and Calderon 2001). In comparison, the presence and growth of *Legionella spp* in the premise plumbing of large buildings would be attributable to 66% of waterborne outbreaks which will be typically contained in large buildings with vulnerable populations such as hospitals (Beer, et al. 2015b) (Figure 1.1). The distribution of responsibilities for *Legionella spp* outbreaks between utilities (providing water to these buildings), large buildings' owners and engineers conceiving the hydraulic design of these buildings is however quite a discussion topic. Among waterborne diseases not related to large buildings issues and reported over the last 20 years in North-America, the Walkerton (Ontario, Canada) *E. coli* O157:H7 outbreak in May 2000 reflect well the potential large scale impacts of a waterborne outbreak occurring in the distribution system. The outbreak affected half of Walkerton population (2 300 people being sick), caused long-term health issues (hemolytic uremic syndrome) for a subset of the population, killed seven people, and clearly marked the drinking water field and the population in general. The economic impact of the Walkerton outbreak was evaluated to $64M (Hrudey, et al. 2003). The evaluation of the impacts of such outbreaks is multi-faceted, and includes severe adverse effects on public health but also on economic and social parameters (Krause, et al. 2008).

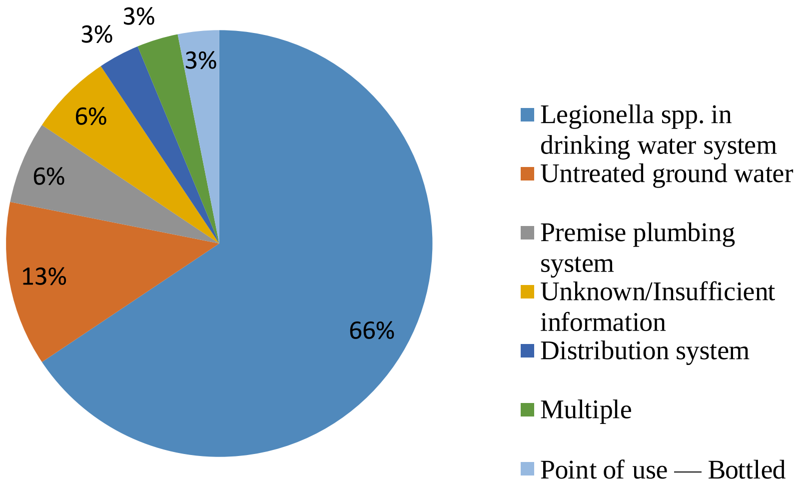

Figure 1.1 Deficiencies assigned to drinking water outbreaks for 2011- 2012 (N=32) (Beer, et al. 2015a; Blackburn, et al. 2004; Brunkard, et al. 2011; Control and Prevention 2013; Dziuban, et al. 2006; Hlavsa, et al. 2011; Hlavsa, et al. 2015; Hlavsa, et al. 2014; Kramer, et al. 1996; Lee, et al. 2002; Levy, et al. 1998; Liang, et al. 2006; Yoder, et al. 2008a; Yoder, et al. 2004; Yoder, et al. 2008b)

Regulated monitoring of the microbiological quality of water in chlorinated systems includes the evaluation of total coliforms, *E.coli*, and residual chlorine through the collection of samples distributed over the distribution system but targeted especially in dead-ends (50% of the samples). In addition, continuous monitoring of chlorine residuals, temperature, conductivity, pH and turbidity is typically performed in re-chlorination chambers located typically in distribution system dead-ends or close to water tanks. Such a monitoring provides a picture of the water quality at a specific time and/or in specific sectors of the distribution system. As a consequence, intrusion events can be missed or detected too late (Khanal, et al. 2005). Uncertainties about the intruded contaminant type, the location and the time of the intrusion event, increases the importance and severity of these threats (Reynolds, et al.). In addition to the accidental degradation of water quality, raising concerns have been brought about intentional contamination of the distribution system since the 9/11 terrorist attacks. The US Environmental Protection Agency has been working on the assessment of the DS vulnerability to acts of terrorism (Chang, et al. 2012). As compared to accidental contamination events, intentional contamination is even more challenging to manage due to its higher unpredictability for time and location (Preis and Ostfeld 2008).

Considering these concerns, utilities have expanded over the last two decades their efforts toward online monitoring of water distribution systems (Preis and Ostfeld 2008). Such a monitoring consists in the equipment of the distribution system with multiple online probes directly inserted into the pipes. Considering the investments that request such an installation, efforts have been done to develop probes that measures multiple water quality parameters, and that require low maintenance. Online monitoring of the distribution system (DS) is an effective tool to increase public protection against any event leading to drinking water quality degradation, occurring either accidentally (e.g. DS deficiency) or intentionally (e.g. terroristic attack) (Preis and Ostfeld 2008).

A water distribution system has some distinctive characteristics, which makes it different from other networks when it comes to real-time monitoring (Hu, et al. 2018):

- Sufficient pressure: a positive pressure is available at each node of the network and untreated water is not a proper source for pressure adjustment.

- Network components: the numerous components of a distribution water system (tanks, reservoirs, fire hydrants, pipes, etc.) make it complex to understand and monitor.

- Entitled to various destructive attacks: a water distribution system consists of a far and wide pipeline network, which makes it vulnerable to various kinds of events including accidental and intentional breaches in the network.

- Hard to monitor: Considering that most of the pipeline is underground and not easily accessible, and considering the substantial cost of monitoring probes, the selection of appropriate locations for online monitoring to provide an accurate picture of water quality is a challenge.

- Public sensitivity: Contaminants released in the water distribution system could propagate over a wide spatial scale, threaten public health protection, and lead to panic among people. At the same time, it is hard to identify the type and source of contaminants.

Given the importance of online monitoring of the DS, we conducted a two-step validation experiment on two types of innovative KAPTA^{TM} probes to evaluate their performance for measuring critical water quality and/or hydraulic parameters in the DS. The probes were first tested in the laboratory at pilot-scale. Specifically, the probe recordings were compared to reference measurements typically used by utilities to validate their reliability for different quality conditions (temperature and turbidity). Then, the probes were tested in a full-scale distribution system in Laval for a period of one month and a half to evaluate their efficiency under field conditions and the stability of their signal over time.

In this MScA thesis, a literature review is first conducted and details previous studies on the importance, evaluation and application of the online probes to measure water quality. The two types of KAPTA^{TM} 3000 probe technologies and the methodology used to validate these probes are presented in the next chapter. Chapter 4 presents the results obtained in the pilot-scale and full-scale experiments. Finally, conclusions and recommendations for future studies are presented in Chapter 5.

The main hypotheses of this project are as follows:

- KAPTA^{TM} 3000 AC4 probes are accurate enough to be used as an online monitoring tool to measure chlorine, temperature and conductivity in the DS
- KAPTA^{TM} 3000 OT3 probes are accurate enough to be used as an online monitoring tool to measure turbidity, temperature and organic matter in the DS
- KAPTA^{TM} 3000 AC4 and KAPTA^{TM} 3000 OT3 probes are capable of recording water quality parameters continuously and without a significant drift, (a significant drift is defined for the cases where the accuracy of probe readings significantly differs from normal performance).
- KAPTA^{TM} 3000 AC4 probes are accurate enough in measuring chlorine in water at different levels of turbidity.

CHAPTER 2 LITERATURE REVIEW

This chapter presents a literature review on monitoring probes and their application in the distribution system (DS). First, the differences between conventional methods and online methods to monitor the quality of drinking water is presented in section 2.1. Regulations and recommendations on distributed water quality from different organizations are gathered in section 2.2, and section 2.3 describes water quality parameters monitored regularly by utilities. Case studies on the application of monitoring probes and on the evaluation of their performance are presented in section 2.4 and 2.5 respectively. Then, sections 2.6 and 2.7 present the strategies used to select appropriate locations in the DS for the installation of the monitoring probes and associated case studies. Finally, section 2.8 introduces the main objectives of this research project which were developed considering the identified gaps in the literature.

2.1 Approaches to monitor drinking water quality

Among contaminants occurring typically in drinking water, microorganisms represent the main threat for drinking water safety (Hrudey, et al. 2003). There are two types of approaches used to identify the presence of pathogens in the DS. First, the direct measurement of pathogens using laboratory methods or kits. Most of these direct measurements needs to be done through the growth of the pathogens in a culture medium over up 3 days, which does not allow utilities to answer quickly to pathogen intrusion in the DS (Hammes and Egli 2010). Furthermore, such measurements necessitate the collection of samples by utility staff in the DS, and are microorganisms-specific. Consequently, it is quite complicated to get an accurate picture of the microbiological water quality in the DS with such an approach, unless this is too late (e.g. *E.coli* spread out all over the DS). Considering this, utilities use also indirect measurements to identify changes in drinking water quality that may indicate pathogen intrusion. In combination to the evaluation of the presence of pathogen indicators, other parameters of interest include water quality indicators associated to a chemical risk. The water quality parameter’s typically monitored include turbidity, conductivity, chlorine residual, pH and temperature for example (Banna, et al. 2014). Among these, the turbidity of the distributed water is a key indicator to predict the possible presence of pathogens in drinking water. The monitoring of chlorine residuals is also a key parameter for the DS associated to microbiological (e.g. sudden loss of chlorine due to its reaction with agents like organic matter) or chemical risks (e.g. excess of chlorine and organic matter associated to THM formation). These parameters are typically monitored online at measurement stations distributed in the DS. Table 2.1 presents the parameters considered as relevant in different countries to monitor drinking water quality. In recent years, a large variety of multi-parameters online probes dedicated to online drinking water monitoring have been developed. As compared to the monitoring of drinking water using sampling and further laboratory analysis, or using measurement stations with one-parameter probes, these tools present the following advantages (Awale, et al. 2019):

- Limit the use of laborious methods with a time delay (sampling, culture)
- Would allow to optimize the chlorine residuals distribution in the DS (limit the formation of chlorine by-products associated with a cancer risk)
- Measure multiple water quality parameters (e.g. turbidity, conductivity and pH) using one instrument
- Record water quality data continuously which gives the opportunity of analyzing the data over a recorded period for different purposes (e.g. post-mortem review of an event; optimization of the DS operation and design)
- Can be installed in critical areas of the DS, and/or directly inserted into the pipes to provide an accurate picture of drinking water quality and improve the DS management overall

Table 2.1 Water quality parameters measured online in the DS in different parts of the world (Banna, et al. 2014)

Reference	**Online Measuring parameters**	**Country**	**City**
Bélisle (2011)	turbidity, dissolved oxygen (DO), pH, residual chlorine, color	Canada	Province of Quebec
Water (2011)	conductivity, total organic carbon (TOC), pH, temperature, hardness, nitrate, sodium, residual chlorine		Tuscon
Conservation (2011)	turbidity, DO, pH, conductivity, temperature		St John’s
Hall and Szabo (2005)	pH, conductivity, TOC, free or total chlorine	USA	New York, San Frasisco, Philadelphia, Dallas, Cincinnati
Water Supply Department (2009)	turbidity, total dissolved solids (TDS), DO, free chlorine, pH	India	Suart
Seoul (2011)	turbidity, conductivity, temperature, pH, chlorine	Korea	Seoul

2.2 Recommendations/regulations on drinking water quality in the DS

The following tables detail the acceptable ranges for microorganisms indicators (Table 2.2), chlorine residuals (Table 2.3), turbidity, pH and pressure (Table 2.4 and Table 2.5) issued by regulators and public health agencies in the US, Canada, and some European countries to ensure the quality and the safety of distributed water throughout the DS. It is worth noting that, among the different countries presented in the tables, Health Canada requires the highest level of chlorine at the treatment plant and into the DS, while some European regulations do not specify any range for free chlorine at the treatment plant (e.g. Germany, Spain and Portugal). In case of turbidity, the regulations in Canada and in the US vary based on the type of filtration, the maximum acceptable values for turbidity ranging from 0.3 to 1 NTU in Canada (Canada 2019) and 0.3 to 5 NTU in the US (USEPA 2009). Minimum pressure ranges between 14 to 30 psi in different countries/states. In addition, the maximum pressure varies from 80 to 100 psi except in Australia and in the US where maximum pressure it is not specified.

Table 2.2 Regulations/recommendations relative to the acceptable range of microorganisms in drinking water

Location	***Escherichia coli. (E coli.)***	**Total coliform**	**HPC**	**Reference**
Canada	None detectable per 100 mL	None detectable/100 mL in water leaving a treatment plant and in non-disinfected groundwater leaving the well	less than 500 cfu/ml	(Canada 2012b) (Canada 2012a)
US	No fecal coliform- or E. coli-positive REPEAT sample or no fecal coliform- or E. coli-positive ROUTINE sample followed by a total coliform-positive REPEAT sample.	Less than 5% ROUTINE/REPEAT sample per month which is total coliform-positive	less than 500 cfu/ml	(USEPA 2013) (Robertson and Brooks 2003)
EU	Most probable number (MPN) < 1	Most probable number (MPN) < 1 in 100 ml	Not specified (Statement: No abnormal changes at the consumer's tap or within treatment works or service reservoirs)	(Directive 1998) (Hydes 1999)

Table 2.3 Regulations/recommendations relative to the acceptable range of free chlorine

Location	**Leaving treatment plant**	**Supplied to user**	**Reference**
Canada	0.4 to 2.0 mg/L	0.4 to 1.2 mg/L at intermediate points in the distribution system 0.04 to 0.8 mg/L at the far end of the distribution system	(Canada 2009)
WHO	NA	0.2–0.5 mg/L at all points in the supply	(Water and Organization 2000)
US	0.2 mg/L	A detectable level be maintained throughout the distribution system	(USEPA 2002)
Austria	0.3–0.5 mg/L	<0.3 mg/L	(Hydes 1999)
Germany	NA	>0.1 mg/L	
Spain	NA	0.2–0.8 depending on pH	
Portugal	NA	0.2 mg/L	
France	0.1	NA	
Switzerland	≤0.1	NA	
Belgium	0.2	NA	

Table 2.4 Recommendations/regulations relative to turbidity, pH and pressure throughout the DS

Parameter	Location	Value	Reference	Factors Involved
Turbidity	US	For systems using conventional or direct filtration: ≤1 NTU For systems using other filtrations: ≤5 NTU	(USEPA 2009)	- Breaches to the DS (main break, backflow, intrusion, cross connection…) - Releasing of corrosion products or disturbances of deposits - Heavy load of sedimentation of inorganic contaminants
	Canada	Conventional and direct filtration: ≤ 0.3 NTU - slow sand and diatomaceous earth filtration: ≤ 1.0 NTU - membrane filtration: ≤ 0.1 NTU	(Canada 2019)	
	Quebec	Conventional and direct filtration: ≤ 0.3 NTU in 95% of measurements Slow filtration or with: ≤ 1.0 NTU Membrane filtration: ≤ 0.1 NTU Other filtration, or exclusion of filtration: Average of 1.0 NTU For systems using other filtrations: ≤5 NTU	(Québec 2013)	

Table 2.5 Recommendations/regulations relative to turbidity, pH and pressure throughout the DS

Parameter	**Location**	**Value**	**Reference**	**Factors Involved**
Turbidity	EU	<0.3 NTU (95%) and not >0.5 NTU for 15 consecutive minutes	(Directive 1998)	- Breaches to the DS (main break, backflow, intrusion, cross connection…) -Releasing of corrosion products or disturbances of deposits - Heavy load of sedimentation of inorganic contaminants
	WHO		(WHO 2017a)	
pH	US	6.5 – 8.5	(USEPA 2019)	- Temperature - Contaminants in the network - Sewage intrusion - Water temperature
	Canada	6.5 – 8.5	(Canada 2016)	
	Quebec	6.5 – 8.5	(Québec 2013)	
	EU	6.5 – 9.5	(Agency 2011)	
	WHO	6.5 – 8.5	(WHO 2003)	

Table 2.5 Recommendations/regulations relative to turbidity, pH and pressure throughout the DS (cont'd)

pressure	US	Minimum: Varies in different states ranging from 20 to 30 psi Maximum: Not specified	(Kirmeyer 2014)	- Pipe diameter - Depressurization events - Demand in the DS
	Canada	Minimum: Varies in different provinces ranging from 20 to 22 psi Maximum: Varies in different provinces ranging from 80 to 100 psi	(Ghorbanian, et al. 2016)	
	UK and Wales	Minimum: 14 psi Maximum: Not specified		
	Australia	Minimum: 29 psi Maximum: Not specified		
	Quebec	Minimum: 20 psi Maximum: 100 psi	(Ministère de l'Environnement et de la Lutte contre les changements climatiques 2019)	

2.3 Parameters of interest for online monitoring of the DS

In addition to the compliance to drinking water quality standards detailed in the previous section, the monitoring of the fluctuations of some critical water quality parameters over time using online probes is particularly of interest for utilities considering that any sudden change could be indicative of an intrusion event that would require immediate actions (Banna, et al. 2014). Each parameter is explained separately in the following sections.

2.3.1 pH

North-American and WHO guidelines recommend maintaining a pH range between 6.5 to 8.5 in normal conditions throughout the DS (Canada 2016; Hall and Szabo 2005). Uncontrolled pH can favour corrosion in the distribution system and increase disinfection by-products (DBPs) (WHO 2003). Fluctuations in pH are also typical during an intrusion event (Hall and Szabo 2005), which is explained by pathogens producing acidic and basic substances in the water (Preis and Ostfeld 2008). Finally, according to USEPA (2002), a pH decrease is an indicator of nitrification. In this regard, continuous monitoring of pH is critical for both ensuring drinking water quality and early responding to intrusion events.

2.3.2 Turbidity

The turbidity, expressed in Nephelometric Turbidity Unit (NTU), is a measure which indicates the light scattering capacity of the water. Turbidity is caused by the presence of colloidal and suspended solids in bulk water. Some regulations (e.g. USEPA and Health Canada) mandate maintaining the turbidity in DS from exceeding 5 NTU (Panguluri, et al. 2009). Although turbidity is a key indicator for drinking water quality along drinking water treatment process and throughout the DS. Changes in turbidity would not indicate necessarily that an intrusion event is occurring (Banna, et al. 2014); however, turbidity particles could act as a host for pathogens (WHO 2017b). Finally, turbidity could be indicative of low pressure in the distribution system.

2.3.3 Residual chlorine

Chlorine is used to fight against detrimental public health effects in drinking water as it inactivates microbial pathogens (Connell 1996). This inactivation causes a chlorine decay in the DS (Propato and Uber 2004). A chlorine decay can also be an indicator of the presence of organic matter, DBPs formation, corrosion, etc. In this way, monitoring residual chlorine would be an effective strategy to detect contaminant intrusion and any extreme chlorine depletion in the DS could be a clue of contaminant intrusion (Helbling and VanBriesen 2008). It should be noted that in most countries, a residual chlorine is mandatory in the DS, the residual chlorine concentration leaving the drinking water treatment plant in normal conditions ranging from a minimum of 0.2 mg/L (Canada 2016) to a maximum of 4 mg/L (USEPA 2019).

2.3.4 Dissolved oxygen (DO)

Dissolved oxygen (DO) in drinking water is a very important parameter, as a change in DO could be an indicator of pathogen presence in the DS. Indeed, pathogens intruded in the DS would increase the total oxygen demand (TOD) in water and as a consequence significantly decrease the DO in the DS (Satone, et al. 2011). However, regulations do not mandate any recommended amount of DO in the DS due to the fact that it does not have any specific effect on public health (Banna, et al. 2014). The DO is measured in the drinking water treatment plant for control purposes, while the DO measured in the DS is an indicator of the water quality (Environment 2018).

2.3.5 Conductivity and temperature

Conductivity of water refers to the ability of water to conduct electricity. The presence of inorganic dissolved solids in water such as sulfate, chloride and nitrate anions or calcium, sodium and magnesium cations can change its conductivity (DeZuane 1997). Therefore, this parameter could be representative of intrusion of exterior substances in the water main (Banna, et al. 2014). Conductivity measurements vary however with temperature as an increase in temperature will result in a decrease in water viscosity and further increase of the ions mobility in bulk water (Barron and Ashton 2005). Consequently, conductivity should be converted to the conductivity at a reference temperature (e.g. 25^0C) to make it comparable (Figure 2.1). Conductivity monitoring should therefore always be done along with temperature monitoring to get a precise evaluation of the water quality

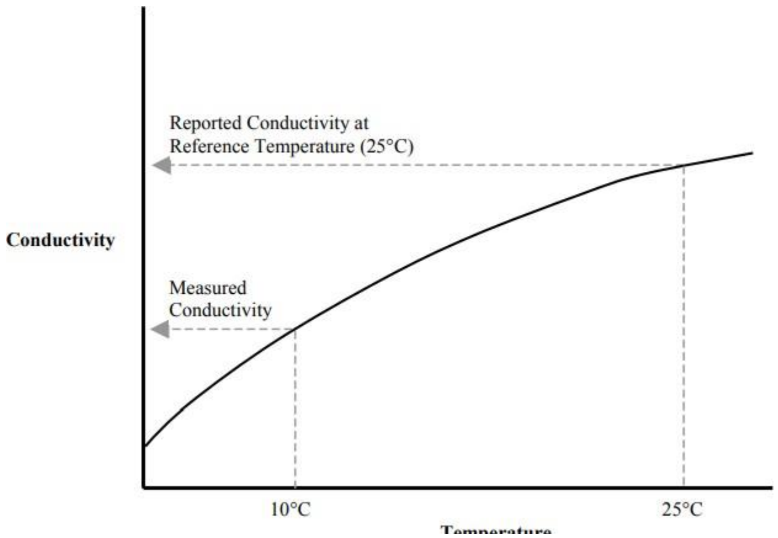

Figure 2.1 Conductivity as a function of water temperature (Barron and Ashton 2005)

2.4 Evaluation of the accuracy of water quality monitoring probes

The continuous monitoring of the chemical contaminants in the DS is challenging especially if the concentration of the particles is low (Gonzalez, et al. 2009). It provides nevertheless significant advantages as compared to conventional off-line monitoring methods which are not continuous and can delay utilities responses to changes in water quality that require corrective actions. In addition, online sensors to monitor pressure and/or several water quality parameters have been developed tremendously in recent years. The ease of use of these probes and their ability to record multiple parameters indicators of drinking water quality are two important characteristics considered by water utilities (Zulkifli, et al. 2018). Furthermore, excluding the initial investments for the deployment of such sensors, their use over long-term could be quite cost efficient for utilities considering they would require less staff resources for DS sampling, and even more considering that, if appropriately used and interpreted, measures from such sensors would help to optimize the DS operation and management and ultimately avoid some events of contamination and reduce boiling advisories.

Helbling and VanBriesen (2008) performed a study on a laboratory scale DS to evaluate the accuracy of free chlorine monitoring sensors to detect bacterial contamination intrusion in the DS. They used colorimetric free chlorine analyzer (Hach CL17, Loveland, CO) for online monitoring of the free chlorine concentration in the DS and concluded that it is efficient enough to rapidly detect the changes in free chlorine residuals due to injected *E. coli*. Authors reported that changes in the measured concentrations of free chlorine residual were proportional to the injected microorganism concentration.

Storey, et al. (2011) performed a survey on the advantages and limitations of the different monitoring sensors that are used internationally. They investigated the performance of 14 monitoring probes used in European countries, United States and Singapore for detecting accidental or intentional contamination of the DS. They categorized the studied probes based on their ease of use, their number and type of measured parameters, their performance in detecting contaminants, and their accuracy in measuring different quality parameters (Table 2.6).

Table 2.6 Advantages and limitations of different monitoring sensors internationally used for intrusion detection (Storey, et al. 2011)

Sensor	**Advantages**	**Limitations**
J-Mar Biosentry^{TM}	- Directly integrated into the water supply through continuous, slip-stream flow analysis - Process is virtually instantaneous providing for real-time detection and classification - Fully automated and remotely accessible, and minimal maintenance requirements	- Does not provide viability data - System cannot differentiate between live and dead organisms, motile or non-motile, organic or inorganic - When the instrument was installed at the intake of a treatment plant, where surface water is monitored, fouling of the flow-cell observed
UVeVIS s::can spectro::lyser^{TM}	- Fully submersible UV/Vis probe suitable for monitoring a wide range of liquids	- When the instrument was installed at the intake of a treatment plant, where surface water is monitored, fouling of the flow-cell observed - When the instrument was installed at the intake of a treatment plant, where surface water is monitored, fouling of the flow-cell observed
Hach Event Monitor (Guardian Blue^{TM})	- Distribution and plant personnel can troubleshoot remotely - Programmed to recognize future occurrences of the same event and notify operations	- The instrument has little maintenance problems however has created several false alarms
s::can Water Quality Monitoring Station^{TM}	- Applicable for wastewater, drinking water, and environmental water - Multiple parameters measured	- Colour measurement not highly sensitive - Some issues with running system without the use of air cleaning have been identified
TOXcontrol^{TM} (microLAN)	- Real-time assessment of microbial populations; quick response time - High sensitivity of Vibrio fischeri to cyanide	- Vibrio fischeri less sensitive to sodium fluoroacetate
Algae Toximeter^{TM} (BBE)	- Precise determination of algae concentrations in water - Highly sensitive with regard to detection of herbicides and their by-products	- Lag time in cultivating slow-growing algae

Table 2.6 Advantages and limitations of different monitoring sensors internationally used for intrusion detection (Storey, et al. 2011) (cont'd)

Sensor	**Advantages**	**Limitations**
DaphniaToximeter^{TM} (BBE)	- Highly sensitive biological system for early detection of potentially dangerous unknown substances - Low maintenance	- Not suitable for finished (chlorinated) water as Daphnia magna is sensitive to chlorine - Adjustable high sensitivity may lead to false positive alarms in some cases
ToxProtect (BBE)	- Rapid detection of toxic substances in water - Capable of detecting low levels of cyanide High toxic response relation between fish and humans exists	- Incapable of detecting considerably high levels of fluoroacetate - Maintenance time, size required to house fish stocks
Fish Activity Monitoring System (FAMS)	- Round-the-clock monitoring of fish activity for continuous water quality monitoring - Quicker response time after event occurrence	- Maintenance time, size required to house fish stocks
Surface enhanced Raman spectroscopy	- Non-invasive and reagentless - Highly specific microbial identification	- Spectral deviations caused by metabolic or environmental factors needs to be smaller than spectral deviation between strains
Laser tweezer Raman spectroscopy	- Allows discrimination between different strains of bacteria and single *Bacillus* spores - Bacteria selected from random growth phases can be classified	- Associated biochemical and biomolecular methods required at same time to confirm effectiveness of - Raman spectral method
Surface acoustic wave (SAW) devices	- Highly specific and low-cost - Array-based sensors and data schemes provide increased utility	- Reduced sensitivity and stability suggests they are not ready to fully replace analytical methodologies
YSI Sonde^{TM}	- Simultaneous measurement of conductivity, salinity, temp, depth, pH, dissolved oxygen, turbidity, chlorophyll and blue-green algae	- Despite best practices sometimes not possible to clean Sonde to a point where the standard is not contaminated by some small amount
Censar^{TM}	- Provides an immediate on-site measurement with good sensitivity at natural levels - Ideal as early warning of algae blooms - Simultaneously measures color, turbidity, and temperature	- Depth sensor can be affected by biological fouling that grows in the water passage tube - Limited parameters measured

2.5 Experimental studies on the application of the monitoring probes

Mashford, et al. (2009) developed a data mining method to process the information gathered by pressure monitoring sensors, and further define the size and location of the leakage orifices present in the DS and where intrusion takes place. In this way, they performed an inverse engineering method linking support vector machines (SVMs) to EPANET using the data obtained from pressure monitoring sensors. They concluded that their suggested method has a reasonable accuracy to target the leakage points by using the online pressure monitoring data. Such a method could be used by utilities to prioritise renovation or reconstruction work in the DS and prevent accidental contaminant intrusion before happening.

Sherchan, et al. (2013) conducted an experimental study to investigate the ability of three different water quality monitoring sensors to detect *B. thuringiensis* bacterial spores using a piping pilot, including :

- the HACH Monitoring Platform which measures pH, Total Organic Carbon (TOC), free chlorine, turbidity, electrical conductivity, pressure and temperature;
- The BioSentry Technology which works based on striking a laser beam and measuring unique scattering in light for each component which exists in water;
- The S::CAN spectro::lyser Technology which uses UV spectroscopy and provides an overall picture of the water quality along with being capable of detecting any type of pathogen intruded to the DS.

They concluded that the BioSentry sensor would be a good option to detect contaminant intrusion as it showed a higher ability to detect the spores at the concentrations tested (10^5-10^9 spores/mL) in comparison to the two other sensors.

Saravanan, et al. (2018) developed a new system of Supervisory Control and Data Acquisition (SCADA) for real time monitoring of the DS. To do so, they used an array of online sensors to measure pressure, pH, temperature, color and turbidity of drinking water in the DS of the city of Metro (Tamil Nadu, India). As Figure 2.2 shows, their proposed method provides better performance than previous systems in different components of a SCADA (sensors, communication and technology).

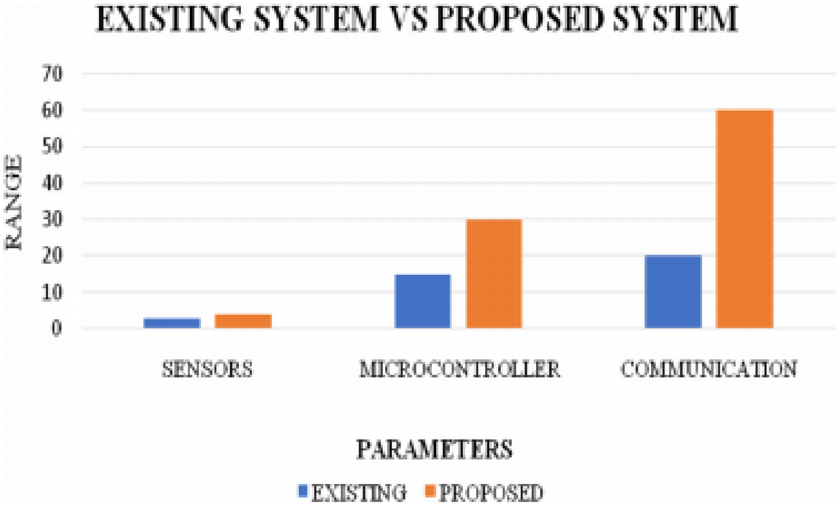

Figure 2.2. The comparison between existing and proposed method in terms of performance of SCADA components (Saravanan, et al. 2018)

Lambrou, et al. (2014) developed also a cost-optimized sensor matrix for real-time detection of *E.coli* using a combination of online optical sensors measuring water flow, temperature, conductivity, pH, ORP and turbidity (Figure 2.3). Nonetheless, performing the same optimization strategy, Che, et al. (2015) concluded that UV254 is not adapted to monitor water quality in the DS considering the fluctuations in the quality of the water source.

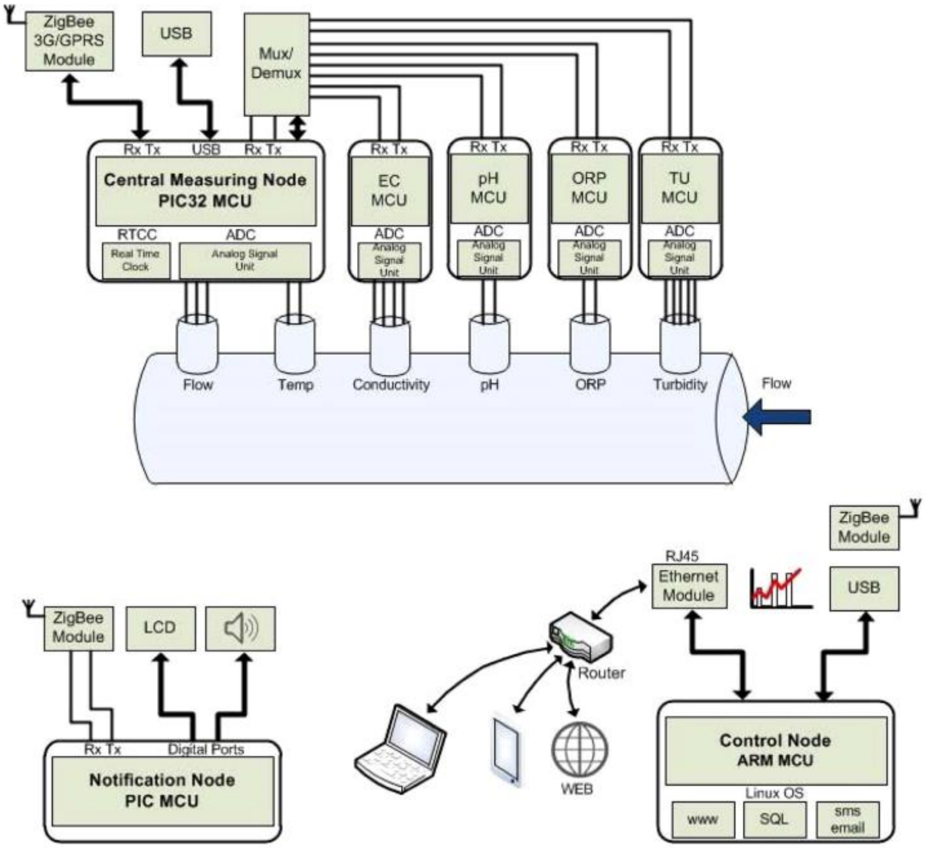

Figure 2.3 Example of system structure for real-time detection of *E.coli* in the DS using online monitoring sensors (Lambrou, et al. 2014)

2.6 Selection of key locations for online monitoring in the DS

Using online probes for early detection of contamination in the DS requires a strategic selection of the sites where such probes will be installed. Indeed, for example one of the many objectives for installing such probes in the DS includes the early detection of intrusion events, however there are uncertainties related to the intruded contaminant type, the location and time of its intrusion. As a consequence, the selection of the key locations to install online monitoring in the DS is critical to detect such threats. Furthermore, the installation of online sensors in the DS requires significant costs and efforts (Krause, et al. 2008).

Inability in on-time data analysis of the sensor records leads to inaccuracy in monitoring of the water quality in DS (Berry, et al. 2005a; Chang, et al. 2007). Though researchers have been performing deep studies on sensor location approaches, the accuracy of the sensors in detecting any concentration of contaminants adds a major uncertainty to the whole procedure (Zulkifli, et al. 2018).

Different optimization approaches have been tested to select key locations for probe installation throughout the DS to get a comprehensive monitoring of the water quality (Gonzalez, et al. 2009; Liu, et al. 2015; Thompson and Gray 2006). Among these approaches, modeling the risk of contamination by combining the hydraulics to the water quality parameters of the DS allows to estimate the spatio-temporal variability of the contaminant being transported throughout the DS. Strategic locations can thereafter be selected according to the risk estimated by the model. For example, early studies on optimal sensor loction modeled the DS in a steady state condition (Berry, et al. 2005b; Ostfeld and Kessler 2001); while some later researches used a dynamic modeling of the DS over an extended period of time (Ostfeld and Salomons 2004; Propato, et al. 2005). The views on the best approaches to use differ from one study to another considering that, following an intrusion event, contaminants could be present at every node though their concentration would differ from one node to another. Moreover, inaccuracy in the location selection approach and low sensor sensitivity for detecting contaminants may affect the ability of detecting contamination events in the DS (Preis and Ostfeld 2008; Weickgenannt, et al. 2010). In this way, contaminant detection in the DS has become a challenging topic.

As another categorization of the optimization methods, single-objective and multi-objective approaches are detailed below. Weickgenannt, et al. (2010) used several monitoring sensors to determine a single contaminant considering the accuracy the monitoring sensors and showed that their suggested method of optimization with genetic algorithm II for sensor placement was successful in reducing response time and simplifying the optimization procedure, which is important in terms of reducing computational complexity.

2.6.1 Single-objective optimization models

Single-objective optimization models to select the key locations for online monitoring have typically one common objective which consists in minimizing the detection time (early detection of contaminant intrusion), the affected population, installation cost, etc. As a complement, these models present also the following caracteristics (Al-Zahrani and Moied 2003; Berry, et al. 2006;

Ghimire and Barkdoll 2008; Kessler, et al. 1998; Kumar, et al. 1997; Lee and Deininger 1992; Woo, et al. 2001):

- older studies using single-objective models (until 2001) did not performed any hydraulic modeling of the DS; however, later studies began to link the optimization model to the hydraulic and water quality model;
- heuristic methods and Integer Programming (IP) are the main approaches used for optimization;
- for the studies in which an hydraulic modeling has been performed, the researchers used a small-scale network model (less than 200 nodes) to represent their suggested approach;
- for the studies in which a hydraulic modeling has been performed, EPANET was the platform selected to model the contaminant transport throughout the DS;
- these studies did not consider any malfunction/damage issue of the monitoring sensors (assuming that all the sensors are in perfect condition);
- the calculation complexity of this method is not considerable and so several scenarios of intrusion events can be easily investigated on a full-scale network (including tens of thousands nodes) (Berry, et al. 2006).

2.6.2 Multi-objective optimization models

Multi-objective optimization models consider a weight-base summation of different objectives based on their relative importance. The objectives typically considered include : minimizing the detection time, reducing the affected population and increasing the coverage of different areas throughout the DS, although the detection time and the affected population are usually combined together in small-scale networks (Afshar and Miri Khombi 2015; Iqbal, et al. 2016). The importance of each objective is evaluated separately using a Pareto front. Other characteristics of these optimization models are as follows (Afshar and Mariño 2012; Dorini, et al. 2008; Hart and Murray 2010; Krause and Guestrin 2009; Preis and Ostfeld 2008; Rathi and Gupta 2017; Yoo, et al. 2015; Zeng, et al. 2016; Zeng, et al. 2018) :

- these models use a search strategy to consider local optimal (undominated) points;

- the approaches used for optimization include: Integer Programming (IP), Mixed Integer Programming (MIP), Heuristic method, Genetic Algorithm (GA) and Ant Colony Optimization (ACO);
- with no exception, all of these models considered a single-specie contamination, and none of these models considered any disinfectant-pathogen reactions;
- though some of these models simulated the DS in pressure loss conditions, none of them did implement a pressure dependent approach to model the DS in pressure loss conditions;
- as for single-objective optimization models, malfunction/damage issues of the monitoring sensors were not considered.

Overall, multi-objective optimization model have been shown to be more flexible and to provide more applicable results due to the consideration of different objectives and more options in the model (Hart and Murray 2010).

2.7 Case studies evaluating the performance of online monitoring probes in a real-scale DS

Salim, et al. (2017) designed a wireless sensor network (WSN) system to monitor in real-time the water quality, using a combination of field sensors to record Dissolved Oxygen (DO), turbidity, temperature, pH, conductivity, Total Dissolved Solids (TDS) and salinity. The monitoring probes were distributed in three different node combinations to measure the different quality parameters, and connected to (i) a Wi-Fi sensor network system (WSN) for data gathering and (Wang, et al.) an online monitoring system (OMS) for analyzing data recorded in the online database in 1-minute intervals (average and standard deviation) (Figure 2.4).

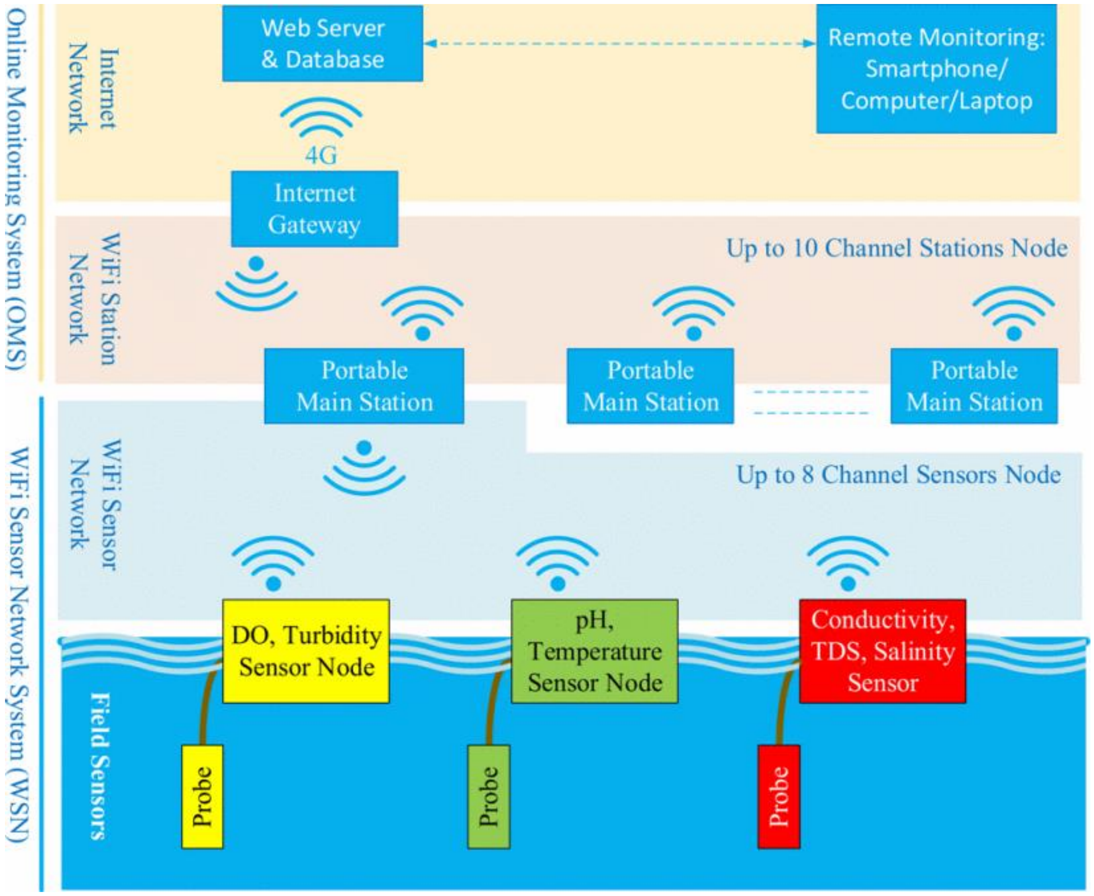

Figure 2.4 The full scheme of monitoring system (Salim, et al. 2017)

They categorized each parameter as dangerous (Boulos, et al. 2005), bad but tolerable and good quality (Kent, et al. 1988) (Table 2.7). They concluded that the sensors work well recording quality parameters every 5 seconds and that the online monitoring system succeeded to return analyzed data every one minute.

Table 2.7 Classification of measured data from different sensors as dangerous, tolerable or good quality according to (Salim, et al. 2017)

Sensors	**Dangerous (Red)**	**Bad but tolerable (yellow)**	**Good quality (green)**
Diss. Oxygen (mg/L)	0-3; 14-20	3-5; 10-14	5-10
Temperature (C)	40-50	30-40	20-30
pH	0-5; 9-14	5-6; 8-9	6-8

Wang, et al. (2010) proposed another system for online quality monitoring of the DS based on WSN and Code Division Multiple Access (CDMA) technology. This system consists of a gateway of nodes connected to multiple nodes to monitor the water quality parameters. Each node is supposed to record the parameters of interest and to transmit data to the gateway nodes which thereafter will transmit data to the control center through CDMA (Figure 2.5). They tested the proposed method in the DS of the south part of Zhanjiang, by monitoring over four days 11 nodes, and compared the data recorded at the gateway node, the data measured at the control center, and the data measured using on-site conventional sampling. The data obtained through both site conventional sampling and online monitoring (computed at the control center or at the gateway node) were quite consistent (Table 2.8).

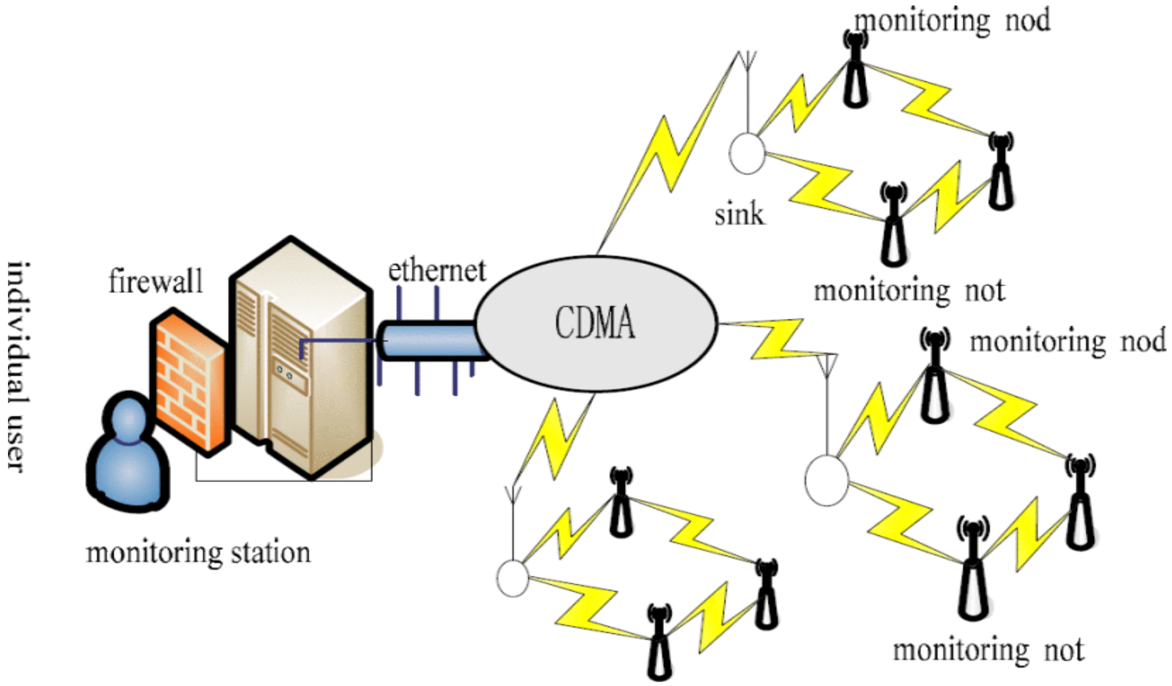

Figure 2.5 The structure scheme of the proposed method (Wang, et al. 2010)

Table 2.8 Comparison between (1) conventional sampling data, (Hallam, et al.) mean values at the nodes gateway and (3) mean values at the control center for each day of monitoring in the DS (Wang, et al. 2010)

		DO (mg.L-1)			**pH (7.0 ~ 9.4)**			**Conductivity (µs/cm)**		
	No.	1	2	3	1	2	3	1	2	3
Day of monitoring	Oct.1	8.8	8.8	8.7	8.7	8.5	8.5	355	355	354
	Oct.2	8.8	8.8	8.8	8.7	8.5	8.4	355	354	354
	Oct.3	8.7	8.6	8.6	8.4	8.4	8.2	355	353	353
	Oct.4	8.7	8.7	8.7	8.7	8.6	8.6	355	353	352

Ikonen, et al. (2017) performed a laboratory-scale study to evaluate the ability of an on-line monitoring system to detect *E.coli* intrusion into a drinking water DS. To do so, they injected a concentration of a total *E. coli* count of 2 × 10^9 CFU in a three-level pilot made of polyethylene-aluminum-polyethylene pipes of 12 mm (level 3) and 41 (levels 1 and 2). The pilot was equipped with various monitoring sensors including two pH sensors (Durafet III electrode, Honeywell), an on-line particle measurement tool (S4031, PAMAS, Rutesheim), eight temperature probes (ST21), two turbidimeters (1720E Low-range, Hatch Lange), two flowmeters (Transmitter 8055, Ingelfingen), a sensor for UV254 measure and six pressure meters (Sitrans P, Siemens) (Figure 2.6). Results showed that the on-line monitoring system detected the contamination instantaneously. Conductivity measurements showed the highest fluctuations in presence of *E. coli*, while turbidity and UV254 measurements showed peak signals as compared to their measured baseline. As a comparison, pH and temperature were not indicative of *E.coli* intrusion as these parameters barely changed during the event.

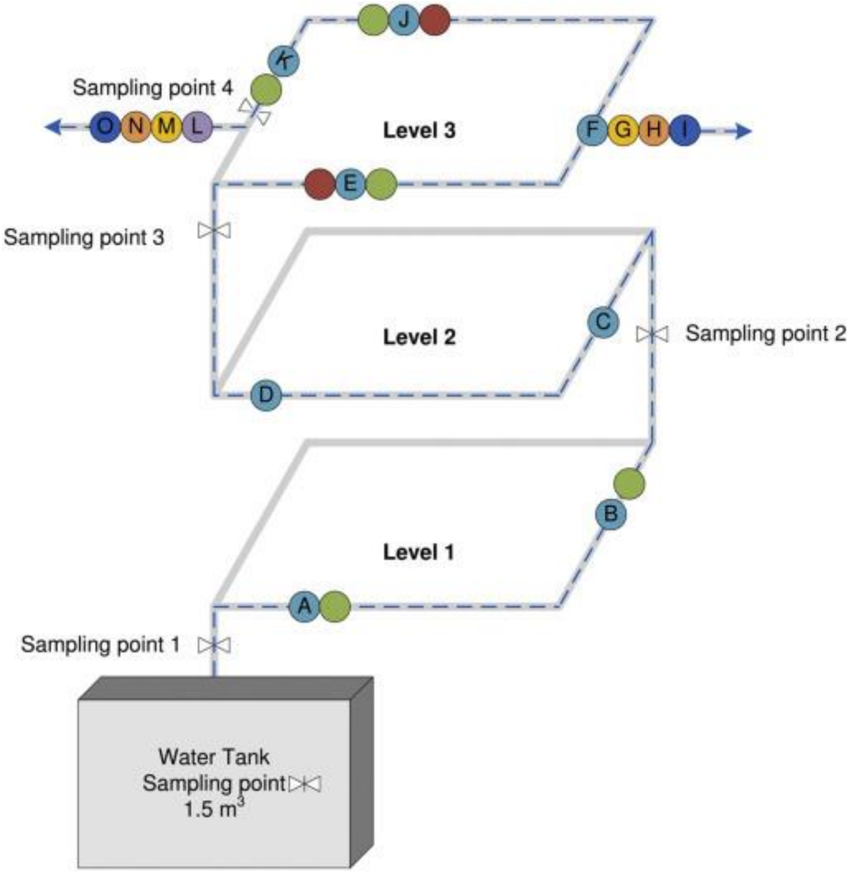

Figure 2.6 Piping pilot scheme used to evaluate the ability of sensors to detect *E coli.* (Ikonen, et al. 2017)

Helbling and VanBriesen (2008) performed an experimental study to validate the ability of free chlorine monitoring probes (Hatch CL17, Loveland, CO) to detect the intrusion of bacterial contaminants into the DS using a laboratory-scale pipe loop consisting of 1-inch PVC pipe, a reservoir, fittings and valves, and equipped with online monitoring of pH and temperature (Figure 2.7). They observed a consistent chlorine decay at the time of *E coli* injection into the pilot, indicating that the probes were quite able to detect bacterial intrusion events with accuracy (Figure 2.8).

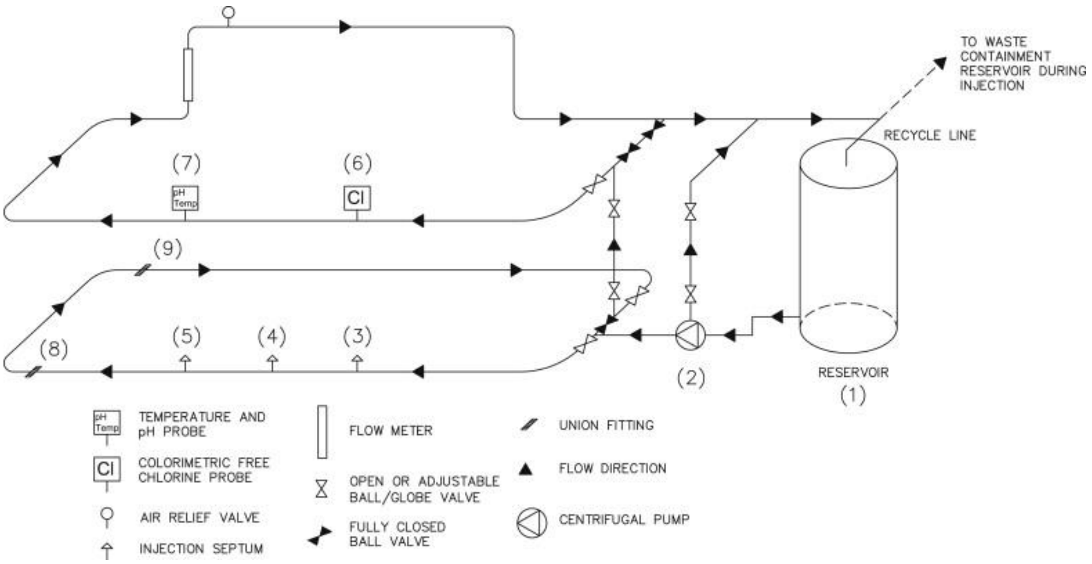

Figure 2.7 Laboratory-scale DS scheme (Helbling and VanBriesen 2008)

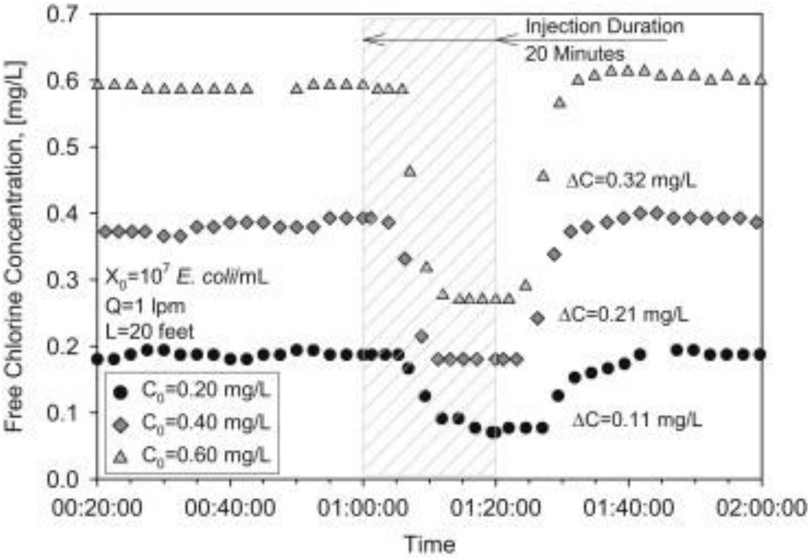

Figure 2.8 Chorine decay trend during intrusion of *E coli*. into the pilot (Helbling and VanBriesen 2008)

2.8 Objectives of this study

In this study, we evaluated the performance of two different online monitoring probes developed to measure critical parameters indicative of its water quality inserting them into the pipes of the DS: the KAPTA^{TM} 3000 AC4 and the KAPTA^{TM} 3000 OT3.

The first objective of this study was to validate the accuracy of the readings of each type of probes at pilot-scale experiment, for different velocities and water quality conditions (turbidity, chlorine, temperature, turbidity source).

The second objective of this study consisted in characterizing the effect of turbidity (source and level of turbidity) on chlorine measurements recorded by the probes.

Finally, the last objective of this study was to evaluate the ability of the probes to record with accuracy the critical water quality parameters over an extended period in a real DS.

CHAPTER 3 MATERIAL AND METHODS

3.1 Specifications of the probes

Two sets of probes were tested, including the KAPTA^{TM} 3000 AC4 and the KAPTA^{TM} 3000 OT3. These probes were developed for online monitoring of a combination of water quality and/or hydraulic parameters of the DS. The KAPTA^{TM} 3000 AC4 records both hydraulic and water quality parameters using a combination of sensors to measure pressure, temperature, conductivity and active chlorine (Figure 3.1). These probes require a minimum speed of 0.3 m/s to give reliable results. The application of these probes includes:

- real-time monitoring of above-mentioned parameters in the DS;
- detection of any change in the key hydraulic/quality parameters caused by main break, low or negative pressure, pipe corrosion, etc.;
- optimizing the maintenance of residual chlorine in the DS.

In comparison, the KAPTA^{TM} 3000 OT3 does not record pressure but uses a combination of optical sensors to measure turbidity, temperature and UV.

These probes provide the following applications:

- real-time monitoring of quality parameters of the DS (UV, turbidity and temperature);
- detection of fluctuations or sudden spike in turbidity of the DS which is helpful in terms of event detection;
- detection of potential formation of DBP;
- the possibility of monitoring areas with low/no-flow condition.

It is noteworthy that OT3 probe is not a direct tool to detect DBP formation. Indeed, the OT3 probe is able to measure OM into the drinking water, but no residual chlorine. Knowing the amount of chlorine is essential to estimate the potential of DBP formation. The following equation is used to relate quality parameters to the amount of DBP formed in drinking water (Kulkarni and Chellam 2010):

$$DBP = k \times DOC^{a} \times UV254^{b} \times Br^{-c} \times Cl_2^{d} \times pH^{e} \times Time^{f} \times Temp^{g}$$

Where:

- k, a, b, c, d, e, f and g are empirical constants.
- DOC is dissolved organic carbon concentration.
- UV254 is the ultraviolet absorbance at 254 nm.
- Br^- is the concentration of bromide ion.
- Cl_2 is the concentration of chlorine (mg/L).
- Time stands for the time of contact.
- And Temp is the temperature of drinking water.

Therefore, twe need to use a combination of both the OT3 and the AC4 KAPTA probes to get the information needed (UV254 and chlorine residual) to estimate the DBP formation in the distribution system. Finally, the measure of other parameters having an impact on DPB formation (pH, Br-, DOC) is not supported by any of the KAPTA probes.

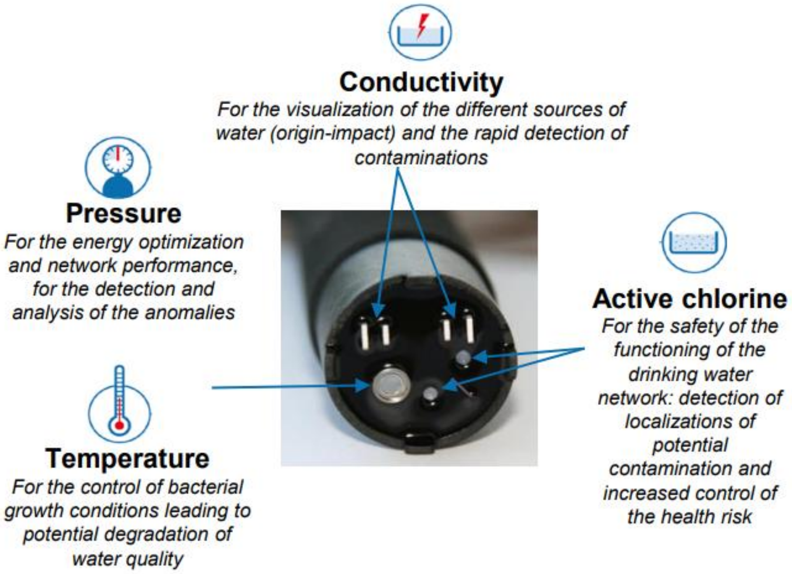

Figure 3.1 KAPTA^{TM} 3000-AC4 components

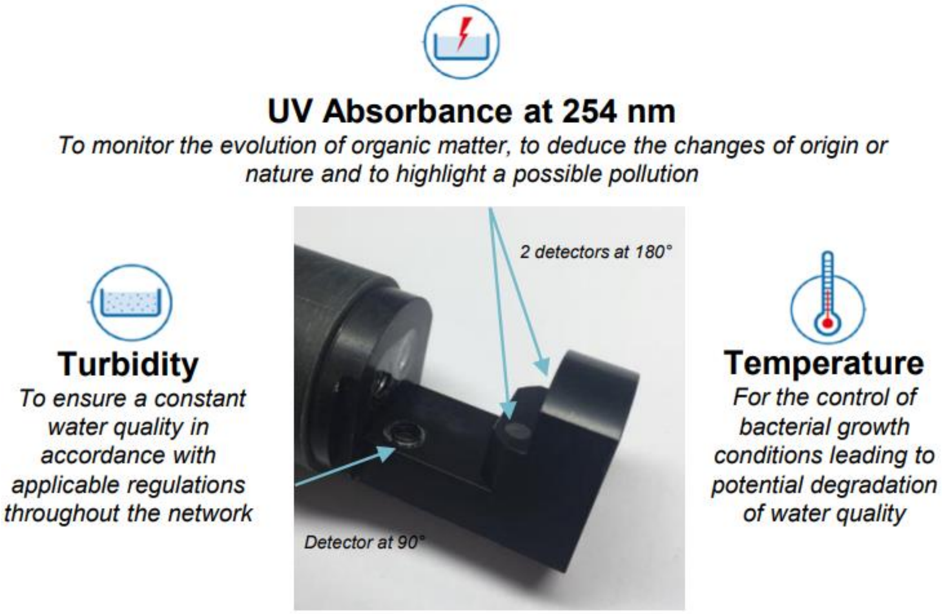

Figure 3.2 KAPTA™ 3000-OT3 components

KAPTA™ 3000 OT3 probes measure turbidity through an optic sensor for Nephelometry measurement at 6-second, 1-minute or 5-minute intervals (Figure 3.3).

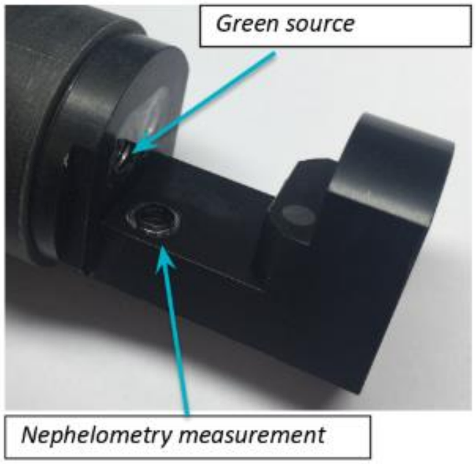

Figure 3.3 KAPTA™ 3000 OT3 optical sensor for turbidity measurement

The following table presents the general specifications of each probe.

Table 3.1 General specifications of KAPTA$^{\text{TM}}$ 3000-AC4 and KAPTA$^{\text{TM}}$ 3000-OT3

Device	Measuring parameters	Measurement range	Resolution	Accuracy
KAPTA$^{\text{TM}}$ 3000 AC4	Pressure	0-12 mbar	1 mbar	± 5%
	Temperature	0-40 °C	0.1 °C	± 1 °C
	Conductivity	50-1000 µScm^{-1}	5 µScm^{-1}	± 5 µScm^{-1}
	Active chlorine	0-2 ppm	0.01 ppm	± 5%
	Accuracy of flow rates measurements	Between 0.03 m/s and 1.5 m/s		
KAPTA$^{\text{TM}}$ 3000 OT3	Organic matter	0-0.3 cm^{-1}	0.01 cm^{-1}	0.01 cm^{-1}
	Temperature	0-40 °C	0.1 °C	± 1 °C
	Turbidity	1-10 NTU	0.1 NTU	0.3 NTU

AC4 monitoring probes record values for active chlorine, however, reported results are based on free chlorine and therefore, a data transfer needs to be done. It should be noted that active chlorine refers to the amount of hypochlorous acid (HOCl) in water, while free chlorine stands for the summation of hypochlorous acid and hypochlorite ion (OCl^-) in water. Temperature and pH could help to turn active chlorine to free chlorine, and this would be possible in case of using following equations.

$$(Free\ Chlorine)\left(\frac{mg\ Cl2}{L}\right) = (Active\ Chlorine)\left(\frac{mg\ Cl2}{L}\right) \times (1 + 10^{(pH-pKa)})$$

And,

$$pKa = \frac{3000}{T} - 10.0686 + 0.0253 \times T \qquad \text{(Beriet, et al. 2016)}$$

Where,

T= temperature (kelvin)

KAPTA$^{\text{TM}}$ probes transfer data through GSM communication boxes. This GSM data passes through a secure server and is accessible in two forms. The raw data is transmitted in XML or CSV format to an FTP server. Data is accessible from anywhere to authorized persons on a BIRDZ web portal via a secure internet connection by login and personal password. The web service for collecting and transmitting data complies with OWASP security rules. To ensure the security of the measured data, BIRDZ is committed to implementing IT structures and data transmission systems to provide:

- Compressed data before transmission.
- Coded frames.
- A transfer of data emitted by the probes in coded binary language.
- An algorithm and a decoding key specific to the KAPTA^{TM} service.
- The absence of a message sent "in clear".
- Communication boxes specific to the KAPTA^{TM} system.
- The impossibility for a third party to insert erroneous data into the transmission system.
- A datacenter ensuring resilience and high availability of the data.
- A record of the data kept until the end of the calendar year following the year of receipt of the data.

3.2 Pilot specifications

The probes were tested at pilot-scale to validate their performance in different conditions. The pilot consisted in a loop of 2 inches pipe, a 200 liters reservoir, a pump and a flowrate meter (Figure 3.4). A valve installed right after the pump allowed adjusting the flow rate and therefore the velocity in the pipeline.

Four KAPTA 3000 probes (two AC4 and two OT3) were installed in parallel for recording both hydraulic and water quality parameters. An online thermometer along with a conductivity meter were used as reference measurement tools for comparison to the KAPTA probes measurements. Figure 3.5 presents a schematic of the pilot.

The probes were directly connected to a laptop for recording data using communication boxes, cables and software provided by NEROXIS SA. The interface recorded each parameter measured by the probes every 6 seconds or at one-minute intervals (depending on the selection of turbo or normal mode).

Figure 3.4 Pipe-loop used for the evaluation of the KAPTA 3000 AC4 and OT3 probes

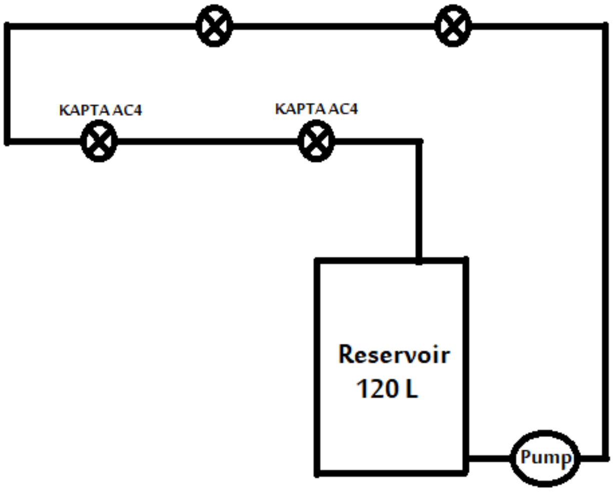

Figure 3.5 Schematic of the pilot used for validation of the KAPTA monitoring probes

3.3 Installation of probes on the pilot

The four probes were installed according to the manufacturer's instruction, i.e. with an angle in the range of 30° to 45° from the vertical axis (Figure 3.6). In addition, to avoid turbulences caused by changes in flow regime, a distance of at least 5 times of the pipe diameter was ensured between the probes, fittings and elbows in the pilot.

Figure 3.6 Angle of installation of the KAPTA 3000 monitoring probes

The probes were directly connected to a laptop using KAPTA 3000 AC4 Viewer and KAPTA 3000 OT3 Viewer interfaces (Figure 3.7), either through a connector box (AC4) or a cable provided by NEROXIS (OT3) (Figure 3.8). This software allows communicating with three probes at the same time. It also provides three choices of time intervals for recording data: 6 seconds, one-minute, or 5 minutes. In this study, we used a 6-second recording interval to gather probe measurements.

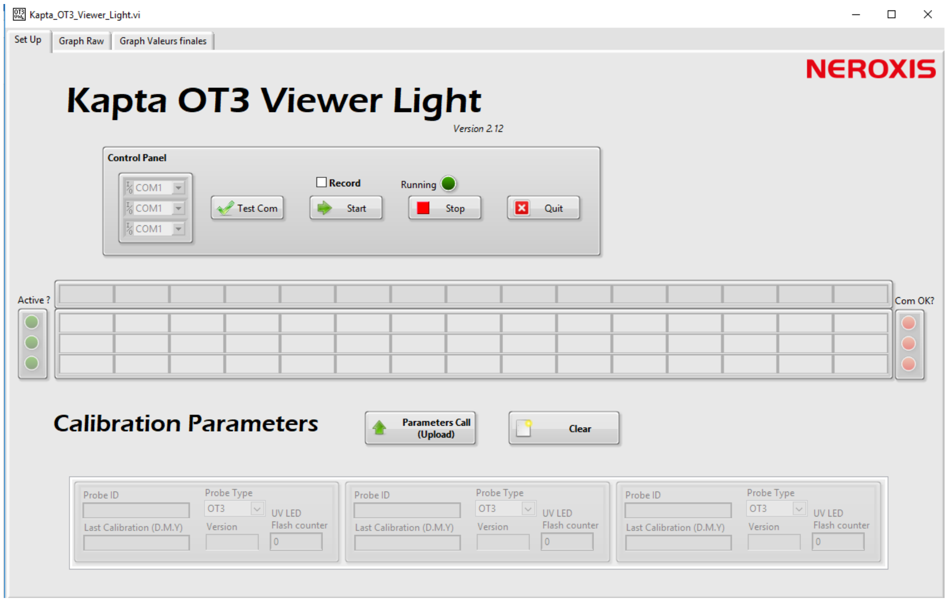

Figure 3.7 KAPTA OT3 Viewer interface for connecting the probes directly to the laptop

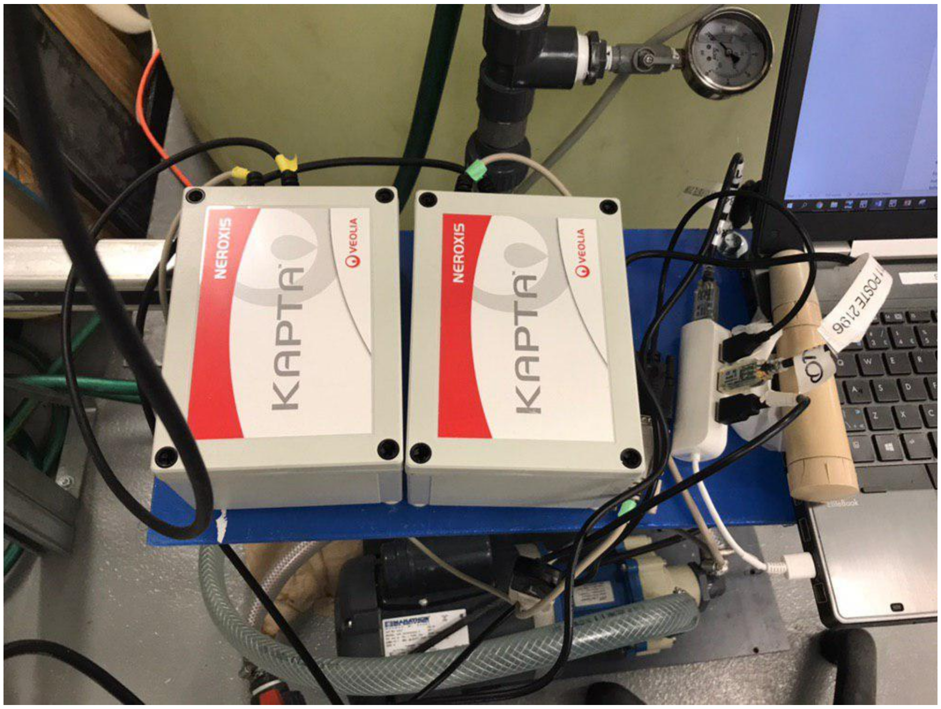

Figure 3.8 Connector boxes for connecting the AC4 probes to the laptop

3.4 Reference measurements used for comparison to the KAPTA probe readings

The two OT3 probes measured turbidity at 6-second intervals. To validate the recorded data, reference turbidity was measured every one hour using an HACH TL 3200 turbidimeter calibrated once a week using a standard turbidity kit (Figure 3.9). Each sample was measured in duplicate and the average of both measures was used for comparison to the probes recorded turbidity.

Figure 3.9 HACH TL3200 turbidity meter

3.5 Data processing and measurement for chlorine

To measure reference free chlorine at each time step, HACH DR 5000 was used at each time step for two samples and the result return the average. The device was calibrated before each test with a blank sample. At the same time, the two KAPTA 3000 AC4 probes recorded the active chlorine at 6-second intervals using sensors showed in Figure 3.10. Reported results represent 10-minute averages of the records for each time step.

Figure 3.10 HACH DR 5000 used for free chlorine reference measurements

3.6 Test conditions applied for validation of the probes at pilot-scale for different ranges of turbidity

The performance of the probes during red water transient events was evaluated using tap water from the laboratory (Montreal distribution system), adjusted thereafter for the experiment regarding turbidity, chlorine, and temperature conditions. Turbidity varied from tap water to 8 NTU during the experiments and was created by adding kaolin/iron powder (Table 3.2). The concentration of kaolin added to the water reservoir as a function of turbidity is presented in Figure 3.11. Iron powder was generated by crushing and sieving scales collected from a rusty water pipe from Montreal DS. Free chlorine (1 mg/L) was added at the beginning of each test to capture the interaction between chlorine and turbidity particles and the ability of the probes to detect it. Finally, tests were completed in warm (21°C) and cold (8°C) water to represent summer and winter conditions respectively. Table 3.2 summarizes the tested conditions.

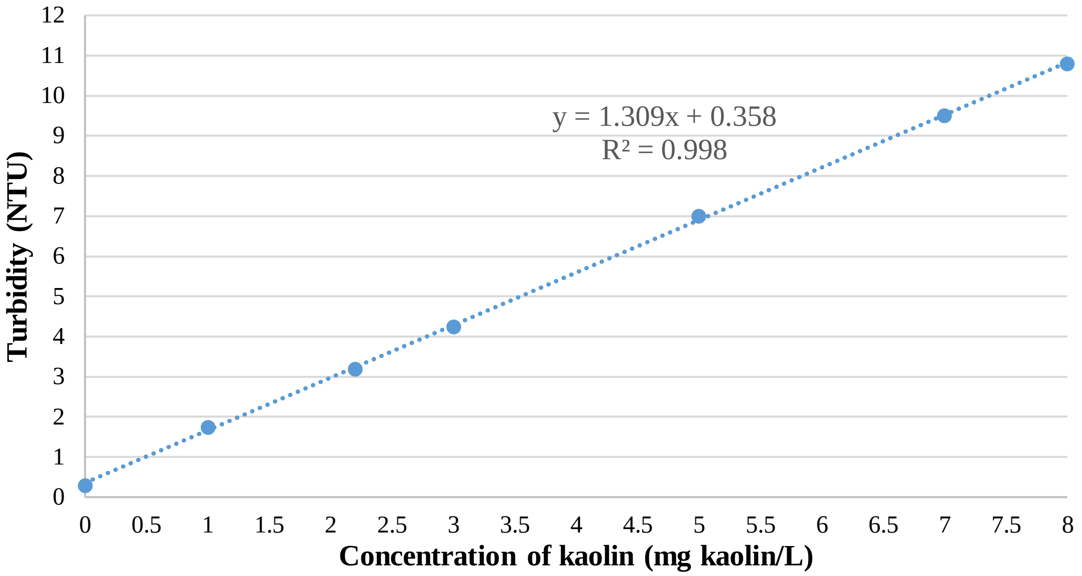

Figure 3.11 Turbidity of water as a function of the concentration of kaolin

Table 3.2 Test conditions for validation of the performance of the probes with different turbidities (velocity=0.36 m/s)

Test	pH	Temperature (C)	Turbidity (NTU)	Initial free chlorine (mg/L)	Source of Turbidity	Velocity (m/s)
1	8.0	21±1	tap water	1.00±0.05	-	0.27
2	8.0	21±1	2	1.00±0.05	kaolin/iron powder	0.27
3	8.0	21±1	5	1.00±0.05	kaolin/iron powder	0.27
4	8.0	21±1	8	1.00±0.05	kaolin/iron powder	0.27
5	8.0	8±1	tap water	1.00±0.05	-	0.27
6	8.0	8±1	2	1.00±0.05	kaolin/iron powder	0.27
7	8.0	8±1	5	1.00±0.05	kaolin/iron powder	0.27
8	8.0	8±1	8	1.00±0.05	kaolin/iron powder	0.27
9	8.0	21±1	2	0.00	kaolin	0.27
10	8.0	21±1	5	0.00	kaolin	0.27
11	8.0	21±1	8	0.00	kaolin	0.27

In order to characterize the red water transient events simulated in the pilot by adding iron field-collected scales into the water, 500 mL samples were collected every hour to measure dissolved and total iron in the water. In addition, the distribution of the iron powder particle size (ranging from millimeter to nanometer) was evaluated every hour during the experiments using a Mastersizer 3000 Laser Diffraction Particle Size Analyzer. The test conditions are summarized in Table 3.3.

Table 3.3 Conditions for testing the dissolution of field-collected iron scale particles over time (velocity=0.36 m/s; sampled hourly for 4 hours)

Test	**pH**	**Temperature (^{0}C)**	**Turbidity (NTU)**	**Initial free chlorine (mg/L)**	**Source of Turbidity**
1	8.0	21±1	2	1.00±0.05	Iron powder
2	8.0	21±1	5	1.00±0.05	Iron powder
3	8.0	21±1	8	1.00±0.05	Iron powder

The methodology of simulating transient red water event along with the tests with organic matter is identical for all tested conditions:

1- Filling up the reservoir up to 120 liters one day before the test to stabilize temperature, free chlorine and pH in the reservoir.

2- Adjusting the pH of water in the reservoir to 8.0 using HCl (0.1 M) or NaOH (0.1 M).

3- Injecting chlorine to the reservoir and mixing it to fix the initial free chlorine to 1 ppm.

4- Adding iron powder or kaolin solution and mixing it to adjust desired turbidity in the pilot.

5- Running the pilot for 6 hours and measuring all quality parameters (chlorine, conductivity, temperature, UV and turbidity) at 1-hour intervals.

6- Emptying the water at the end of the test and flushing the pipeline and reservoir for three times.

7- Filling up the reservoir for the next day test.

3.7 Test conditions applied for validation of the probes at pilot-scale for different hydraulic conditions

Red water transient events reproduced using kaolin and iron powder particles were performed at two different velocities, 0.11 and 0.36 m/s. Table 3.4 presents the conditions during these tests.

Table 3.4 Conditions for tests in different velocities

Test	**pH**	**Temperature (°C)**	**Turbidity (NTU)**	**Initial free chlorine (mg/L)**	**Source of Turbidity**	**Velocity (m/s)**
1	8	21±1	2	1±0.05	kaolin	0.11
2	8	21±1	8	1±0.05	kaolin	0.11
3	8	21±1	2	1±0.05	kaolin	0.36
4	8	21±1	8	1±0.05	kaolin	0.36
5	8	21±1	2	1±0.05	Iron powder	0.11
6	8	21±1	8	1±0.05	Iron powder	0.11
7	8	21±1	2	1±0.05	Iron powder	0.36
8	8	21±1	8	1±0.05	Iron powder	0.36

3.8 Field experiment

In order to validate the performance of the probes to capture water quality fluctuations in real conditions, we performed a field study installing the probes (two AC4 and two OT3) in a chlorination station in Duranleau, Laval. The Duranleau chlorination station is located at 6645 rue Duranleau, in Saint-François, in a building annexed to the fire station no. 5. The average of quality parameters at the station at the time of installation are as follow: pH=7.5, free chlorine=0.66 mg/L, turbidity=0.127 NTU, conductivity=146 (µS), temperature=15.5 ^{0}C.

The station consists of a building housing the sodium hypochlorite dosing system (tank, pumps, etc.) and water analysis measurement tools (conductivity, pH, temperature, turbidity, corrosivity and residual chlorine) systems (Figure 3.12). Table 3.5 presents the specifications of quality instruments. The station is used all year round to correct the chlorine dosage on the DS.

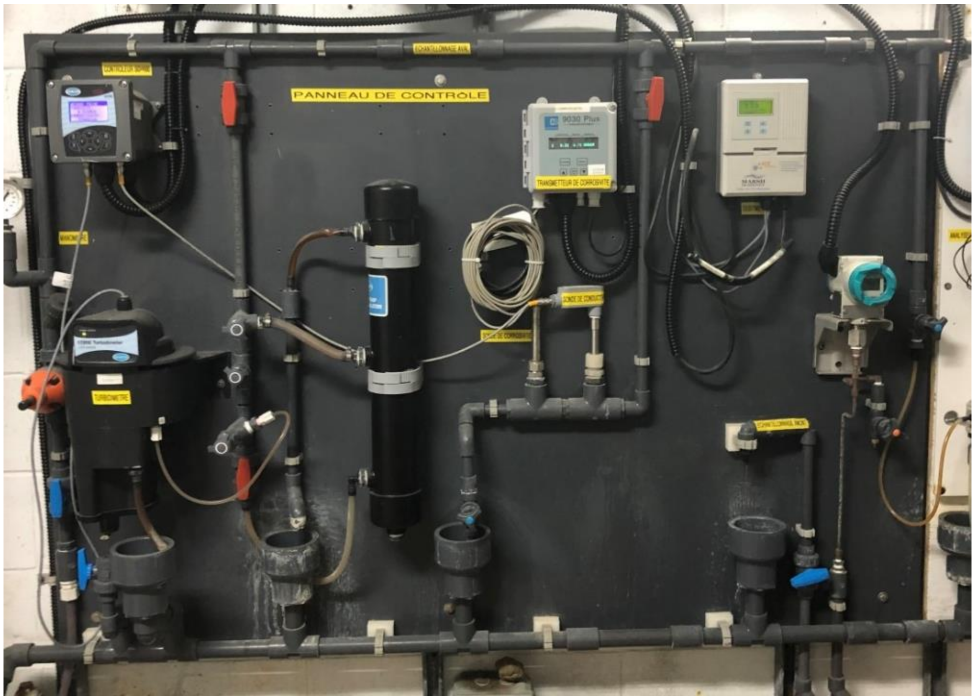

Figure 3.12 Water analysis system at Duranleau station

The metering is carried out near the substation, on the main gray cast iron pipe 6069 of 350 mm Ø, in a new underground chamber (the metering chamber) at the end of rue Duranleau. The range of flow rates observed on the pipe varies from 220 L/min to 2,500 L/min with an average of 500 L/min. Figure 3.13 shows the scheme of KAPTA set up along with the water analysis board.

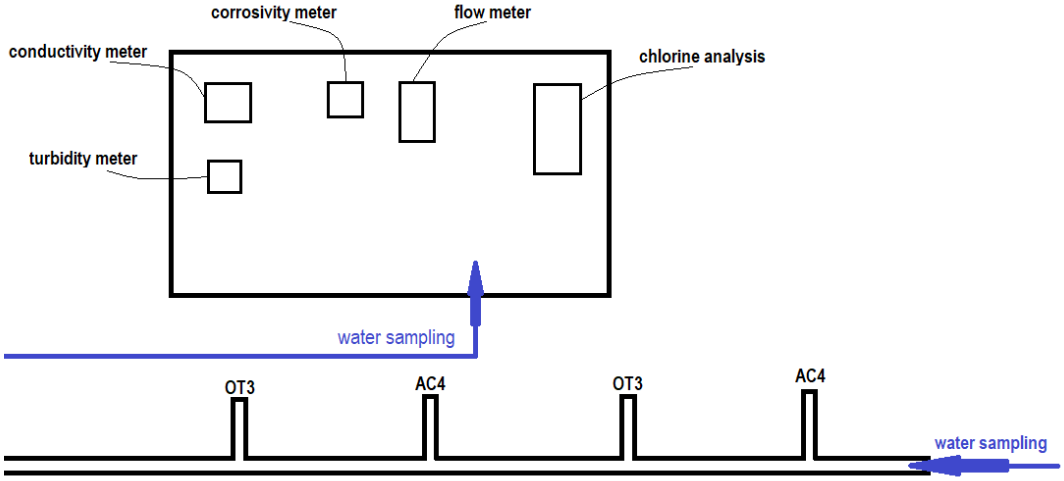

Figure 3.13 Scheme of KAPTA set up at Duranleau station

Table 3.5 Specifications of the quality recording instruments

	Brand	**Model**	**Frequency of Measurements**
Turbidity	HACH	1720E	Every 5 minutes or when the value change for more than 0,005 UTN
Chlorine	Swann Analytical Instruments	AMI Trides	1 minutes or when the value change for more than 0,01 mg/L
Corrosivity	John Meunier inc.	7012 CS	-
Flowmeter	Marsh McBirney	Multi-Mag 285L	-
Conductivity	HATCH	3422B3	-
pH	pH Swansensor	-	-

In addition to the probes, we installed an auto-sampler (Isco 780 Avalanche Transportable Sampler) to capture any high turbidity event occurring in the DS. A 0.5 NTU trigger point was defined to initiate automatic online sampling, at a 5-minute time-step until turbidity decreases below 0.5 NTU (Figure 3.14).

Figure 3.14 ISCO 780 Avalanche transportable sampler

CHAPTER 4 RESULTS

This chapter presents the results of the tests performed with the probes at pilot- and full-scale experiments.

4.1 Technical definitions

This section presents some definitions of the technical terms used to discuss the results along with the description of the implemented statistical tests.

4.1.1 Accuracy, precision and bias

Accuracy (validity) and precision (reliability or repeatability) are the two important metrics to evaluate the quality of data produced by sensors. Accuracy depicts the differences between the estimated value and real value; while precision refers to closeness of the estimations performed by a specific method/device (Mandel 2012). According to these definitions, technical measurements from different laboratories or sensors could be accurate but not precise or could be precise but not accurate (Figure 4.1). In this regard, the best case would be a set of data that are both accurate and precise (valid and reliable at the same time).

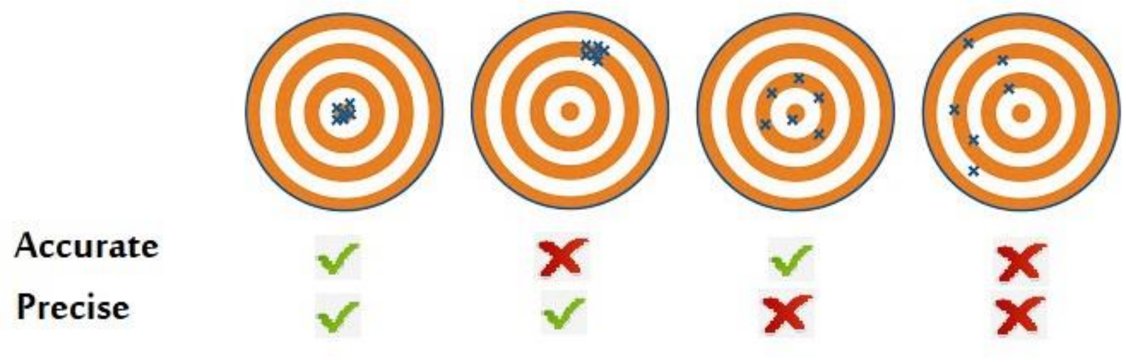

Figure 4.1 Accuracy vs. precision. Adapted from (Mandel 2012)

When interpreting accuracy, the first step to define an acceptable difference between the estimations and the real values (the acceptable distance between the dart and the inner bullseye on the dartboard depicted in Figure 4.1), considering the objective of the measurements and the manufacturers claim. Therefore, based on this definition, the validity of a method/device can be assessed for a specific application. Absolute error or relative error can be used to determine data accuracy.

Absolute error: The absolute value of the subtraction of estimated value from real reference value is called absolute error. Absolute error is based on the unit of measurements and therefore is scale-dependent which makes it difficult to compare it with a data set measured in a different unit.

Relative error: In order to facilitate the comparisons between the accuracy of different data sets and making measured errors unit-less, relative error should be used. Relative error is the ratio of absolute error to the real value. It also helps to put the errors into perspective, for instance, a 3^0C error is significant when temperature is at 25^0C, but it is non-significant when the real value is at 250^0C.

Bias: Bias is any systematic deviation (overestimation/underestimation) whereby the expected value of the results differs from the true underline value. Statistically, it refers to the deviation of data from reality. In fact, statistical bias gives an overall idea about how the sample represents the whole population (Simundic 2013). One way of bias calculation for a sample is to draw a scattered graph for data versus real values and fit a linear regression graph with a y=mx+b equation in which the “b” value represents the bias of the measurements.

4.1.2 Statistical tests

Using statistical tests is another tool to assess the reliability of sensor measurements. There are different statistical tests that must be selected considering the distribution of the measurements. Parametric tests can be conducted for normally distributed samples, while non-parametric tests should be used for non-normally distributed samples. However, some tests are independent of the distribution of data. In this study we implemented following tests to compare data sets:

- Wilcoxon Sign-Rank Test: A matched paired test used for related data samples and independent from the distribution of data.
- Wilcoxon Rank-Sum Test: For tests between two independent data sets, independent from data distribution.

- Tukey's range test: Method to compare multiple data sets that could be significantly different from each other.

4.2 Repeatability of reference measurements

To investigate the repeatability of performed tests at the laboratory as compared to the reference data, we performed a set of tests at three turbidity levels of 2, 5 and 8 NTU turbid water created with kaolin, keeping other parameters unchanged; free chlorine at 1 ppm, temperature at 21±1 C, pH at 8 and velocity at 0.27 m/s. Each test was ran for 1 hour and quality parameters were measured every 10 minutes. We considered the accuracy claimed by the manufacturer of the KAPTA probe (Table 3.1) as a basis to evaluate the acceptable repeatability of our reference measurements. Therefore, maximum acceptable error for turbidity would be 0.3 NTU (absolute error), for chlorine 5% (relative error), and UV254 0.01 cm^{-1} (absolute error).

Table 4.1 to Table 4.3 show the results for turbidity, free chlorine and UV254 measurements respectively. Accordingly, maximum absolute differentials for turbidity measurements is 0.1, 0.1 and 0.2 NTU for tests at 2NTU, 5NTU and 8NTU turbid water respectively, which is less than 0.3NTU and therefore HACH TL 3200 is precise enough to be used for turbidity reference measurements. On the other hand, the maximum relative differentials for chlorine measurements is 2%, 3% and 3% for tests at 2NTU, 5NTU and 8NTU turbid water, which is lower than 5% (acceptable relative error). Therefore, HACH DR 5000 is precise enough for free chlorine reference measurements. According to Table 4.3, maximum absolute errors for UV measurements is at 0.004 cm^{-1}, 0.007 cm^{-1}, and 0.007 cm^{-1} for tests at 2NTU, 5NTU and 8NTU turbid water, respectively which is less than 0.01 cm^{-1} and so HACH TL3200 is precise enough to be used as a tool for our reference measurements.

Table 4.1 Turbidity (NTU) measurements to test the precision of HACH TL3200

	Time steps						Max absolute differences
Turbidity	1st 10 min	2nd 10 min	3rd 10 min	4th 10 min	5th 10 min	6th 10 min	
2 NTU	1.9	1.9	1.9	1.8	1.8	1.8	0.1
	1.9	1.8	1.9	1.9	1.8	1.7	
5 NTU	5.0	5.0	4.8	4.8	4.8	4.7	0.1
	5.0	4.9	4.8	4.7	4.7	4.7	
8 NTU	7.8	7.7	7.5	7.5	7.4	7.3	0.2
	7.6	7.6	7.4	7.3	7.3	7.3	

Table 4.2 Free chlorine (ppm) measurements to test the precision of HACH DR 5000

	Time steps						Max relative differences
Turbidity	1st 10 min	2nd 10 min	3rd 10 min	4th 10 min	5th 10 min	6th 10 min	
2 NTU	1.03	1.02	1.02	1.02	1.01	1.00	2%
	1.05	1.03	1.01	1.00	0.99	0.98	
5 NTU	0.99	0.97	0.94	0.92	0.89	0.88	3%
	1.02	0.99	0.95	0.91	0.90	0.88	
8 NTU	1.02	0.97	0.95	0.90	0.88	0.85	3%
	1.00	0.96	0.92	0.88	0.87	0.83	

Table 4.3 UV254 (cm^{-1}) measurements to test the precision of HACH TL3200

	Time steps						Max absolute differences
Turbidity	1st 10 min	2nd 10 min	3rd 10 min	4th 10 min	5th 10 min	6th 10 min	
2 NTU	0.040	0.040	0.039	0.039	0.039	0.038	0.004
	0.037	0.036	0.036	0.036	0.035	0.034	
5 NTU	0.069	0.069	0.068	0.067	0.068	0.069	0.007
	0.064	0.064	0.063	0.062	0.062	0.062	
8 NTU	0.077	0.075	0.072	0.072	0.073	0.071	0.007
	0.071	0.070	0.068	0.067	0.066	0.066	

4.3 Pilot-scale results: simulation of red water transient events for different conditions of water temperature and velocity

This section presents results from the pipe loop study in which probes were subject to chlorinated water of different levels and sources of turbidity (iron or clay particles), in cold and warm water. The main objective of these experiments was to validate the accuracy and therefore the reliability of the probe readings during transient red water events, in winter and summer, and for different hydraulic conditions in the DS. A second objective included the evaluation of the repeatability of the probe readings for reference measurements, in other words its precision with regards to a reference measurement.

4.3.1 Characterization of the iron powder

As described in the Material and Methods section, pipe-loop tests included the use of iron powder, generated from field collected scales, as a source of turbidity. A set of tests was performed to determine the range of particle sizes and the total and dissolved iron in the pilot for each experiment completed at different levels of turbidity (2, 5 and 8 NTU).

To determine the particle sizes and its distribution during the period of running the pilot, we measured the distribution of particles using Mastersizer 3000. Figure 4.2 to Figure 4.4 present the distribution of the iron powder during a 4-hour test for different levels of turbidity. The results show that the particle size increased with the turbidity: the 90th percentile of particles distribution is about 150 (μm) for 2 NTU turbid water (start of the experiment), while it is around 250 (μm) and 325 (μm) for 5 and 8 NTU turbid waters respectively. The same trend is observed for the 50th and 10th percentile distributions. Finally, the results show that the particle size decreases over time, which is due to sedimentation of the iron powder in the reservoir. Figure 4.5 shows the accumulation of iron particles in the reservoir for each level of turbidity.

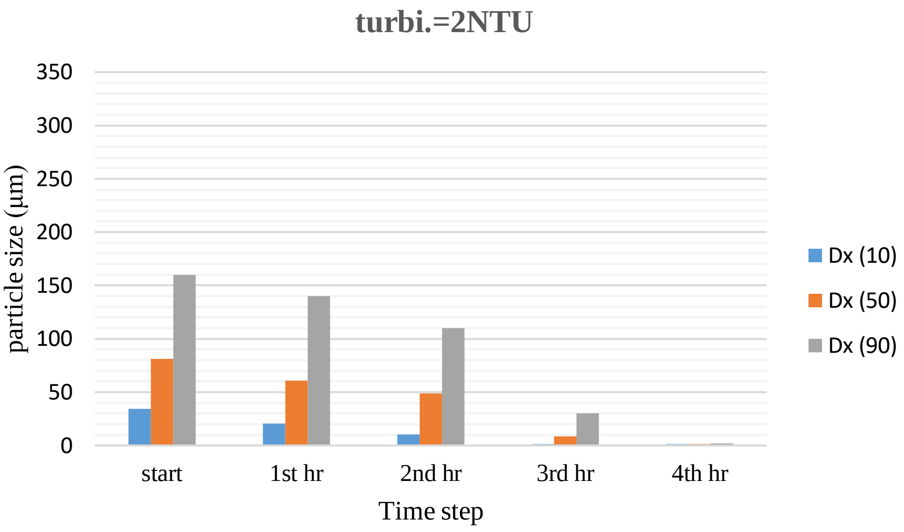

Figure 4.2 Distribution of iron particles over the 4 hour pilot test running time (turbidity=2NTU). 10, 50 and 90 corresponds to the 10th, 50th and 90th percentile of the particle size distribution

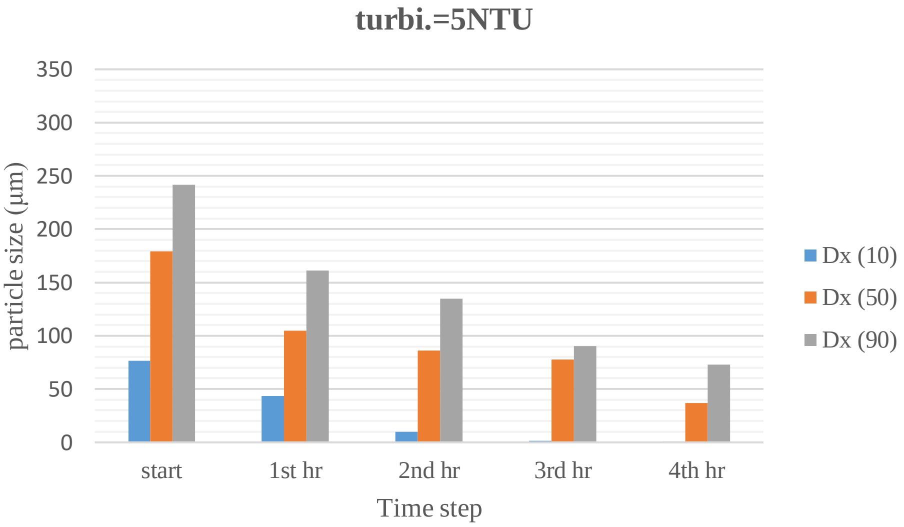

Figure 4.3 Distribution of iron particles over the 4 hour pilot test running time (turbidity=5 NTU). 10, 50 and 90 corresponds to the 10th, 50th and 90th percentile of the particle size distribution

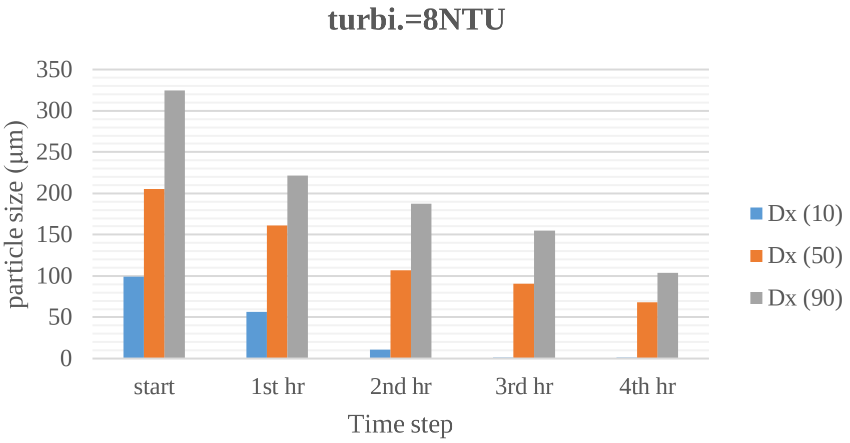

Figure 4.4 Distribution of iron particles over the 4 hour pilot test running time (turbidity=8NTU) 10, 50 and 90 corresponds to the 10th, 50th and 90th percentile of the

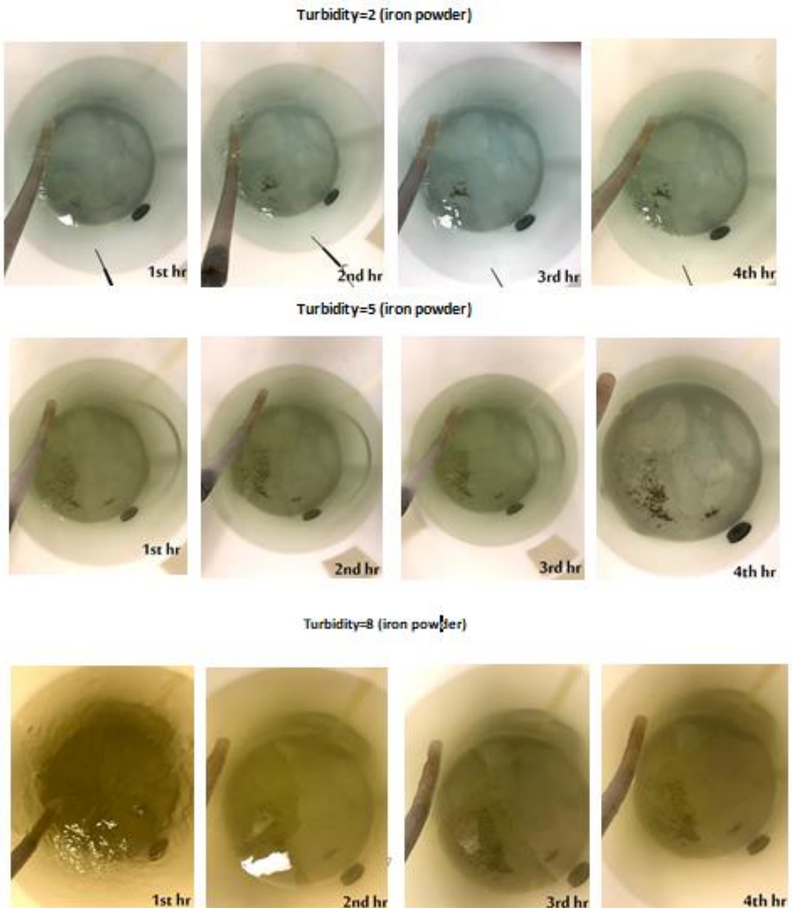

Figure 4.5 Accumulation of iron particles in the reservoir over the 4-hour pilot test running time, for the three levels of turbidity tested

We analyzed total and dissolved iron to identify the amount of iron solubilizing in the water over time during the experiments. Figure 4.6 to Figure 4.8 detail the total and dissolved concentrations and the particulate iron concentration over the 4-hour running time of the experiments, for 2, 5, and 8 NTU turbid water respectively. Dissolved and total iron concentrations decrease rapidly after the start of the experiment, and then tend to decrease slowly over the remaining duration of the experiment (1-4 hours). In agreement with the low dissolved iron levels, the average particulate fraction is high (80%) in 5 and 8 NTU experiments. As a comparison, the particulate fraction is lower (62%) in 2 NTU experiments.

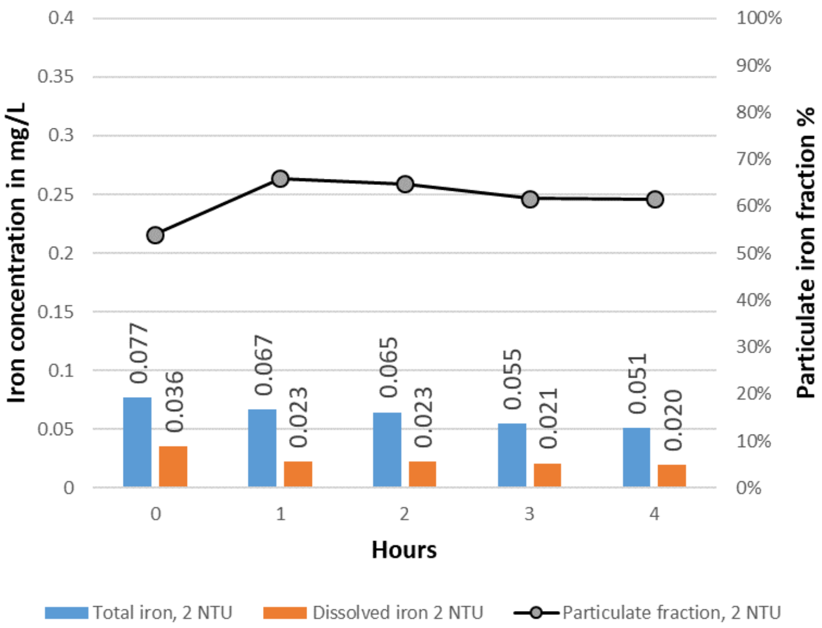

Figure 4.6 Total and dissolved iron concentration (mg/L, left axis) and associated particulate iron fraction over the 4-hour pilot test running time in 2 NTU turbid water

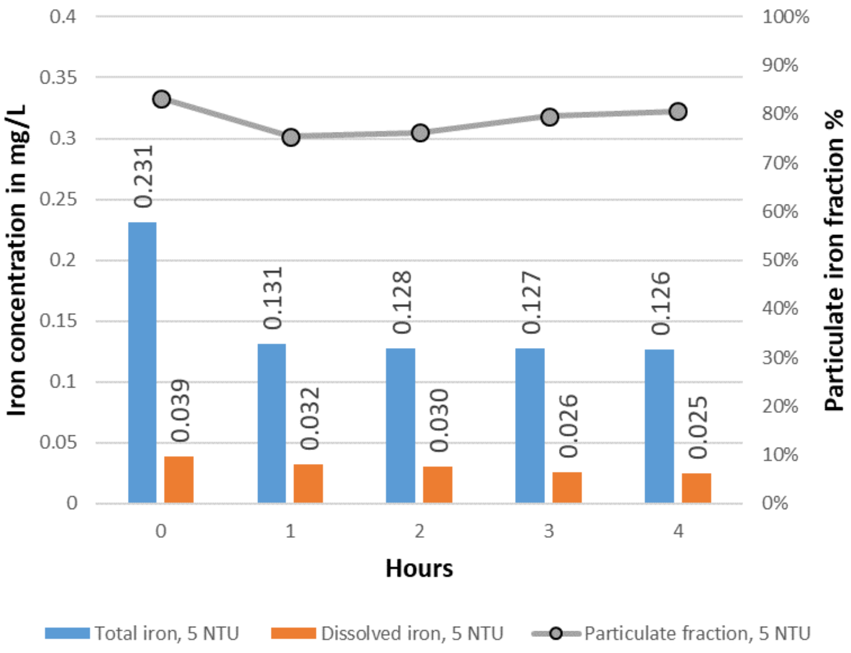

Figure 4.7 Total and dissolved iron concentration (mg/L, left axis) and associated particulate iron fraction over the 4-hour pilot test running time in 5 NTU turbid water

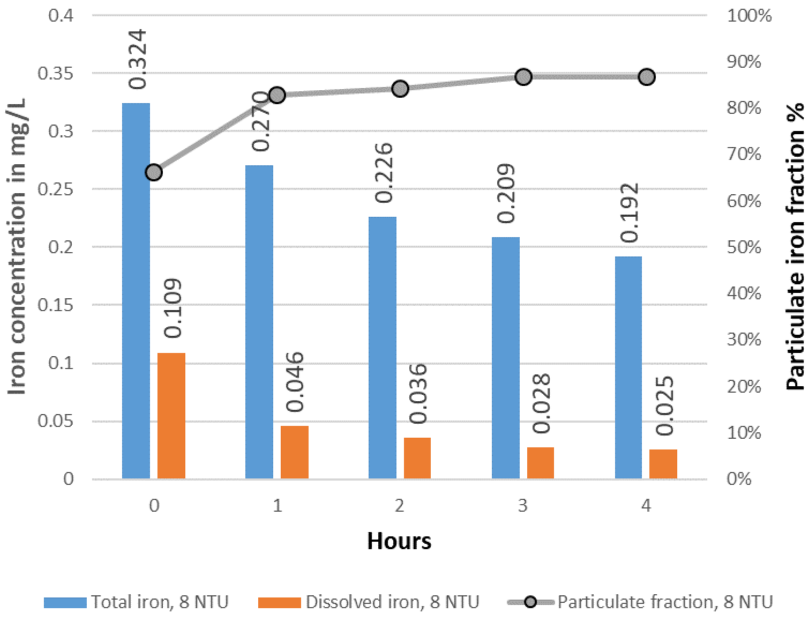

Figure 4.8 Total and dissolved iron concentration (mg/L, left axis) and associated particulate iron fraction over the 4-hour pilot test running time in 8 NTU turbid water

4.3.2 Turbidity measurements by KAPTA™ OT3 probes

Figure 4.9 presents the results of turbidity measurements from the two OT3 probes (12729 and 12747) in the pilot-scale study, for tap water, 2NTU, 5NTU and 8 NTU turbidity in warm water using kaolin powder as the source of turbidity. For each probe presented in each graph, the time series of probe readings are presented as well as the moving average calculated over 1 min and 10 min time spans.

The time-series graphs of probe readings show fluctuations for real-time data. As expected, the more the turbidity increases, the more the probe readings fluctuate. However, the 1-minute and 10-minute moving averages suggest that recordings conform the overall trend of reference measurements.

Comparison tests were performed for the same water at 2 and 8 NTU, but different turbidity sources (kaolin vs iron powder). Specifically, the absolute error was calculated by considering the absolute value of the difference between reference measurement and probe reading. Results presented in Figure 4.10 show no considerable variation in absolute errors; however, according to the figure, the noisiness and fluctuations for the tests performed with iron powder are smaller as compared to the tests performed with kaolin. One explanation could be the aggregation of kaolin particles during the period of the tests, which would affect the uniformity of the particles and therefore, would lead to fluctuations in probe readings.

In addition, the differences between the characteristics of particles affects the results of tests with kaolin and iron powder. The density of wet clay (1780 kg/m^3) is lower than the iron powder density (2380 kg/m^3). Moreover, the average particle size of kaolin (25 to 35 μm) is lower than iron particles (50 to 100 μm) which leads to lower sedimentation of kaolin particles. In addition, according to the results, in short time steps (less than 1 min) the probe readings for tests with kaolin show high fluctuations. Such observations are critical considering that some immediate actions are taken by utilities over a turbidity threshold.

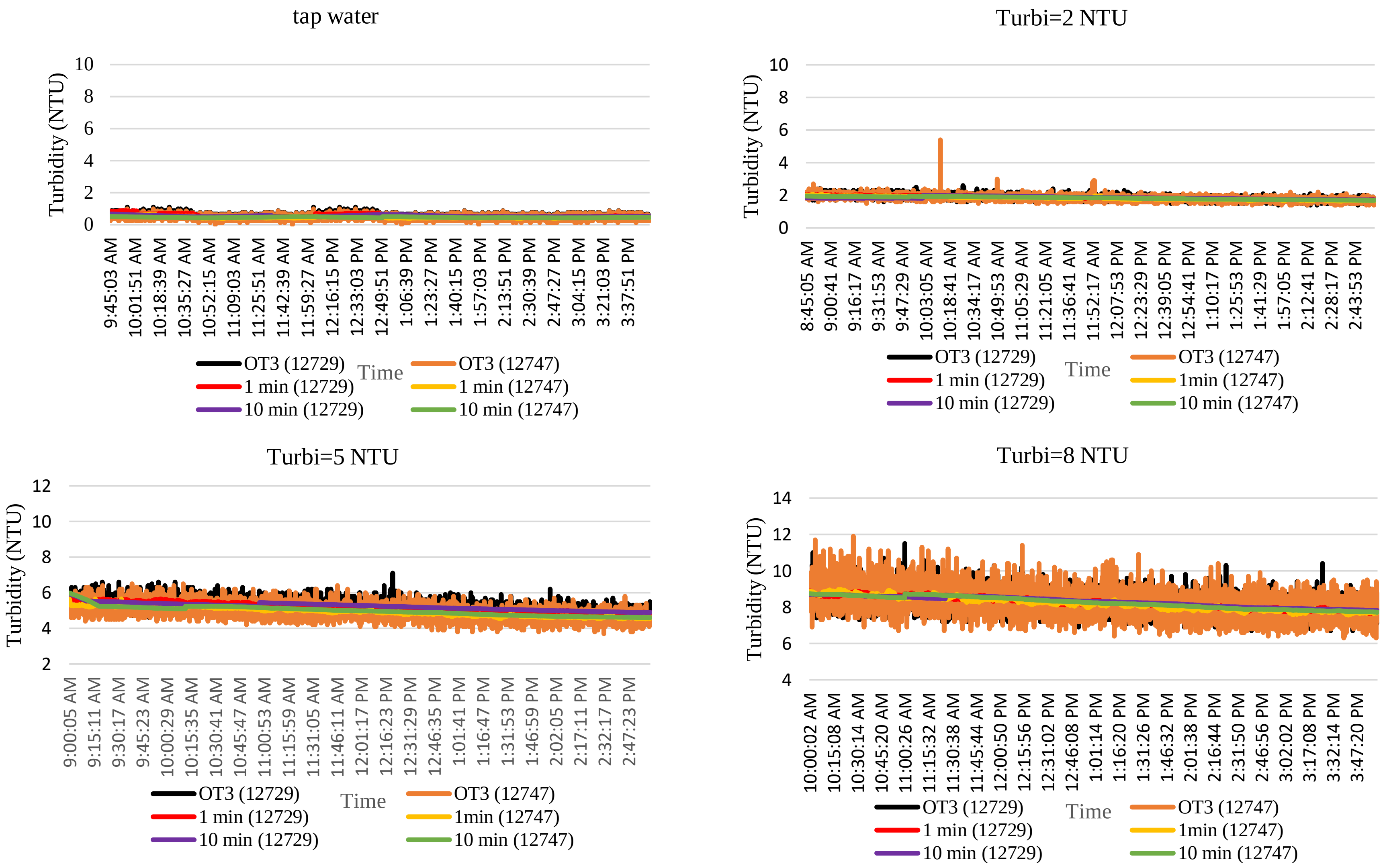

Figure 4.9 Time series and moving averages for turbidity measurements (Turbidity source: kaolin; PH=8; temperature: 21±1^{0}C; free chlorine=1 ppm)

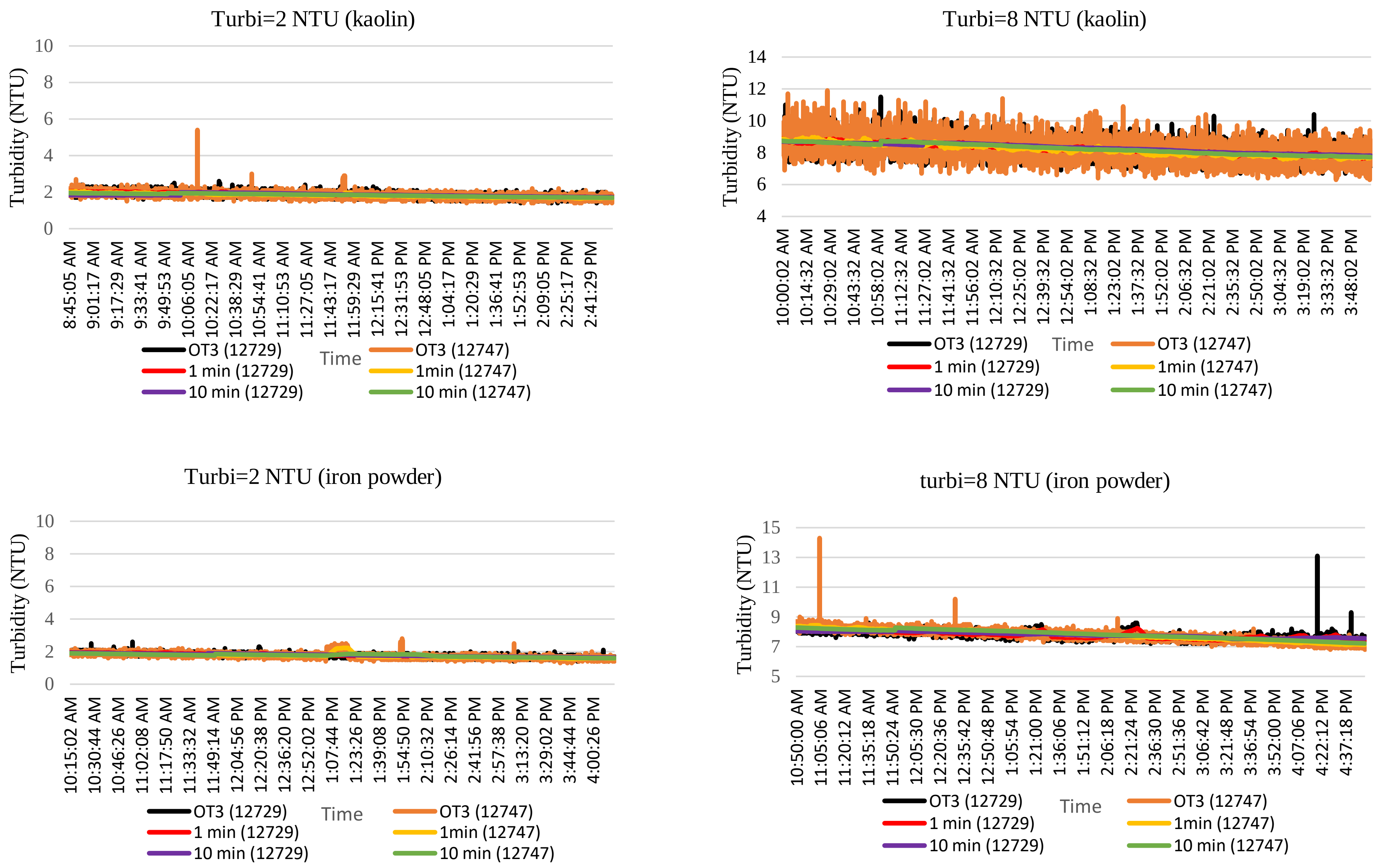

Figure 4.10 The comparison of results for tests with iron powder and kaolin (PH=8; temperature: 21±1^{0}C; free chlorine=1 ppm)

Using Nephelometry measurement at 525 nm, KAPTA^{TM} 3000 OT3 captures turbidity without requiring any in-place calibration or chemicals to perform the measurements. For each of the four levels of turbidity tested in this pilot study (tap water at around 0 NTU, 2, 5, and 8 NTU), we calculated the absolute error by doing the subtraction of the reference measurements from the probe readings for each test, the average of probe readings for half an hour and reference measurements every hour.

Figure 4.11 presents the absolute errors of turbidity measurements for each level of turbidity. The absolute errors range between 0 to 0.8 NTU. However, as Figure 4.9 shows, fluctuations in recordings increase in highest turbid water (8 NTU). This could be explained by the fact that the 2 inches pipe we used for these tests does not provide enough space for the water around the probe to pass through smoothly and therefore some extra micro-bubbles may be produced around the sensors, which leads to noisiness in turbidity measurements.

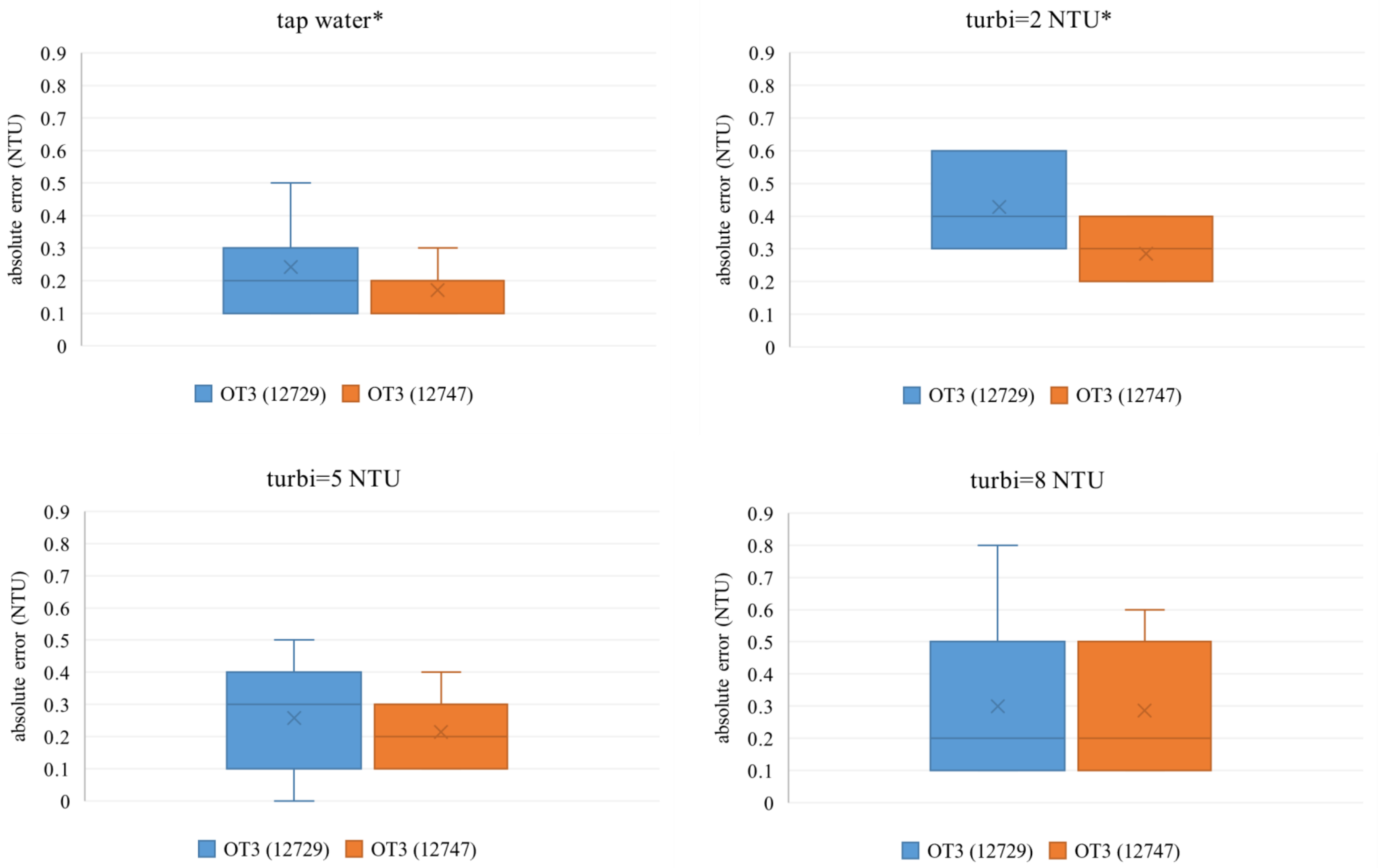

Figure 4.11 Absolute errors for turbidity recordings in different scenarios (turbidity source: kaolin, PH=8, temperature: 21±1^{0}C, free chlorine=1 ppm, n=420) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

The results show that for the first two tests (tap water and 2 NTU) the OT3 (12729) errors tend to be larger than the OT3 (12747) measurements (Wilcoxon signed-rank test, $p<0.005$). For the other two tests (5 NTU and 8 NTU), the errors of measurements with the two probes are not significantly different (Wilcoxon signed-rank test, $p>0.005$). To compare the errors with different levels of turbidity, Tukey's comparison method is applicable. According to the results, the errors of the measurements between the tests are as following, 8 NTU > 5 NTU> 2 NTU > tap water.

4.3.3 Impact of turbidity on the chlorine readings with KAPTA^{TM} 3000AC4 probes

Particles of turbidity present in the distributed water react with chlorine residual. Therefore, chlorine decay is typically observed during a red water transient event or any high turbidity event. One of the side objectives of this study is to investigate the ability of the probes to detect the changes in chlorine residual concentrations for different levels of turbidity (tap water, 2, 5 and 8 NTU).

Figure 4.14 presents the chlorine decay over time measured by the reference DPD method, and by the two KAPTA AC4 probes tested for tap water and water at 2, 5 and 8 NTU turbidity. As expected, higher chlorine decay is measured over time for the 8 NTU turbid water.

To investigate the accuracy of the probe readings for chlorine, the relative error was calculated by dividing the absolute error (absolute value of the subtraction of reference value from probe readings) to the reference value. As it stated before, the AC4 probes measure active chlorine. Equations mentioned in section 3.1 were used as a first step to transform it to free chlorine. As a second step, the relative error was calculated. Figure 4.12 presents the relative errors in chlorine readings for the tests performed with kaolin, while Figure 4.13 presents the relative error for the tests performed with iron powder.

The average of relative errors vary between 5 to 10 percent for the two probes, which is equal or higher than the manufacturer claim (5%). This could be due to the transformation of active chlorine to free chlorine using the equations explained in section 3.1. At the same time, the results show that the differentials between the probe readings and reference measurements remain in the same range during time. Therefore, in case of using these probes in a real DS, it is appropriate to perform regular reference measurements and compare it to probe readings.

In terms of probe accuracy for measuring chlorine, for the tests performed with kaolin in 8NTU turbid water, the AC4 (12467) shows smaller errors than the AC4 (12459) (Wilcoxon signed-rank test, $p<0.005$). In comparison, the relative errors were not significantly different for tests performed with tap water, 2NTU and 5NTU turbid water (Wilcoxon signed-rank test, $p>0.005$). Therefore, the accuracy of chlorine measurements is comparable for the two probes tested except in higher turbid water. For the tests with iron powder, the chlorine readings are not significantly different in 5 NTU and 8 NTU turbid water (Wilcoxon signed-rank test, $p>0.005$), while for the test with 2 NTU turbid water, the AC4 (12467) shows lower errors than the AC4 (12459) (Wilcoxon signed-rank test, $p<0.005$).

To compare the errors between the tests, Tukey's comparison method can be applied. Accordingly, the results show following order for the tests with kaolin: 8NTU, 5NTU > 2NTU > tap water; which means as the turbidity increases, the errors in chlorine measurements escalates respectively. For the test set with iron powder, the same trend is observed with measurement errors sorting as following: 8NTU, 5NTU > 2NTU, tap water. In another view, a higher turbidity would result in a bigger dissipation of free chlorine (Figure 4.14 shows the same trend for our experiments); and this can be used to evaluate the probes. In another word, the combination of AC4 and OT3 probes is a tool to investigate the performance of the probes.

The comparison of errors between tests with iron powder and kaolin show that errors of chlorine readings for tests with iron powder are significantly higher than tests with kaolin for experiments completed at 2NTU and 8NTU turbid water (Wilcoxon–Mann–Whitney test, $p<0.005$). These differences are however not observed at 5NTU nor in tap water. These differences can be explained by the heterogeneity of the iron powder as compared to the standard kaolin powder, making it difficult to get comparable conditions of particle sizes and distribution for the four tests with iron powder.

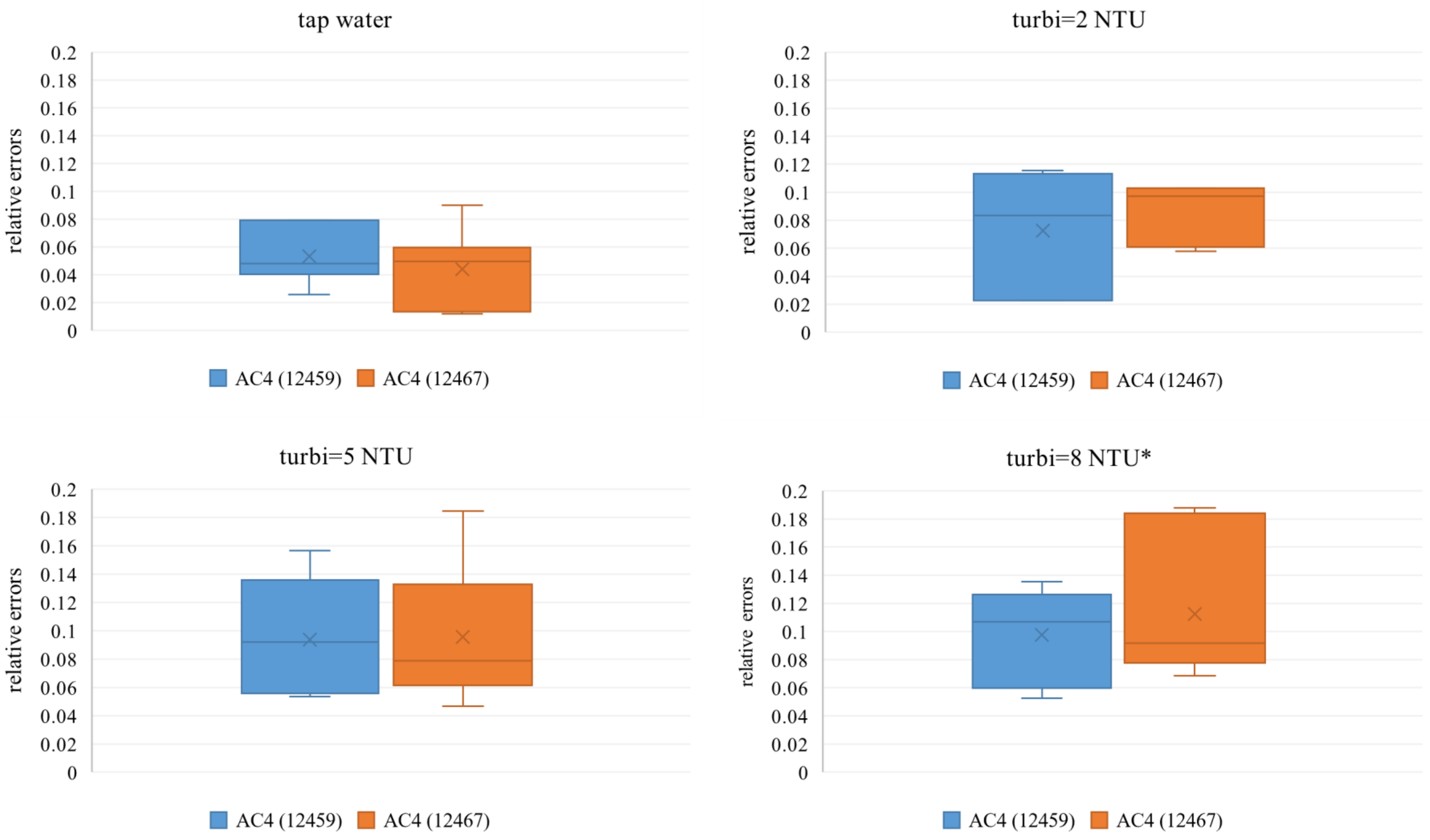

Figure 4.12 Comparison of relative errors for chlorine measurements in different levels of turbidity (turbidity source: kaolin, pH=8, temperature: 21±1^{0}C, free chlorine=1 ppm, n=600) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

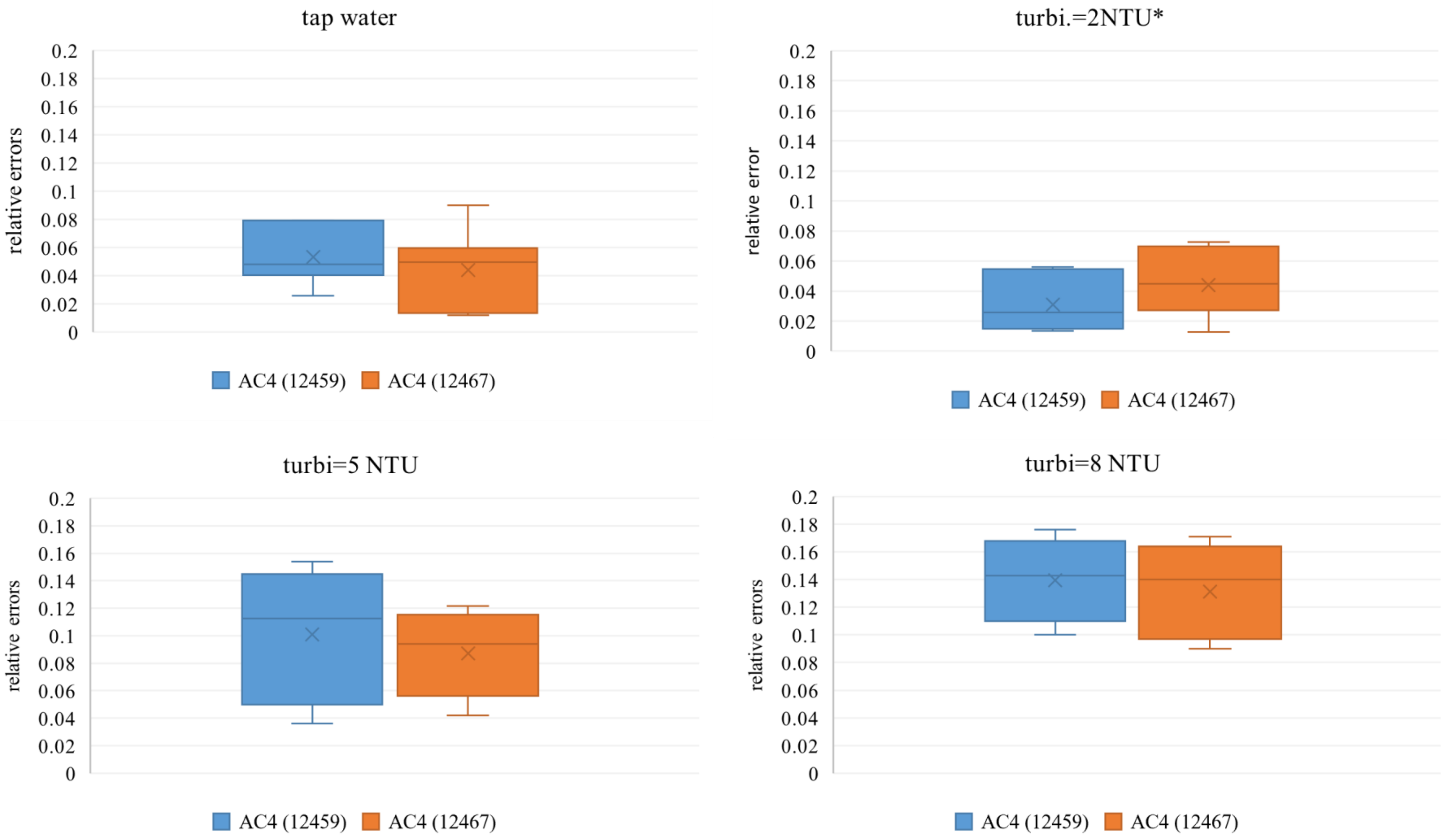

Figure 4.13 Comparison of relative errors for chlorine measurements in different levels of turbidity (turbidity source: iron powder, pH=8, temperature: 21±1^{0}C, free chlorine=1 ppm, n=600) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

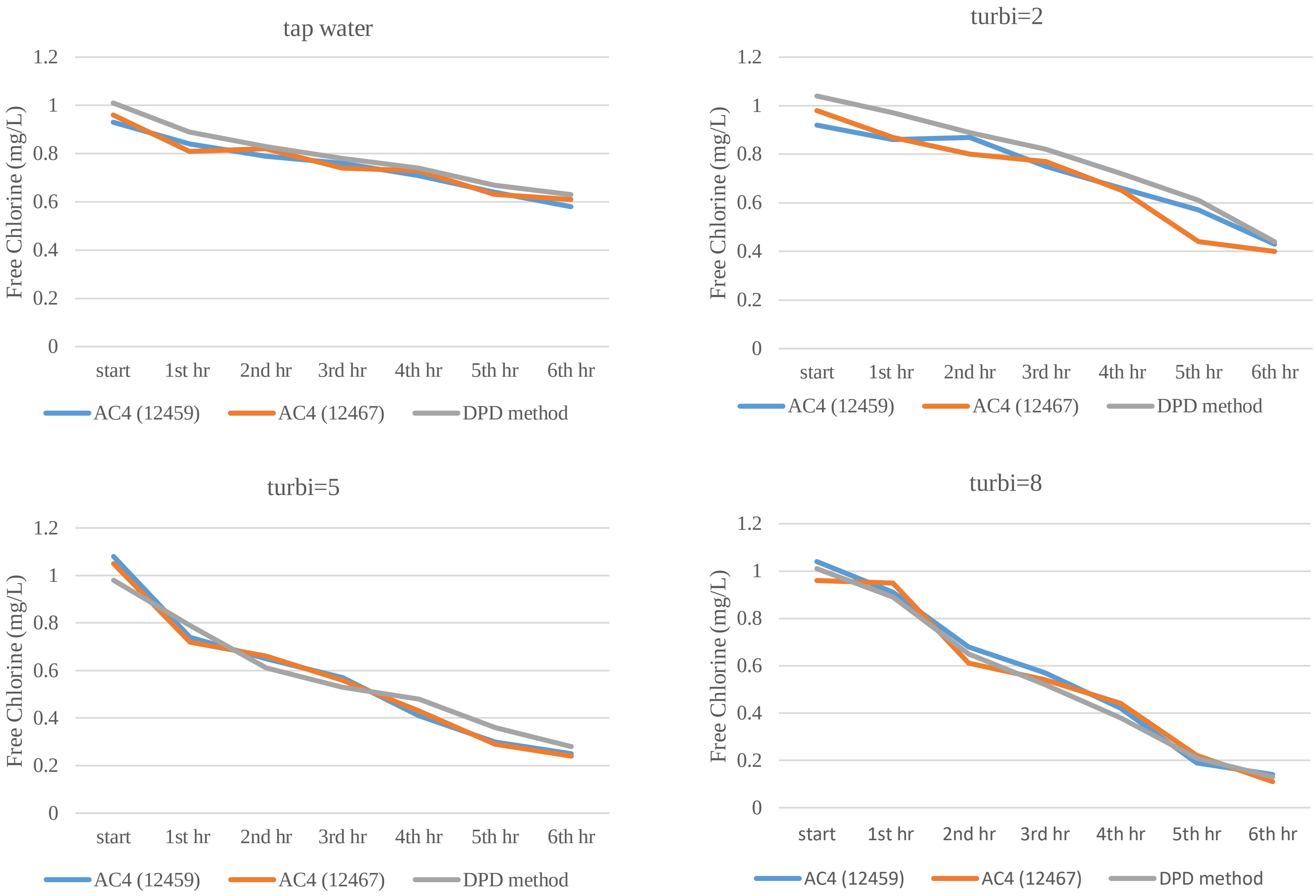

Figure 4.14 Chlorine decay over time for tap water at different levels of turbidity (turbidity source: kaolin, pH=8, temperature: 21±1^{0}C, free chlorine=1 ppm)

As mentioned before, for tests with kaolin, the test at 8 NTU was the only case in which the performance of the two probes was significantly different. Figure 4.15 and Figure 4.16 present the linear regressions for the measurements of the two KAPTA probes. Accordingly, the calculated bias for the two case equals 0.009 and 0.0156 for AC4 (12459) and AC4 (12467) respectively, meaning that the former is slightly less biased.

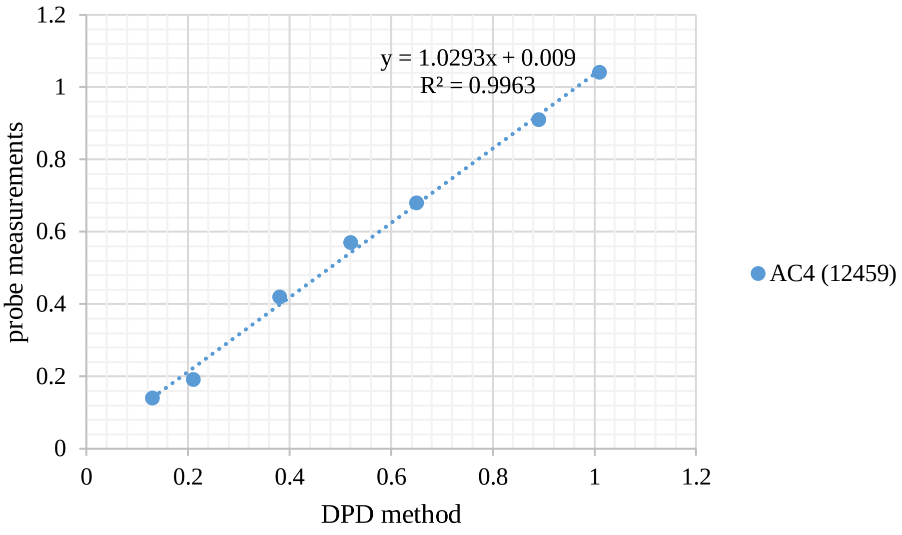

Figure 4.15 Linear regression for chlorine measurements by AC4 (12459)

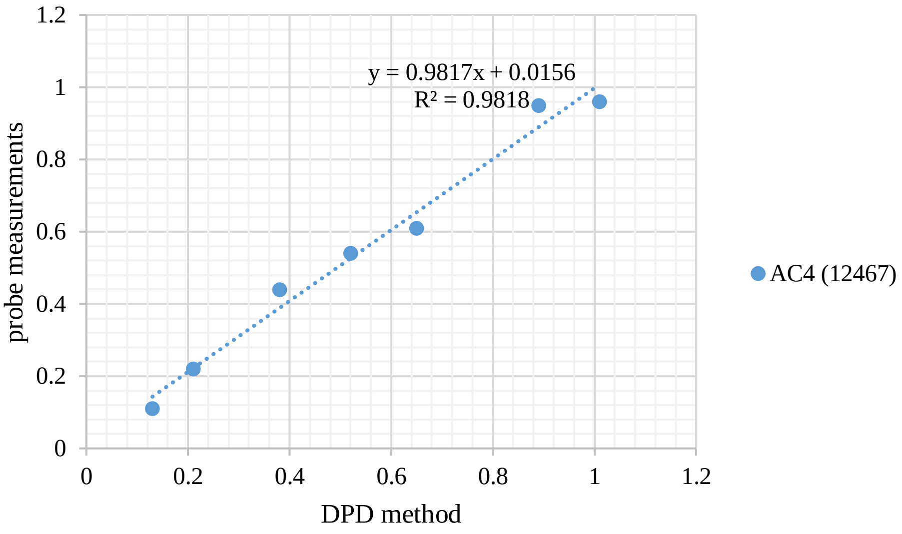

Figure 4.16 Linear regression for chlorine measurements by AC4 (12467)

4.3.4 The effect of temperature on probe readings for chlorine measurements by KAPTA^{TM} 3000 AC4 probes

To investigate the effect of water temperature on chlorine reading, all tests have been repeated in two temperatures of 8±1^{0}C and 21±1^{0}C. Table 4.4 presents the results of a test conducted with cold water. As it shows, the temperature increases during the period of water circulation in the pipeline (up to 6^{0}C).

Table 4.4 Summary of the results during a test with cold water (turbidity=5 NTU)

Condition: **Injected chlorine: 1 ppm** **PH=8** **V=0.27 m/s** **T=8±10C** **Turbidity=5 NTU (Kaolin)**		**start**	**1st hr**	**2nd hr**	**3rd hr**	**4th hr**	**5th hr**	**6th hr**
Free chlorine (mg/L)	AC4 (12459)	1.09	1.04	0.96	0.90	0.88	0.84	0.82
	AC4 (12476)	1.05	1.02	0.93	0.85	0.80	0.78	0.75
	DPD method	0.95	0.92	0.90	0.82	0.79	0.78	0.73
Temperature (^{0}C)	OT3 (12729)	7.5	10.3	11.3	11.8	12.1	13.3	12.9
	OT3 (12747)	7.2	9.9	11.0	11.4	11.6	12.4	13.0
	AC4 (12459)	6.8	9.0	10.0	11.1	11.8	12.4	12.8
	AC4 (12476)	6.9	9.1	10.5	11.3	12.0	12.6	13.0
	gauge	6.2	8.7	9.3	10.9	11.5	12.1	12.6
Conductivity (µS)	AC4 (12459)	285	281	279	279	279	279	278
	AC4 (12476)	286	233	235	233	234	233	235
	conductivity meter	270	271	269	268	270	273	277
Turbidity (NTU)	OT3 (12729)	5.4	5.4	5.1	5.0	4.9	4.8	4.8
	OT3 (12747)	5.3	5.2	5.0	4.9	4.9	4.7	4.6
	lab. measurement	4.9	5.0	4.8	4.9	4.7	4.5	4.4
UV254 (cm^{-1})	OT3 (12729)	0.120	0.117	0.119	0.118	0.121	0.121	0.123
	OT3 (12747)	0.111	0.106	0.105	0.105	0.105	0.104	0.099
	lab. measurement	0.085	0.087	0.088	0.085	0.088	0.092	0.089

Figure 4.17 presents free chlorine decay measured in cold and warm water for the test completed at turbidity of 8NTU. In both cases, initial residual chlorine is 1 mg/L. As expected, the chlorine decay is higher in warm water (chlorine residual is around 0,1 mg/L by the end of the experiment) as compared to cold water (chlorine residual is around 0,5 mg/L by the end of the experiment).

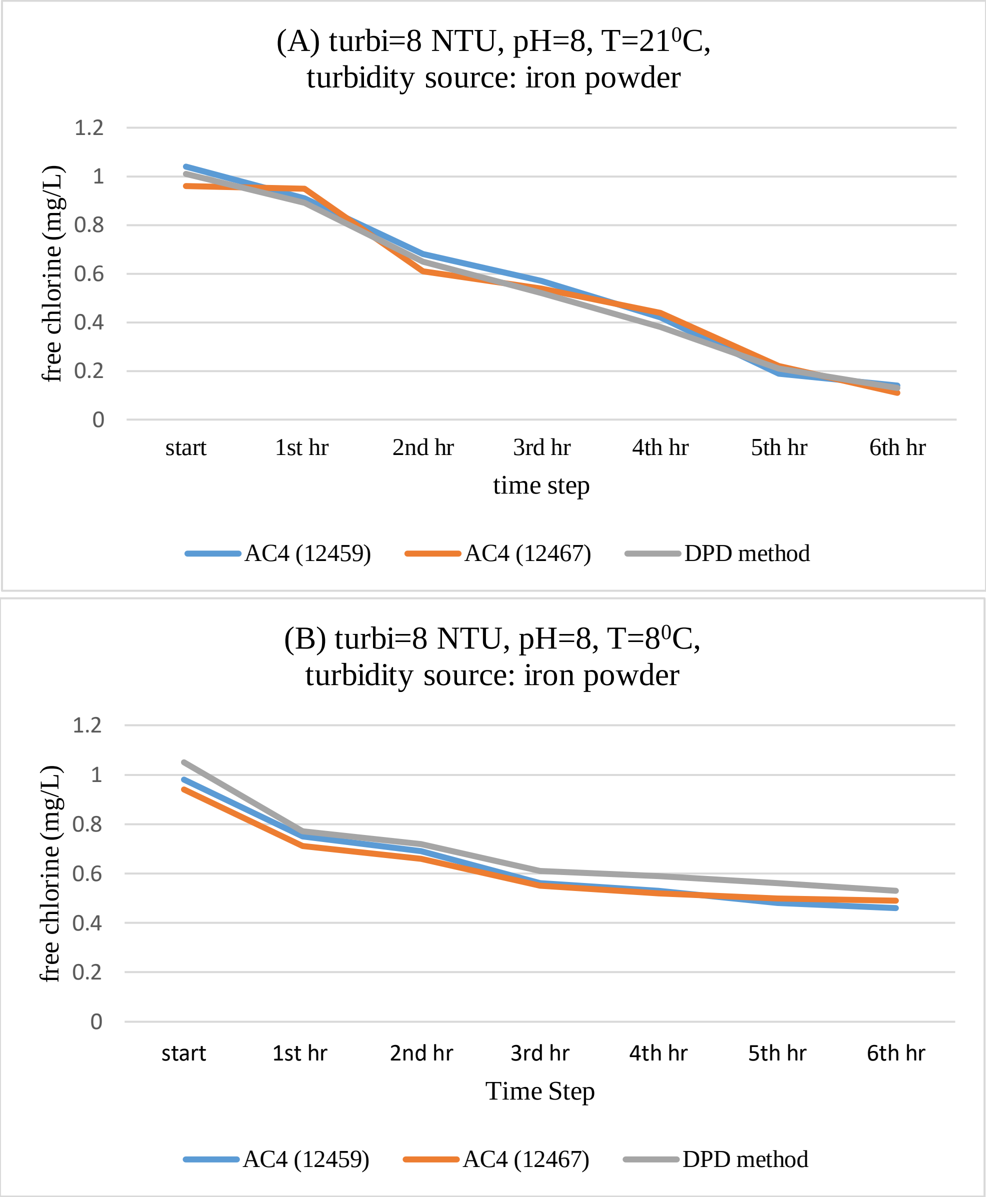

Figure 4.17 Chlorine decay measured over time by the reference DPD method and the two KAPTA AC4 probes in (A) warm water, and (B) cold water

Figure 4.18 compares the relative errors for chlorine measurements calculated for each KAPTA AC4 on both cold and warm water for a turbidity level of 8NTU. According to this figure, the average of relative errors is around 10 percent for the two tests which is more than claimed accuracy by the manufacturer (as explained in section 4.3.3), but it suggests that the performance of the probes did not change with temperature.

A rank-sum test is used to compare the errors between the two experiments with warm and cold water. Accordingly, the chlorine readings of AC4 (12467) show greater errors in warm water than cold water (Wilcoxon–Mann–Whitney test, $p<0.005$); however, the same test show non-significant difference between cold and warm water for AC4 (12459). In addition, AC4 (12467) shows greater errors than AC4 (12459) for test with warm water (Wilcoxon signed-rank test, $p<0.005$). While the same test for the cold water shows that the errors are not significantly different for the two probes ($p>0.005$). As a conclusion, in these tests, one of the AC4 probes show slightly lower accuracy in chlorine measurement in warm water (as compared to cold water).

Turbidity is another main factor that affects the trend of chlorine decay; however, to exclude it the graphs represent the tests for the same turbidity (worst case; 8NTU). On the other hand, the source of turbidity (i.e., kaolin or iron particles) could affect this. The fact that chlorine decay shows a drastic depletion in the span of 6 hours for the test with warm water could be explained by high chlorine demand of kaolin particles as the turbidity source.

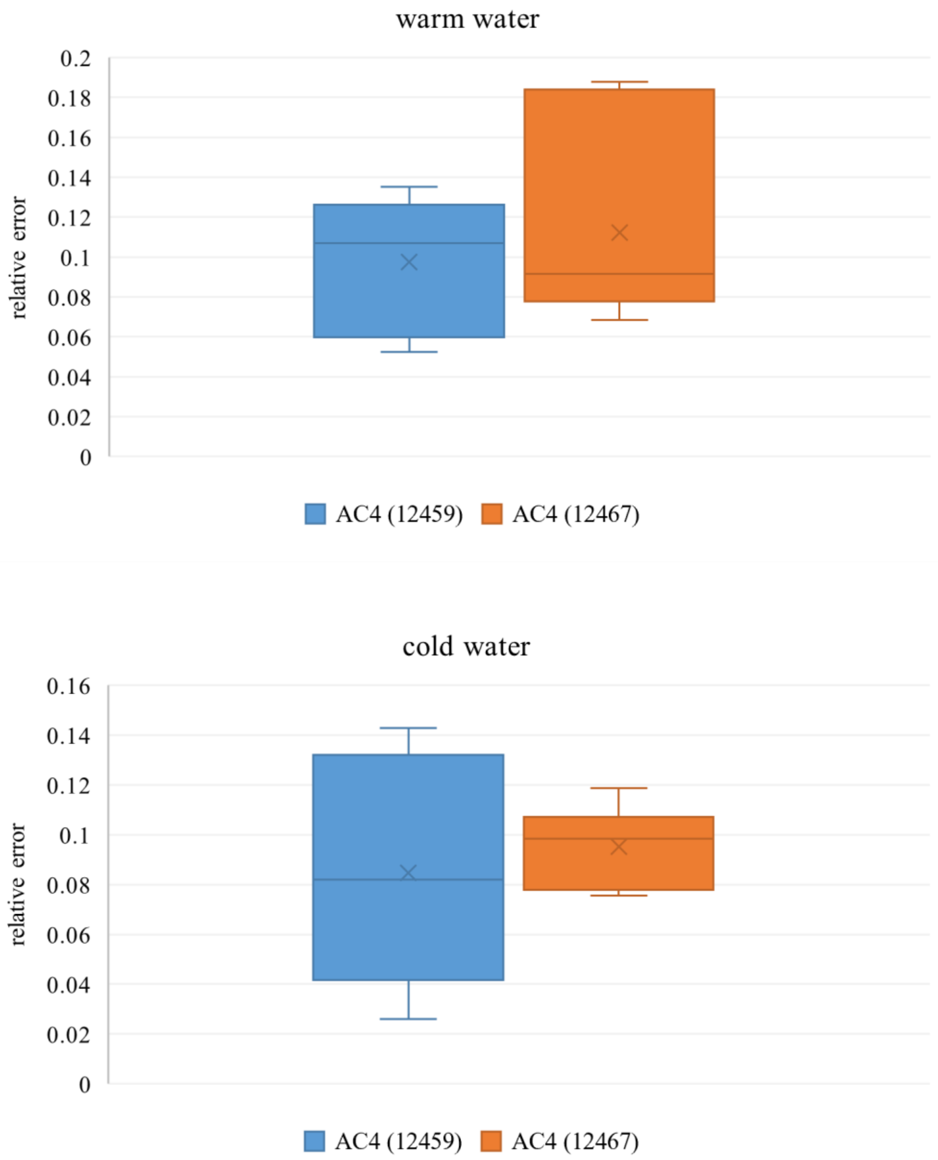

Figure 4.18 The comparison of relative errors of chlorine measurements for tests with warm and cold water (Turbidity=8NTU (kaolin), pH=8, free chlorine=1 ppm, V=0.27 m/s, n=600) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

4.3.5 The effect of velocity on the accuracy of chlorine and turbidity measurements

In order to investigate the performance of KAPTA monitoring probes in different hydraulic conditions, we performed a set of experiments in two velocities of 0.11 m/s and 0.36 m/s. In a real DS, the hydraulic parameters are subject to continuous fluctuations and so it would be critical for utilities to be ensured about the accuracy of the quality parameters monitored using on-line instrumentation in different hydraulic conditions. We compared the results of the tests in the two mentioned conditions to evaluate the accuracy of the probes in recording chlorine and turbidity for KAPTA^{TM} 3000 AC4 and OT3, respectively.

Figure 4.19 shows the comparison of relative errors for chlorine measurements with KAPTA 3000 AC4 probes for tests in 8NTU turbid water for two velocities of 0.11 and 0.36 m/s. The average of relative errors is around 0.1 to 0.12 for the two probes, which is quite the same as tests with velocity of 0.27 m/s.

We performed a rank-sum test to compare the errors of each probe between the two tests. Accordingly, the test results show that the errors are not significantly different for both AC4 (12459) and AC4 (12467) (Wilcoxon–Mann–Whitney test, $p>0.005$) implying that the changes in velocity does not affect the accuracy of AC4 probes in recording chlorine. However, it should be noted that in a real DS, there might be sudden changes in hydraulic conditions, which make the situation quite different from what we experienced with our steady condition.

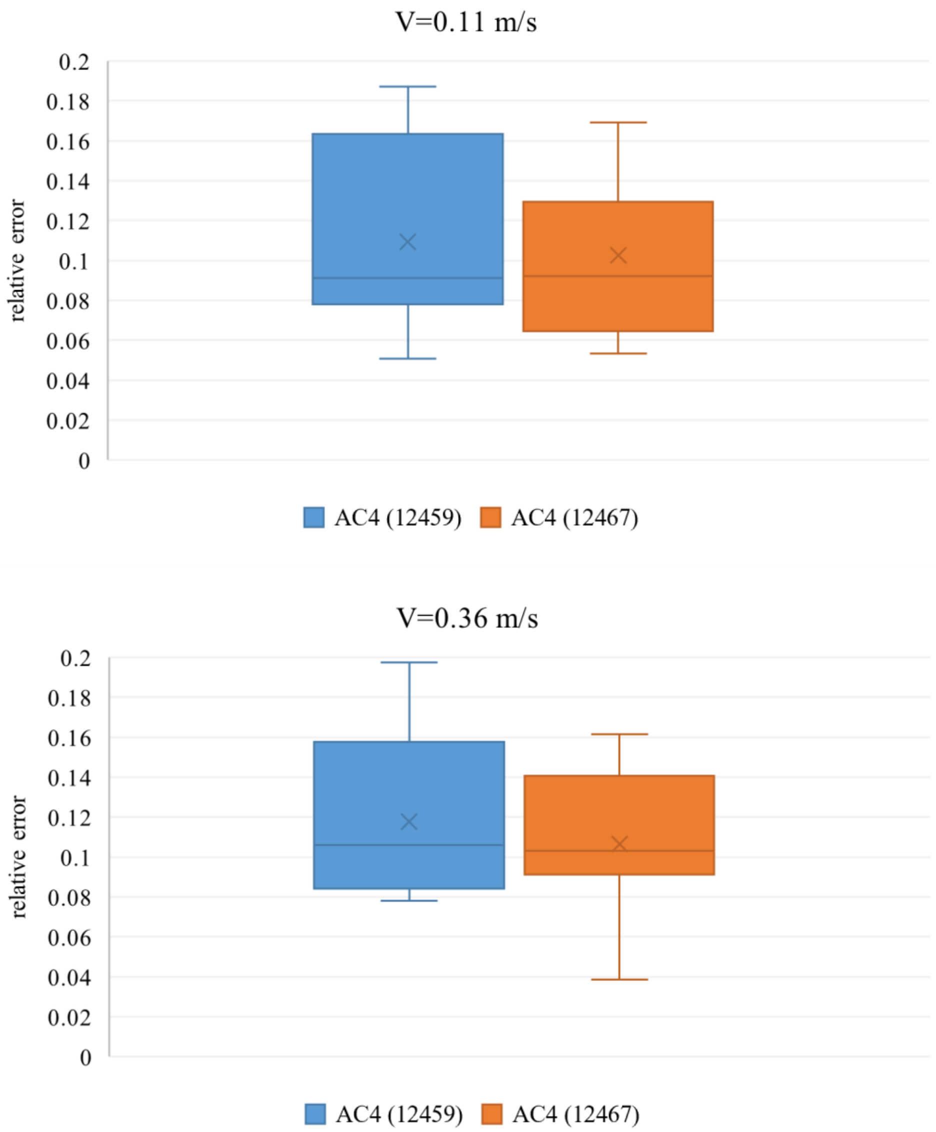

Figure 4.19 The comparison of relative errors for chlorine measurements by KAPTA^{TM} 3000 AC4 probes in different velocities (Turbidity=8NTU (kaolin), PH=8, free chlorine=1 ppm, n=600) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

Velocity also affects turbidity readings by KAPTA^{TM} 3000 OT3 probe. This could be due to changes in flow regime and the probability of bubble creation inside the pipeline, which directly influences the performance of OT3 probe as it uses optical sensors to measure turbidity. According to Bernoulli equation, velocity and pressure are inversely related meaning that in higher velocities the DS might experience a low-pressure event, which is more critical to be monitored as the chance of contaminant intrusion increases in this situation. The tested velocity of 0.36 m/s allowed us to evaluate the performance of OT3 probes at lower pressures.

Figure 4.20 presents the absolute errors for turbidity measurements with KAPTA^{TM} 3000 OT3 probes for velocities of 0.11 m/sand 0.36 m/s. The average of absolute errors ranges between 0.3 to 0.4 NTU and the maximum measured error equals to 0.9 NTU. The rank-sum test for comparing the results show that the errors between the tests for both OT3 (12729) and OT3 (12747) are not significantly different (Wilcoxon–Mann–Whitney test, $p>0.005$) meaning that changes in velocity does not affect the average accuracy of turbidity measurements.

On the other hand, Figure 4.21 present the moving averages for OT3 (12729) and OT3 (12747) probes. Accordingly, the fluctuations for 1-minute intervals is higher for velocity of 0.36 m/s. This could be due to lower pressure at this velocity level (15 psi for test at 0.36 m/s velocity), which probably occurs due to creation of micro bubbles inside the pipeline. Therefore, it would be more appropriate for utilities to use higher intervals (>5 minutes) for averaging turbidity readings. This way, the likelihood of taking an unnecessary preventive/corrective action during a low-pressure event decreases. However, it is noteworthy that in real condition where we install the probes on a real DS, the sudden changes in velocity (and pressure correspondingly), might affect the accuracy and stability of turbidity readings more than what we observed in our steady state experiment (having the same velocity, pressure and temperature at any single point of the system).

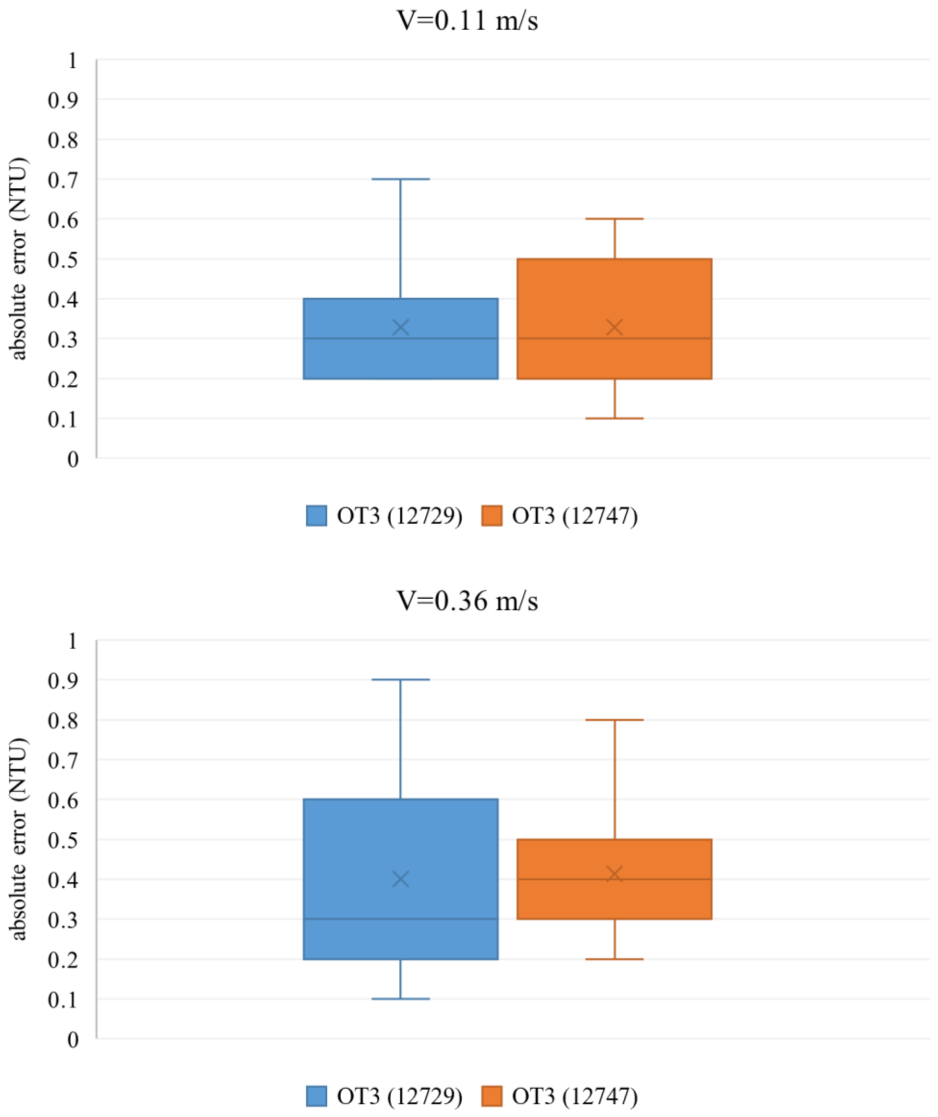

Figure 4.20 The comparison of absolute errors for turbidity measurements by KAPTA^{TM} 3000 OT3 probes in different velocities (Turbidity=8NTU (kaolin), PH=8, free chlorine=1 ppm, n=600) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

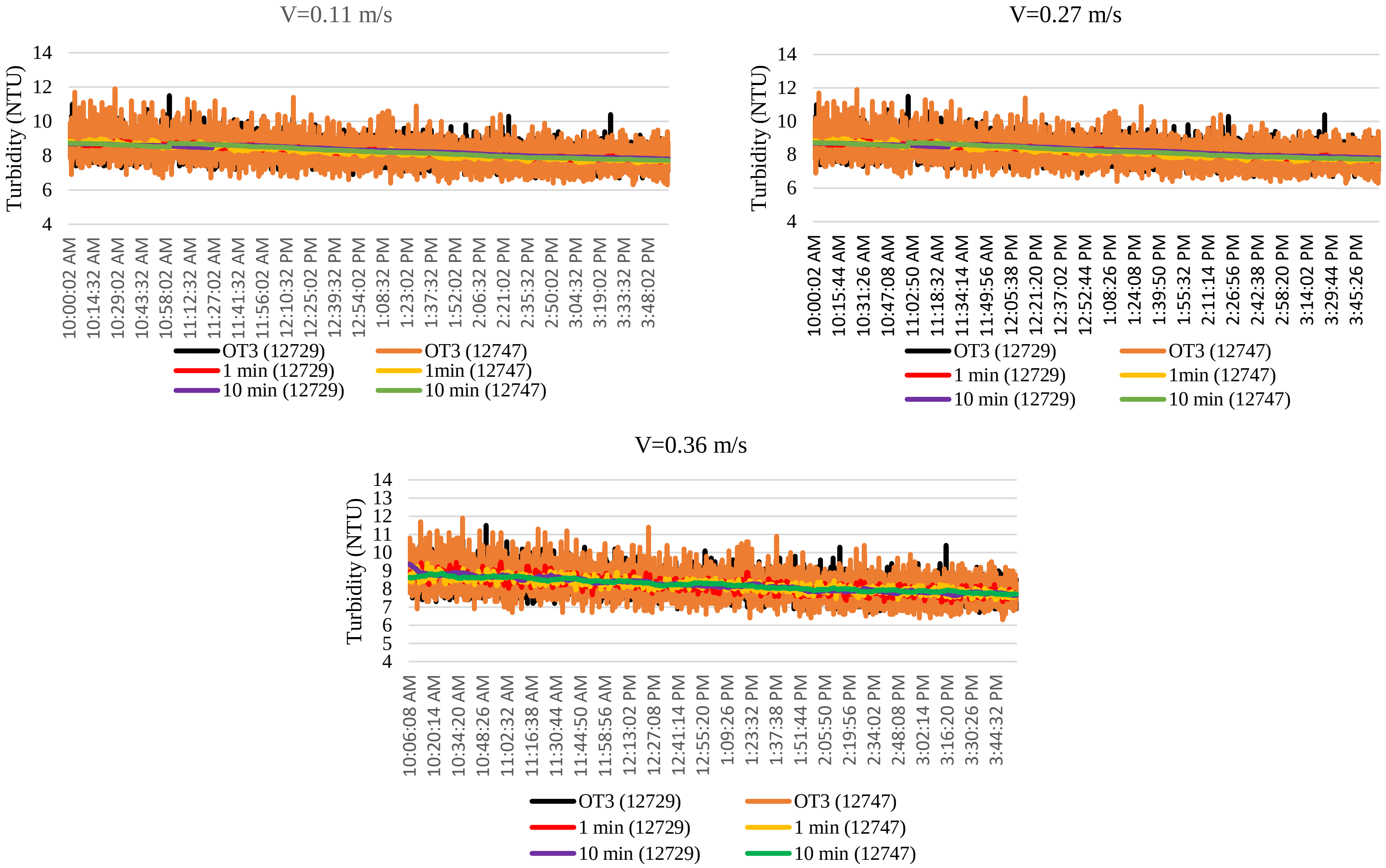

Figure 4.21 Time series and moving averages for turbidity measurements at 0.11 m/s, 0.27 m/s and 0.36 m/s velocities (Turbidity=8NTU (kaolin); PH=8; temperature: 21±1^{0}C; free chlorine=1 ppm)

4.3.6 UV readings by KAPTA^{TM} 3000 OT3 probes

In order to validate the accuracy of KAPTA^{TM} 3000 OT3 probes for measuring organic matter, we compared the OT3 readings with reference UV254 measurements using HACK DR 5000 (two measurements per half an hour). Figure 4.22 shows the absolute errors in UV measurement calculated for each experiment completed with tap water, 2NTU, 5NTU, and 8NTU turbid water respectively. The average of absolute errors ranges from 0.014 to 0.022 cm^{-1} for OT3 (12747) and OT3 (12729) probes respectively, which is slightly higher as compared to the measurement accuracy indicated by the manufacturer. The comparison between the probes show that OT3 (12729) turns larger errors than OT3 (12747) for tests performed in 5NTU and 8NTU turbid water (Wilcoxon signed-rank test, $p<0.005$), while the same test shows that the errors of the two probes are not significantly different ($p>0.005$) for tests with tap water and 2NTU turbid water.

Figure 4.22 Absolute errors for UV measurements (Turbidity source: kaolin, PH=8, temperature: 21±1 C, free chlorine=1ppm, n=450) (The whiskers correspond to the minimum and maximum values, the box represents the 10th and 90th percentile, the middle line and the cross correspond to the median and the mean respectively.)

Table 4.5 and Table 4.6 summarize the comparison of the results obtained with the four tested probes for different experiment conditions. To compare the results between the experiments an average of the errors between the two probes has been used. Accordingly, OT3 (12729) tends to be more accurate than OT3 (12747) in measuring turbidity and UV. In addition, AC4 probes show almost the same accuracy for chlorine readings.

Table 4.5 Comparison of the accuracy of measurements between the probes for each parameter

parameter	condition	OT3	AC4	Average of abs./rel. error values
Turbidity (kaolin)	Tap water	12729 > 12747		0.27 vs. 0.16
	2 NTU	12729 > 12747		0.43 vs. 0.26
	5 NTU	Non-significant		0.27 vs. 0.25
	8 NTU	Non-significant		0.29 vs. 0.28
Turbidity (iron powder)	Tap water	Non-significant		0.37 vs. 0.34
	2 NTU	Non-significant		0.26 vs. 0.23
	5 NTU	Non-significant		0.29 vs. 0.27
	8 NTU	12729 > 12747		0.44 vs. 0.29
Chlorine (kaolin)	Tap water		Non-significant	5.1% vs. 4.7%
	2 NTU		Non-significant	8.0% vs. 8.6%
	5 NTU		Non-significant	8.5% vs. 8.6%
	8 NTU		12467 > 12459	9.4% vs. 12.0%
Chlorine (iron powder)	Tap water		Non-significant	5.0% vs. 4.5%
	2 NTU		12467 > 12459	4.6% vs. 6.7%
	5 NTU		Non-significant	11.0% vs. 10.2%
	8 NTU		Non-significant	13.2% vs. 13.6%
UV	Tap water	12729 > 12747		0.013 vs. 0.006
	2 NTU	Non-significant		0.015 vs. 0.011
	5 NTU	Non-significant		0.021 vs. 0.019
	8 NTU	12729 > 12747		0.027 vs. 0.020

Table 4.6 Comparison of the accuracy of measurements between the experiments for each parameter

Parameter	**OT3**	**AC4**
Turbidity (kaolin)	8 NTU > 5 NTU > 2 NTU > tap water	
Turbidity (iron powder)	2 NTU > 8 NTU > 5 NTU > tap water	
Chlorine (kaolin)		8 NTU > 5 NTU > 2 NTU > tap water
Chlorine (iron powder)		8 NTU > 5 NTU > 2 NTU, tap water
UV	8 NTU > 5 NTU > 2 NTU > tap water	

4.4 Field tests using KAPTA^{TM} 3000 AC4 and OT3 probes

This section presents the results from the full-scale experiment completed at the chlorination station of Duranleau, Laval (QC). In normal condition, the average of quality parameters is as following: pH=7.2, free chlorine=0.62 ppm, conductivity=126 cm^{-1}, temperature=12.2 C. The probes were installed for one and a half months and then the results were compared with the quality parameters recorded at the station by standard utility instrumentation. The objective was to investigate the accuracy and stability of the probes to monitor water quality over time. Moreover, the performance of the probes during a red water event that occurred during the field experiment are presented. Such results are important to evaluate the reliability of the probes during transient events typical in the DS as such probes may be used as part of a warning system for the DS.

4.4.1 Chlorine measurements using KAPTA^{TM} 3000 AC4 probes

As mentioned in the Material and Methods section, the two KAPTA^{TM} 3000 AC4 probes were installed on a 2-in. pipe to capture chlorine fluctuations during the period of the experiment. The results were compared with the recordings of the instrument already deployed at the station (Swaan Analytical, AMI Trides). Figure 4.23 shows the time series of measurements for the two probes along with the recordings by reference instrument. Results show that the probes readings overestimate the reference utility instrumentation readings almost over the entire field installation experiment (between 0.02 to 0.12 ppm).

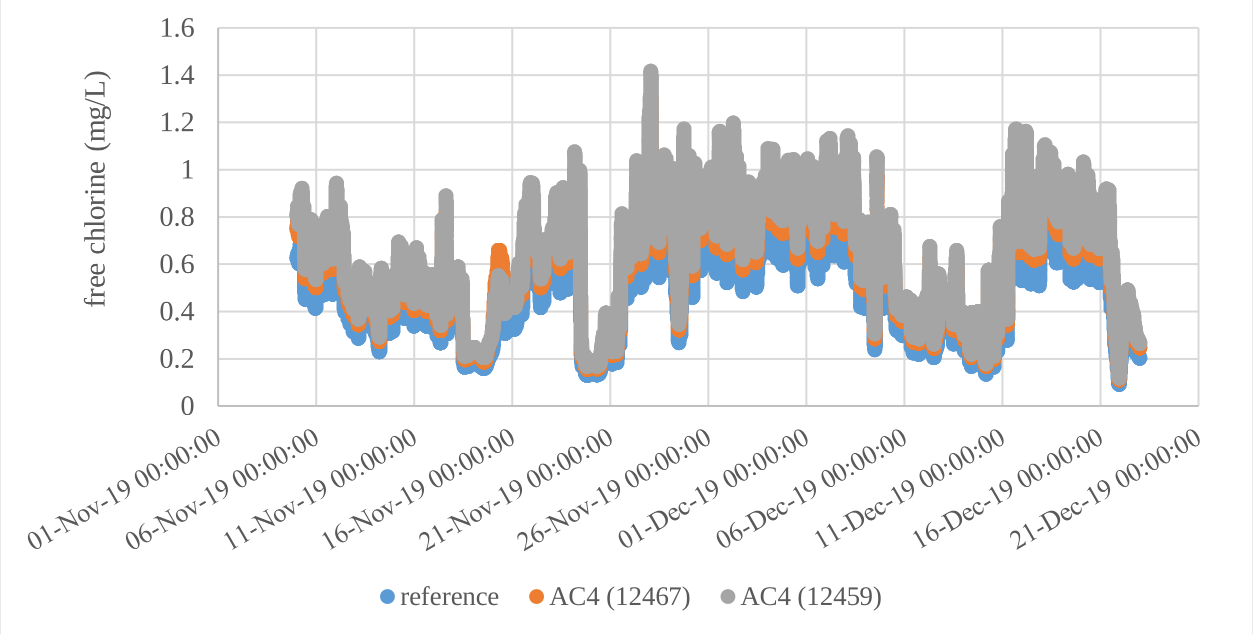

Figure 4.23 Time series for chlorine measurements during the period of experiment

Figure 4.25 presents the relative errors for each probe showing that the average of relative errors varies between 7% to 11%. This is bigger than the 5% accuracy claimed by Veolia; however, the trend of measurements shown in Figure 4.23 are comparable to reference measurements suggesting that a calibration could compensate the differences observed for the KAPTA^{TM} 3000 AC4 chlorine measurements as compared to the reference measurements. The deviation of the KAPTA probe measurements from the reference measurements could be due to many factors including: (1) the transformation of the probes “active chlorine” signal into an equivalent free chlorine concentration (Julien, 2016), (2) the different impacts of water quality on the probe measurements and the other online instruments to which they are compared, and (3) the differences between time intervals of reference measurements and probe readings (1 minute vs. 6 seconds respectively). It could also bedue to the variability of the reference measurements that we could not quantify, although the partner utility does regular maintenance and QA/QC on their instruments. The comparison of the errors for the probe readings shows that AC4 (12459) readings turns greater errors than AC4 (12467) (Wilcoxon signed-rank test, p<0.005).

Figure 4.24 presents the 1hour moving averages of the probe readings vs. the reference measurements. As the linear regression shows, the bias values for AC4 (12459) and AC4 (12467) are 0.092 and 0.035 respectively which is in accordance to their overall accuracy during the experiment.

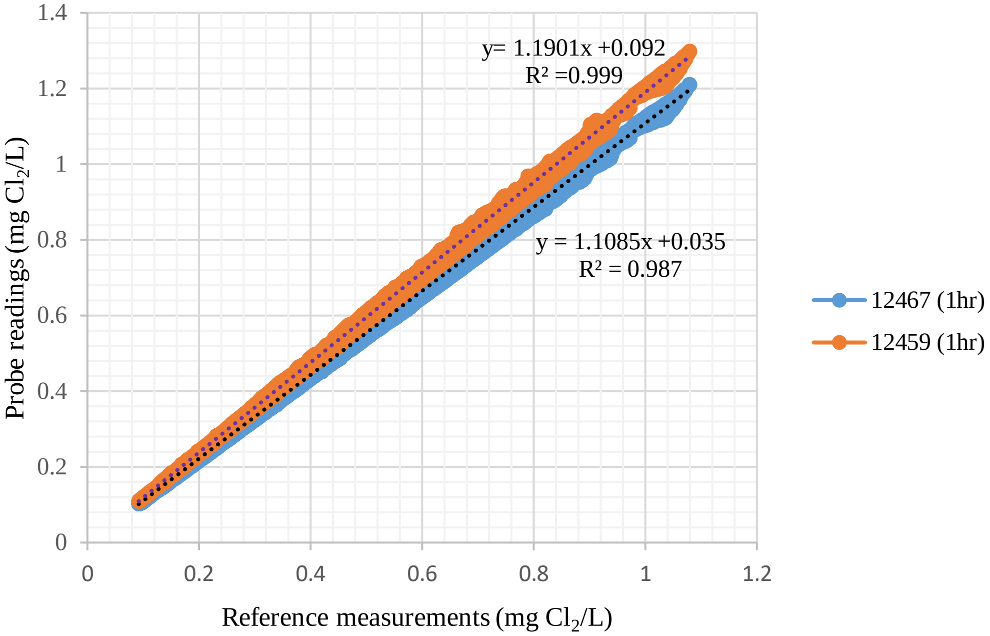

Figure 4.24 Probe readings for free chlorine versus reference measurements (1 hr moving averages)

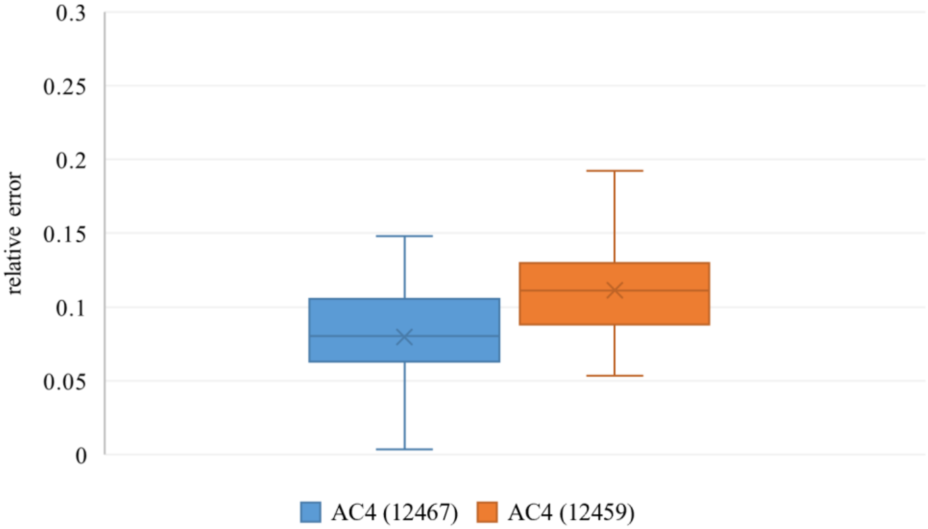

Figure 4.25 Relative errors for chlorine measurements (The whiskers show the location of minimum and maximum, bars represent 10% to 90% of data, the middle line and the cross correspond to the median and the mean respectively)

4.4.2 Turbidity measurements using KAPTA^{TM} 3000 OT3

As presented by the manufacturer in the probe specifications, KAPTA^{TM} 3000 OT3 probes use Nephelometry measurement at 525 nm to record turbidity using a LED lightening. Figure 4.26 shows the time series for the two probes comparing them with the reference measurements. According to the figure, the trend of measurements reveals a gradual increase in differences with reference measurements. It starts at 0.2 and 0.4 NTU and ends to 0.6 and 0.7 NTU for OT3 (12747) and OT3 (12729) respectively. According to the manufacturer, the OT3 should be cleaned when the fouling index reaches 80%. In this case, the fouling index by the end of the experiment for the OT3 (12729) was 68% (during the red water event). Accordingly, there was no clue that the probe was providing deviating values. Therefore, it may be worthwhile considering a probe calibration/maintenance when an increasing turbidity trend is observed in the recorded data over a minimum period of time.

Figure 4.27 presents the 1 hour moving averages for probe readings vs. reference measurements for turbidity during normal condition. Accordingly, the bias for OT3 (12729) and OT3 (12747) equals 0.974 and 0.754, respectively meaning that turbidity reading by OT3 (12729) are more biased.

Figure 4.28 presents the absolute errors over the entire period of the experiment. It shows that the average of differentials is about 0.4 to 0.6 NTU, which is around the 0.3 NTU accuracy claimed by Veolia.

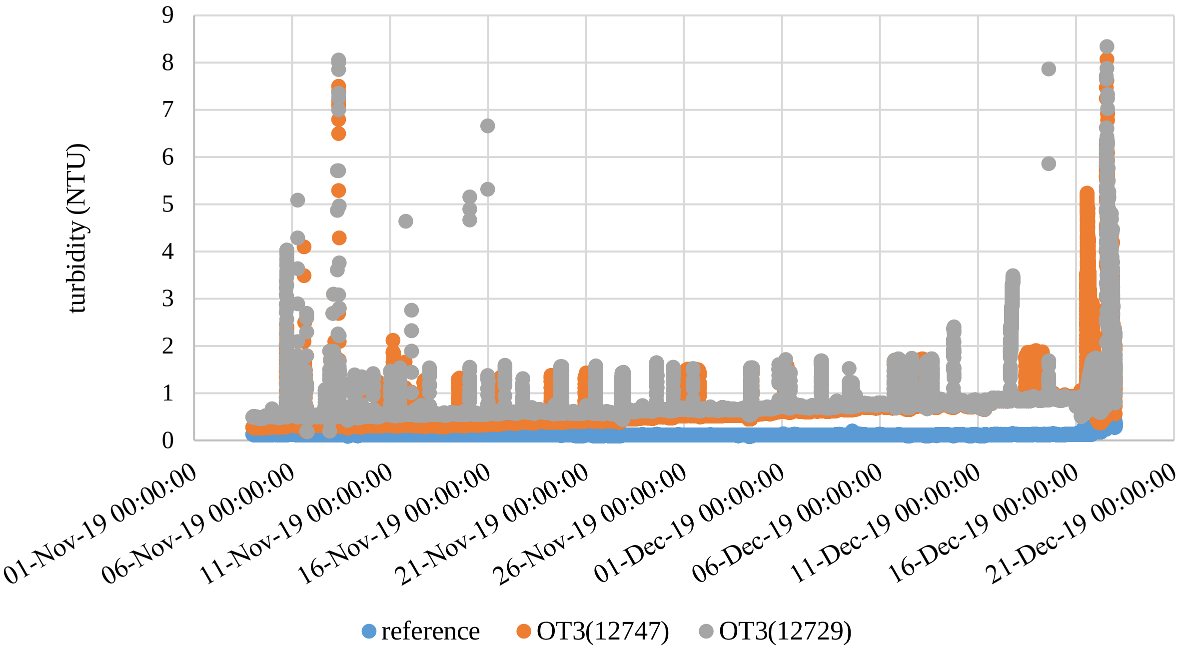

Figure 4.26 Time series for turbidity measurements and the comparison of probe readings with reference measurements (field experiment)

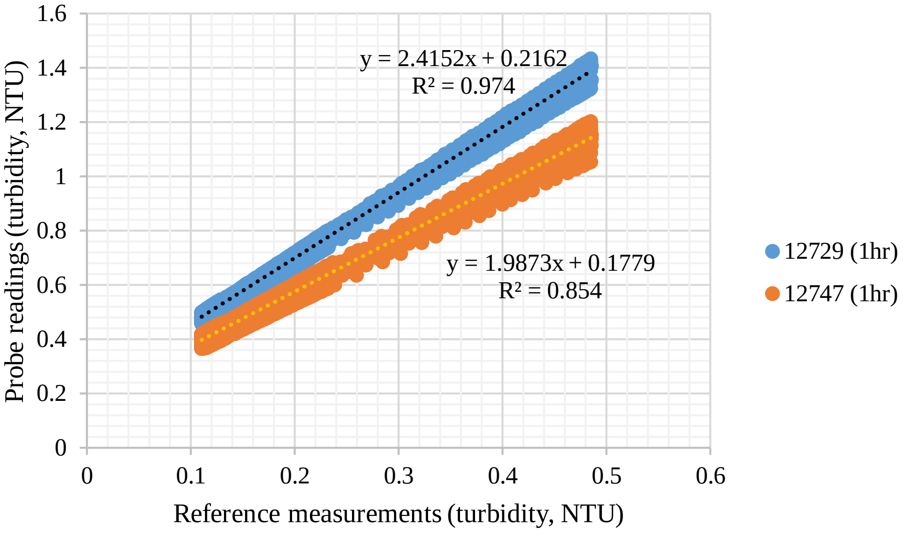

Figure 4.27 Probe readings for turbidity versus reference measurements (1 hr moving averages)

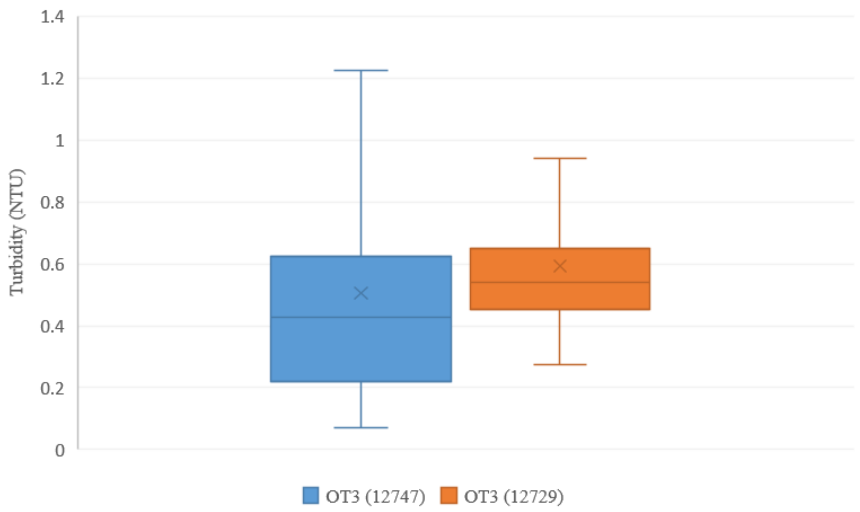

Figure 4.28 Differentials for turbidity readings by KAPTA^{TM} 3000 OT3 probes

4.4.3 KAPTA^{TM} 3000 AC4 and OT3 probes readings during a red water event

Investigating the performance of the probes during a transient event was one of the objectives for conducting the tests in the field experiment. We succeeded to capture an event on December 17, 2019. We also deployed an auto-sampler and programmed it for sampling whenever the turbidity increases over 0.5NTU. The samples collected were analysed for *Enterococci* and *Legionella* using Enterolert and Legiolert tests respectively. Samples were also analyzed for *E. coli* using the Colilert test and a coliminder apparatus. Table 4.7 summarizes the microbiological results in the samples collected during the red water transient event. All of the samples collected during the transient event were negative for the pathogens tested, except for *Enterococci*. One sample was positive for *Enterococci* (5.2 MPN/100 ml). This positive sample was detected in a 1L concentrated volume, increasing the probability of detection. More importantly, this positive sample was detected after several hours of elevated turbidity, as the average turbidity from 12:45 to the time of sampling was 1.49 NTU. The detection of *Enterococci* in the distribution system is considered to be an indication of fecal concentration. Although the detection of *Enterococci* is not mandatory in the Quebec drinking water regulations (Du Québec 2019), the presence of Enterococci in a volume of 100 ml of potable water is not considered acceptable by the RQEP and Health Canada. Several causes may explain this positive sample: (1) *Enterococci* have been shown to be an indicator of intrusion of the contaminated water into the DS. However, we were not aware of any major loss of pressure in the time frame of the sampling that would be indicative of pressure deficient condition. (2)

Enterococci could result from the sloughing of biofilm or the resuspension of sediments. During the sampling period, operating pressures were lower than normal condition (5 to 10 psi). It is probable that the lower pressure was associated with higher demand and higher velocities that would increase the shear and potential for resuspension of the loose deposits. This sole detection of a positive *Enterococci* raises questions about the impact of detachment and resuspensions during periods of high turbidity. Additional investigations should be conducted to confirm our observations.

In this study, the red water event was not associated with *Legionella* occurrence although some studies suggest otherwise (e.g. Wang, et al. (2012)). Considering these microbiological results, the red water event of December 17 was not associated with a health risk associated with *E. coli* and *Legionella*.

Table 4.7 The results of tests on pathogens

#	Hour (hh:mm)	Date (AA/MM/JJ)	Turbidity NTU	Total coliforms MPN/100 ml	*E. coli* MPN/100 ml	Enterococci MPN/100 ml	*Legionella* MPN/100 ml	coliMinder mMFU/100ml
1	8:42	12/17/2019	0.23	<1	<1	<1	<1	<LOD
2	9:42	12/17/2019	0.25	<1	<1	<1	<1	<LOD
1	12:40	12/17/2019	0.76	<1	<1	<1	<1	
2	12:45	12/17/2019	1.32					
3	12:50	12/17/2019	1.55	<1	<1	<1	<1	
4	12:55	12/17/2019	1.63	<1	<1	<1	<1	<LOD
5	13:00	12/17/2019	1.59	<1	<1	1	<1	<LOD
6	13:05	12/17/2019	1.51	<1	<1	<1	<1	
7	13:10	12/17/2019	1.45					<LOD
8	13:15	12/17/2019	1.43	<1	<1	<1	<1	
9	13:20	12/17/2019	1.46	<1	<1	<1	<1	
10	13:25	12/17/2019	1.47	<1	<1	<1	<1	<LOD
11	15:20	12/17/2019	1.00	<1	<1	5.2	<1	
12	15:30	12/17/2019	1.02	<1	<1	<1	<1	
13	15:35	12/17/2019	0.96	<1	<1	1	<1	

The differences in turbidity measurements between the OT3 probes and the online field measurements under different conditions could be due to various reasons:

First it should be noted that the measurement intervals of the probe readings (6 seconds) and reference measurements (1 minute) were different. The greater noise in the reported readings could provide a more detailed picture of turbidity by KAPTA probes and therefore more fluctuations in the report (as Figure 4.26 presents).

- Under normal monitoring conditions:
    - The probe reading presented in Figure 4.26 over a month period shows a progressive drift of the OT3 probe readings. This drift could be due to the gradual fouling of the probes as we did not clean them during the experiment to test their long-term performance. However, during the normal water condition, the fouling index was greater than 80% and the manufacturer recommends long term autonomous use (1-3 years). It is possible that some constituents of the water tested caused a fouling that is not captured by the two fouling indexes provided by the manufacturer.
    - The overestimation of turbidity by the OT3 probes when first installed was quite limited (0.3 NTU) and increased to 0.8 NTU at the end. These differences are of the same order of magnitude as the differences seen in the laboratory testing.
    - The feed lines to the two online devices tested were distinct but not tapped on the same feed pipe. The OT3 was tapped on a secondary 51mm building pipe while the reference method was directly tapped on the 350 mm main pipe. It is possible that the incoming turbidity to the two devices may have been influenced by the tap position on the feed pipe and the length of the intermediate connecting piping, which was longer in the case of the OT3 probe. However, both devices ran online and water circulated through these pipes. Therefore, depending on the piping configuration, it is possible that the distribution of turbidity particles was different from one tap to the other.
- Under ‘red’ water conditions
    - The differences between the probe reading and the field reference measurements showed in Figure 4.29 increased drastically when the red event began. Two possible causes could explain this drastic difference: fouling or changes in the adsorption spectra of the particles.
    - In the case of fouling, an apparent quick but somewhat reversible fouling of the OT3 probes occurred during the red water event. According to the reference

measurements, the turbidity levels were around 0.127 NTU before the event and went up to 1.7 NTU at its peak. During pilot-scale experiments, no fouling was observed although the probes were tested using 8 NTU turbid water containing kaolin and iron powder. One explanation would be the differences of particle types in the field study experiment, which may have had a significant effect on the probe performance. Also, the probe readings do go down at the end of the red water event which suggest that fouling, if present, was at least partially reversible. Finally, during the red water event, the fouling index (62%) was lower than the recommended value (more than 80%), which fairly explains part if the differences with the reference measurements during the event.

- As for the normal conditions, the difference between the way that the two devices compared were connected may have also payed a role.

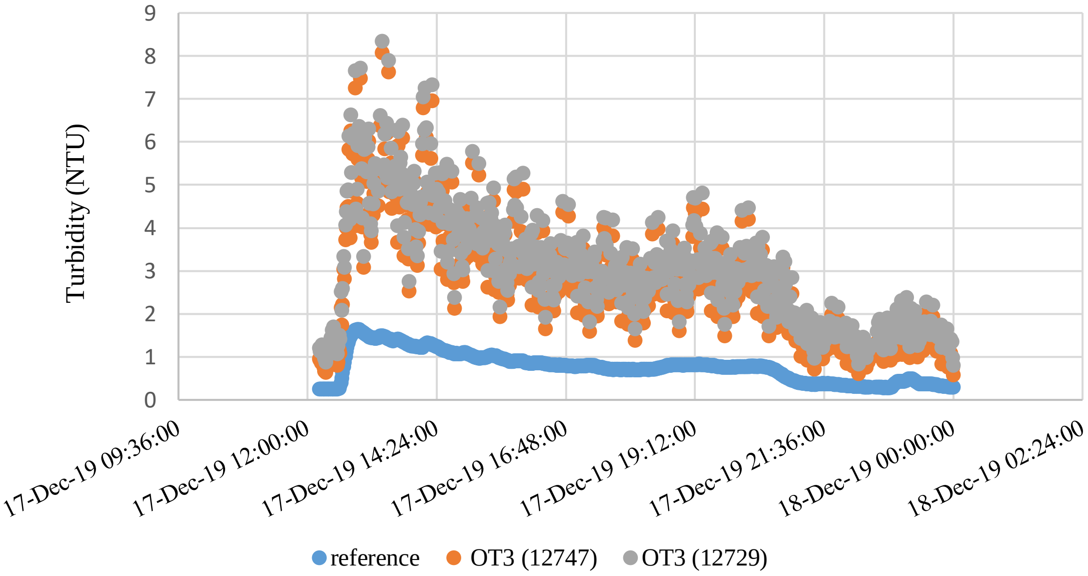

Figure 4.29 Time series for turbidity measurements during the red water event

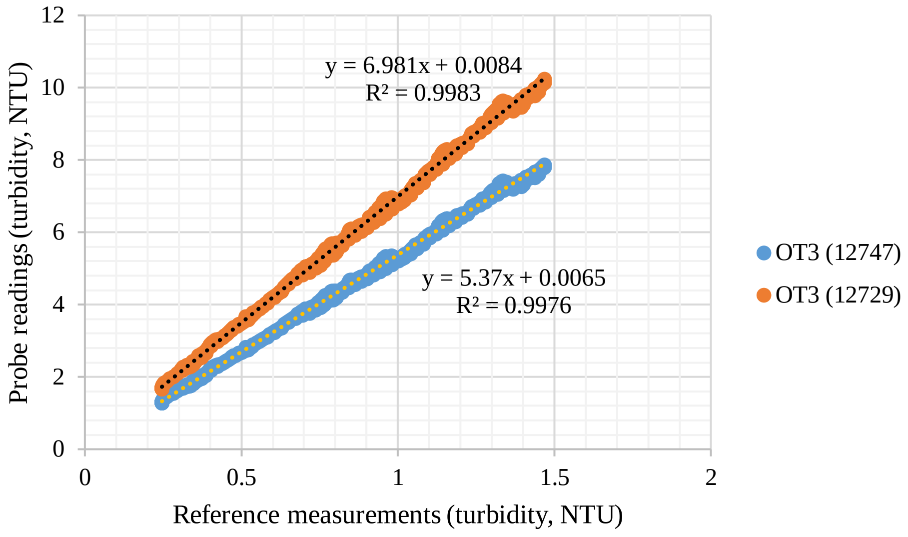

Figure 4.30 Probe readings versus reference measurements for turbidity during the red water event (10 min moving averages)

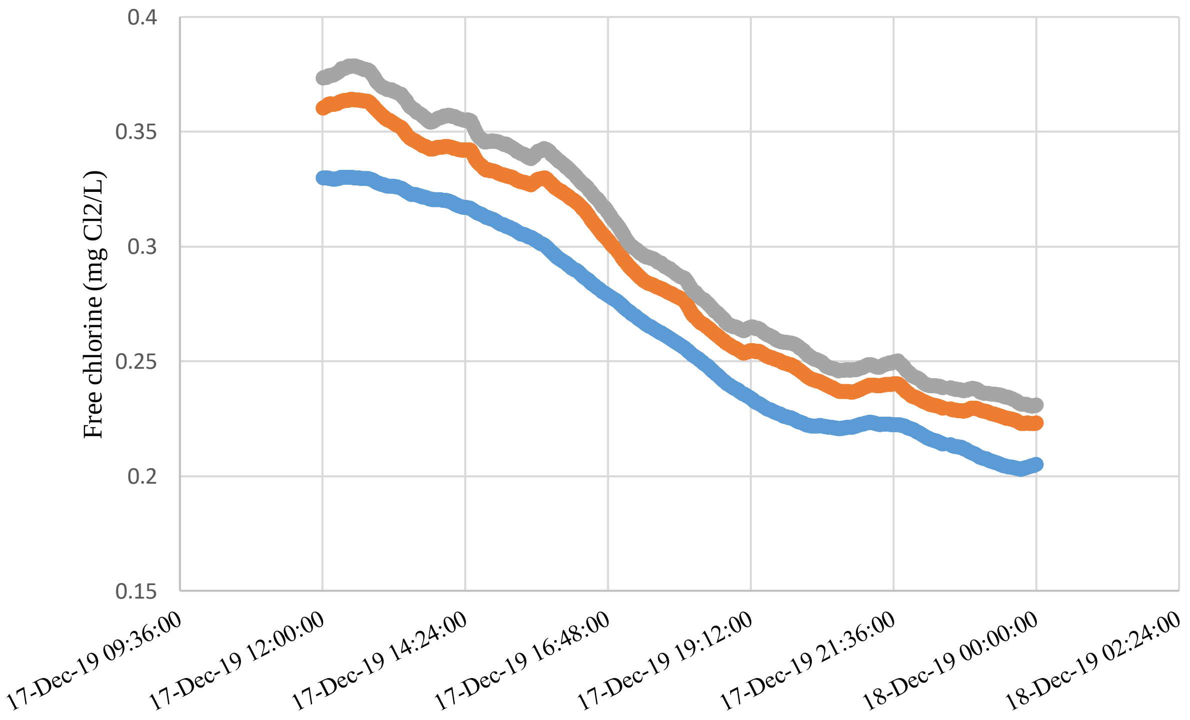

Figure 4.31 Time-series of chlorine measurements during the red water event

On the other hand, AC4 probes measured higher chlorine concentration as compared to the reference measurements. Assuming that the reference measurements from the utility instrumentation are accurate and reliable, this deviation could be due to transforming active chlorine to free chlorine or even due to the presence of bubbles, as they can create errors in chlorine measurements. Another explanation would be the fluctuations in pH (varied between 0.1 to 0.4 for 10-min intervals) and its impact on the calculations of free chlorine (as pH affect the HOCl/OCl ratio in chlorine), while, in pilot tests, the pH was constant during time. In addition, the time spans for pH measurements and chlorine readings is not the same (1-minute and 6 seconds, respectively) which can also create variability in free chlorine calculation.

When comparing all probe readings to reference online measurements, a few observations can be made:

1) Differences between the two AC4 probes and the online reference measurements for chlorine were rather constant and in agreement with the results of the laboratory testing.
2) Readings for turbidity between the two OT3 probes were similar in normal conditions as expected from laboratory trials, but differences increased during event measurements over the time of the field monitoring.
3) Differences between the OT3 probes and the reference online measurements were not predictable in terms of accuracy and drift and not easily explained. This is not in agreement with the laboratory testing results showing accuracy and stability of readings in the presence of mineral turbidity and particulate and dissolved iron. These differences could be caused by several sources alone or in combination: the nature of the particles causing turbidity, fouling, and the operational set-up.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

The results obtained in this study were used to validate (or invalidate) the performance of the KAPTA^{TM} 3000 AC4 and OT3 probes for online monitoring of the water quality parameters in a distribution system. This chapter summarizes a set of conclusions on the parameters tested during this research along with some recommendations for future studies.

- **The KAPTA^{TM} 3000 AC4 probes are reliable tools for real-time monitoring of free chlorine in a distribution system.**

Results from the pilot-scale and full-scale tests on the pilot and on the distribution system presented in the previous chapter show that the KAPTA^{TM} 3000 AC4 probes are a reliable tool to monitor free chlorine over short and longer term. Nonetheless, during the field experiment, the AC4 probes showed an average of 0.12 ppm deviation from the reference measurements in the worst situation which exceeds the 5% accuracy claimed by Veolia. This was attributed partly to the transformation of active chlorine to free chlorine. This was also attributed in particular to one probe, as probe AC4 (12467) was shown to be more accurate than probe AC4 (12459) during the field experiment. Such an issue could however be corrected providing a proper quantification of the differences between the KAPTA and the reference utility instrumentation.

- **The KAPTA^{TM} 3000 OT3 probes are tools capable of monitoring turbidity in a water distribution system**

During the two sets of tests performed on the probe validation, we investigated the ability and reliability of KAPTA^{TM} 3000 OT3 to monitor turbidity online. Reference measurements were used as a tool to compare and assess the precision of the probes to record turbidity.

According to the results, short-time recordings from pilot-scale experiments indicate that the KAPTA OT3 probes measures higher fluctuations of turbidity in high turbid water (8 NTU). This was attributed partly to their 6-seconds interval time step which allow for a more detailed portray of turbidity fluctuations, as moving averages calculated from the probe turbidity readings every 1 to 10-minutes erased this trend.

Higher differences were measured in the field-scale study. In the case of the field study, it is however not clear if the observed differences were due to the probe itself, the probe set up or the nature of particles. Both field and pilot-scale observation brings questions about the way probes data needs to be processed by utilities to balance well between protecting public health and avoiding costly interventions on the DS that may not be justifiable. As an example, a one-time event at 5 NTU turbidity measured with a 6-second interval reading may not present the same level of risk as compared to ten 5 NTU events measured successively every 6-second interval. Another possible explanation for the fluctuations in turbidity measurements is the fact that the probes were installed on 2 inch (51mm) pipe, which may not be optimal as they could be more susceptible to the presence of micro-bubbles around the sensors.

The extent and source of turbidity could also have affected the accuracy of measurements for both turbidity and chlorine recordings. According to the results presented in section 4.1.2, the fluctuations of turbidity measurements for tests performed with kaolin (clay) particles are higher than that for tests performed with iron scale powder particles (Figure 4.10). Moreover, according to the comparison of experiments with kaolin and iron powder regarding chlorine measurements, we experienced higher relative errors for experiments with iron powder with 2 NTU and 8 NTU turbid water; while, for tap water and 5 NTU turbid water the differences were not significant. As a side note, iron powder also led to higher rates of chlorine decay. Therefore, when developing a methodology to process probes data to trigger an alarm, and considering again the small interval of measurement (which increase the probability of detecting spikes); one has to consider the various types of particles that can be released in the DS.

- **KAPTA^{TM} 3000 OT3 is capable of recording organic matter accurately**

The average of errors varied from 0.014 to 0.022 cm^{-1}, which is slightly higher than 0.01 cm^{-1} (the predicted accuracy for the OT3 probes). Organic matter is one of the three measured parameters by KAPTA^{TM} 3000 OT3 probes using UV absorbance at 254nm. To investigate their accuracy in UV recordings, we used kaolin (clay) as the source of organic matter and repeated the tests for three levels of turbidity (2, 5 and 8 NTU as described in methods section). According to the results obtained in this study, the probes accuracy for UV measurement is close to the value claimed by the manufacturer. However, we did not test the accuracy and stability of the probes for measuring organic matter in a real distribution system for an extended period due to the absence of reference monitoring for organic matter in the chlorination station used for the field validation of the probes.

Recommendations

Regarding the tests performed during this project, the following recommendations are issued:

1- As mentioned in the Material and Methods chapter, to gather data recorded by the probes, we used an interface provided by Veolia to connect them directly to a PC. However, using GSM communication modules is the preferable way of data gathering. Nevertheless, one important limitation of the probe observed along this project is that the signal strength for data transmission should be high enough for the communication boxes to work properly, which was not the case during the tests neither in our laboratory nor at Duranleau station. In order to perform real-time monitoring of the DS with direct insertion of the probes into the pipes (in chamber valves for example), an online data transmission is necessary using an interface developed by Veolia to connect KAPTA probes via GSM modules (FUSION). Therefore, a sufficient signal strength is a critical parameter for installing the KAPTA probes and can be a limiting factor in some areas of the DS. Selecting the service providers based on the strength of the signal would be part of the solution but may not be sufficient. Using signal amplifiers would be another way to address this issue. Finally, although probes are designed to be installed underground, it is a proper practice to install the GSM boxes outside of the chamber valves to enhance the signal strength. Such an installation requires additional investments for utilities, but may facilitate the maintenance of the probe system (e.g. replacement of the GSM box batteries).

2- KAPTA^{TM} 3000 OT3 probes use a LED to lighten and measure turbidity and therefore it is important to deploy them on a pipeline spacious enough for the probes to work precisely. If not, there will be microbubbles creating around the probe tip submerged inside the pipe. According to Figure 5.1, which shows an OT3 probe installed on a 63 mm (~2.5 in) pipe, the limited space for flow to pass through leads to creation of excessive bubbles around the pipe, which make noises, fluctuations and misleading data for turbidity. Using pipes diameters of 4 inches and above would be a solution to limit this issue.

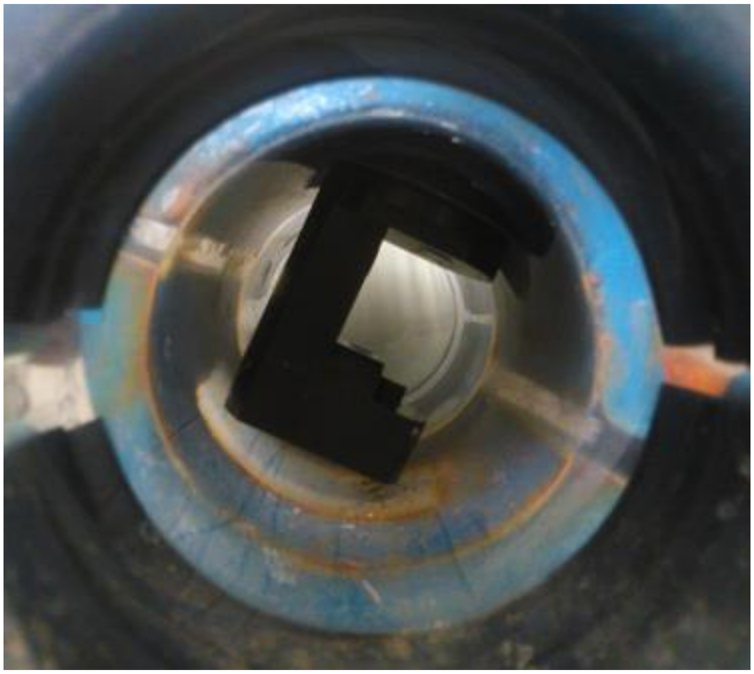

Figure 5.1 KAPTA^{TM} 3000 OT3 probe installed on a 63mm (~2.5 IN) pipe

3- Microbiological tests on samples collected during the red water event in the DS indicated once the presence of *Enterococci* in the DS, during a turbidity event. This is a strong clue that KAPTA^{TM} 3000 OT3 is a promising tool to detect contaminant intrusion or detachment in the DS. In this way, the combination of KAPTA^{TM} 3000 AC4 and KAPTA^{TM} 3000 OT3 would make it possible to monitor several quality parameters along with pressure, which provides valuable information to make instant decision and to perform prompt actions in case of occurrence of accidental intrusion or intentional contamination.

4- In this research, we did not field tested the probes for long enough to conclude properly on the stability of their signals over time. We captured a slow but significant deviation of the turbidity readings (KAPTA OT3) from the reference measurements over time of the pilot scale experiments (around 0.8 NTU at the end of the experiment). This could be due to fouling of the probe lens as KAPTA^{TM} 3000 OT3 to measure turbidity and UV. The manufacturer recommends indeed wiping the probes whenever the fouling indices (C.T. UV and C.T. Vis) fall below 80%. Nonetheless, the deviation observed over short time (one and a half months) may indicate that the probes need to be cleaned more frequently than the manufacturer recommendation. To evaluate this aspect properly, a possible solution would be to compare probe readings with reference measurements (if available) regularly (e.g. every couple of days).

5- Considering the probe field results indicating a systematic overestimation of turbidity and chlorine, we recommend investigating this aspect more. One way to obviate this issue would be developing a proper procedure to calibrate the probes so that these probes can be used reliably. As these probes are meant to be autonomous over a long period of time, it would be beneficial to quantify the impact of fouling for a given water quality under conditions prescribed by the manufacturer. This verification could inform the probe user about the extent and stability of any drift and take effective actions to mitigate it (cleaning or signal adjustment).

6- The combination of sensors present in OT3 and AC4 probes would be helpful to detect DBP formation as they measure OM and residual chlorine, respectively. The possibility of DBP formation can be calculated through the equation presented in Section 3.1. It would be appropriate to perform a pilot or field experiment to test the performance of the combination of the sensors used on the KAPTA^{TM} in predicting the amount of DBP formed during an event.

7- One important observation during the field experiment was the gradual drift of OT3 probes in turbidity readings in compare to the reference measurements. Given the fact that this observation was made during 5 weeks of field testing on one water sources using a non optimal set-up) (2 inch pipe), additional verification against reference online measurements appears warranted. Additional laboratory experiments could address the impact of the nature of particles on the OT3 turbidity readings and fouling. As mentioned in chapter 4, sources of turbidity could have a significant impact on the performance of OT3 probes according to the results during red water event. One way to investigate this aspect would be to monitor over long-term the use of the OT3 probes in a real DS to evaluate their performance during different events involving different turbidity sources. To make this process easier, water samples collected during real events occuring in the DS could be gathered and filtered to get higher concentrations. These concentrated samples could then be used at pilot-scale to investigate the response of the OT3 probes to various red water events.

8- A red water event can be caused by pression transient events or changes in flow. During such events, pathogen intrusion or detachment of indicatoirs and pathogens from the biofilm can occur. The decision on when to perform a laboratory test to detect the presence of pathogens in drinking water is critical. As observed in our study, the captured event was not associated with health risks indicated by fecal contaminantion (*E. coli)* or the presence of a pathogen *(Legionella)*. Turbidity varied between 0.8 NTU and 1.7 NTU. As turbidity peaks may be an indicator of the potential presence of pathogens in drinking water, deciding on performing microbiological test on samples based on the turbidity level would be avalid approach. According to Québec (2013) the highest acceptable turbidity level for drinking water is 5 NTU. Therefore, a 5 NTU turbidity level might be a proper threshold for that matter.

9- As installation of such monitoring probes is expensive (€5000 to €7500 for AC4 and OT3, respectively), the best way of choosing deployment nodes on the network is to implement a multi-objective optimization to minimize the number of probes, response time and affected areas and to maximize the coverage of critical infrastructure and the probability of detecting catastrophic events. This process requires pairing the hydraulic-quality modeling of the DS to an optimization method to investigate different events and to choose the best sectors for probe deployment.

10- In case of deploying the KAPTA probes in the DS without performing an optimization, key locations for the probes would include:

- Upstream of critical infrastructures (e.g. hospitals, long-term care centres).
- Areas in the DS where a higher number of incidents leading to an event (main break, blackouts, etc.) has been reported
- Areas with repeated complaints from the residents about the quality of drinking water.
- Dead ends as these sections of the DS are more at risk of deficiencies and water quality degradation due to increased stagnation times. It should however be noted that the KAPTA AC4 probes are not designed for areas with velocities smaller than 0.03 m/s, while the OT3 probes work in no flow condition.

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