Australian Water Recycling
Centre of Excellence

Final Report

An inline sensor to detect cross-connections between potable and recycled water systems in real-time

A report of a study funded by the
Australian Water Recycling Centre of Excellence

TH Muster, M Best, A Trinchi, September 2015

An inline sensor to detect cross-connections between potable and recycled water systems in real time

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Contributing Partners

Smart Water Fund Victoria, Melbourne Water, Yarra Valley Water, Western Water.

About the Australian Water Recycling Centre of Excellence

The mission of the Australian Water Recycling Centre of Excellence is to enhance management and use of water recycling through industry partnerships, build capacity and capability within the recycled water industry, and promote water recycling as a socially, environmentally and economically sustainable option for future water security.

The Australian Government has provided $20 million to the Centre through its National Urban Water and Desalination Plan to support applied research and development projects which meet water recycling challenges for Australia's irrigation, urban development, food processing, heavy industry and water utility sectors. This funding has levered an additional $40 million investment from more than 80 private and public organisations, in Australia and overseas.

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Executive summary

Due to the possibility of cross-connections of recycled water intrusion into potable water systems, there is a need to protect the investment in water recycling infrastructure and public health, as well as manage public perception and supplier reputational risks. Whilst inspections methods are currently a workable solution, with the anticipated increases in numbers of customers with recycled water connections and rising labour costs, auditing targets may become difficult to achieve.

Over recent years, CSIRO, along with contributing partners, have undertaken various projects to develop reliable means for detecting and sensing cross-connections between potable and recycled water systems, with the aim of enabling close management of risks and help maintain consumer confidence in recycled water schemes. Previously electrical conductivity (EC), ultra violet (UV) absorbance and UV fluorescence were found to be a good basis for cross-connection detection. EC has since been demonstrated as an effective means to detect down to 10% of a recycled water in potable water. However, the quality of the both the recycled water and potable water can have seasonal variations, and further variations in water quality of both potable and recycled water can occur sporadically due to the daily operating procedures of the water supplier and of course the water source itself. For this reason, a combination of EC and UV methods has been proposed as a way to more confidently detect cross-connections across a wider range of waters with variable quality. Furthermore, the complementary nature of EC, which detects dissolved salt levels, is somewhat independent of UV methods, which are sensitive to the presence of aromatic carbon, humic acids and proteins.

The work carried out in this project sought to explore the application of UV absorbance and UV fluorescence for detecting cross-connections in more detail. More specifically, the aims of the project were:

1. To develop an alternative indicator to electrical conductivity to detect the presence of recycled water in potable water.
2. To have both the UV parameters (absorbance and fluorescence) available which, together with an EC sensor, could make a universal cross-connections device that would be effective within most consumer premises.
3. To develop the sensitivity of fluorescence sensors using excitation with cheaper LEDs (e.g. 365 nm) such that costs would be reduced and enable in-home units to be more affordable.
4. During the construction, stability issues such as temperature compensation, calibration drift and fouling resistance will be addressed.
5. The target detection limit was 10% contamination with recycled water, with very low rates of false positives and false negatives.
6. Subsequent to this project, it was planned to manufacture the device(s) commercially.

UV fluorescence was found to offer superior sensitivity as opposed to UV absorbance, and furthermore, offered improved affordability in enabling excitation of fluorescence to be carried out in the range of 310-370 nm, as opposed to expensive UV sources operating in the traditional 254 nm range. Consequently, operational prototypes were developed with a component cost under AU$200. The final prototype was able to detect under 1% recycled water in a potable water and was demonstrated to work effectively in two field trials conducted on varying water quality types at Brushy Creek (Yarra Valley Water) and Surbiton Park (Western Water). An effective means of temperature compensation has been established and no fouling issues were experienced during repetitive testing over 6 months in both the laboratory and field trials.

The ultimate accuracy of a cross-connections device is highly dependent upon an effective means of ongoing calibration. Whilst this is not to say that either EC or fluorescence have significant issues regarding their drifting of calibration, future work in the development of the device is suggested to explore ways to achieve calibration whilst in service. Aside from calibration uncertainties, the fluorescence prototype has been demonstrated to provide an excellence means of differentiating water quality over long periods of time at low cost and commercialisation opportunities are currently being explored.

1. Introduction

Upon the installation of water recycling schemes in Australia, a need has developed to protect public health and the investment in infrastructure, as well as manage public perception and supplier reputational risks (Radcliffe, 2010). The potential for cross-connections to occur between potable and recycled water remains a concern for the water industry. Public perception and public confidence in water utilities to manage and provide water that is safe and fit for purpose can be severely affected if cross-connections are detected. This would undoubtedly become an even bigger issue if any illnesses could be attributed to the consumption of recycled water. For this reason, water utilities continue to invest considerable money and effort into ensuring that such events do not occur. However with an increasing number of households being connected to recycled water schemes each year, the ability to monitor all these with labour-intensive inspections and reliance upon laboratory analyses is increasingly difficult. Rather, water utilities currently focus on checking the plumbing connections of new dwellings (connected to a recycled water scheme) and an ongoing inspection program that inspects the plumbing of 5-20% of properties connected to recycled water annually. Whilst inspections methods are currently a workable solution, with the anticipated increases in numbers of customers with recycled water connections and rising labour costs, auditing targets may become difficult to achieve.

Over recent years, CSIRO, along with contributing partners, have undertaken various projects to develop reliable means for detecting and sensing cross-connections between potable and recycled water systems, with the aim of enabling close management of risks and help maintain consumer confidence in recycled water schemes (O'Halloran and Toifl, 2008; O'Halloran *et al*., 2010; O'Halloran, 2012). Previously, electrical conductivity (EC), ultra violet (UV) absorbance and UV fluorescence were found to be a good basis for cross-connection detection (O'Halloran *et al*., 2010). EC has since been demonstrated as an effective means to detect down to 10% of a recycled water in potable water (O'Halloran, 2012). However, the quality of the both the recycled water and potable water can have seasonal variations, and further variations in water quality of both potable and recycled water can occur sporadically due to the daily operating procedures of the water suppliers (i.e. chlorinating regimes, variability in filtration equipment, equipment shut down, among many other factors) and of course the water source itself. For this reason, a combination of EC and UV methods has been proposed as a way to more confidently detect cross-connections across a wider range of waters with variable quality. Furthermore, the complementary nature of EC, which detects dissolved salt levels, is somewhat independent of UV methods, which are sensitive to the presence of aromatic carbon, humic acids and proteins. The ability of UV fluorescence to detect a cross-connection was reported to identify a positive analysis at 45% recycled water in a potable water (Hambly *et al*., 2010) and UV absorbance has been not been further explored.

The work carried out in this project sought to explore the application of UV absorbance and UV fluorescence for detecting cross-connections in more detail, and furthermore, to build a cheap and robust UV-based sensor with the associated intelligence capable of achieving a detection limit of 10% contamination of a recycled water in potable water. This represents the final report, however, further detail of the project may also be found within the following documents:

R.J. O'Halloran and S. Gould (2013). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 2a report. CSIRO Water for a Healthy Country Flagship, Australia.

A. Trinchi, M. Toifl, S. Gould, M. Best, R. O'Halloran and T. Muster (2013). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 3 report. CSIRO Water for a Healthy Country Flagship, Australia.

A. Trinchi, M. Best, S. Gould, M. Toifl and T. Muster (2014). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 4 report. CSIRO Water for a Healthy Country Flagship, Australia.

M. Best M, A. Trinchi and T Muster (2015). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 5 report. CSIRO Land & Water Flagship, Australia.

M. Best, T.H. Muster, A. Trinchi, M. Toifl, S. Gould and R. O'Halloran. (2015). An inline sensor to detect cross-connections between potable and recycled water systems in real time. Proceedings of Ozwater'15, Adelaide, May 2015.

The specific aims of the project were captured in the executive summary above, however are repeated again below for clarity:

1. To develop an alternative indicator to electrical conductivity to detect the presence of recycled water in potable water.
2. To have both the UV parameters (absorbance and fluorescence) available which, together with an EC sensor, could make a universal cross-connections device that would be effective within most consumer premises.
3. To develop the sensitivity of fluorescence sensors using excitation with cheaper LEDs (e.g. 365 nm) such that costs would be reduced and enable in-home units to be more affordable.
4. During the construction, stability issues such as temperature compensation, calibration drift and fouling resistance will be addressed.
5. The target detection limit was 10% contamination with recycled water, with very low rates of false positives and false negatives.
6. Subsequent to this project, it was planned to manufacture the device(s) commercially.

2. Background

Throughout this project, CSIRO have worked towards the development of an affordable inline sensing system for monitoring cross-connections between potable and recycled water in real time.

As discussed in the Milestone 3 report, potable and recycled water samples were obtained from several different suppliers nationwide and detailed spectroscopic analyses of the water were conducted. From the optical absorption experiments, the UV-vis absorption spectra from the majority of water samples were virtually featureless in the range from 240 to 800nm, with only an absorption peak in each spectra centred at around 210 nm (Figure 1). This suggested that with current technologies available, building a sensor for monitoring wavelengths in the range from 200 to 240 would not fall within the guidelines of being affordable as it would involve costly light sources and detectors, and nor would utilizing such wavelengths in the UV spectrum be desirable due to power usage and material suitability and degradability.

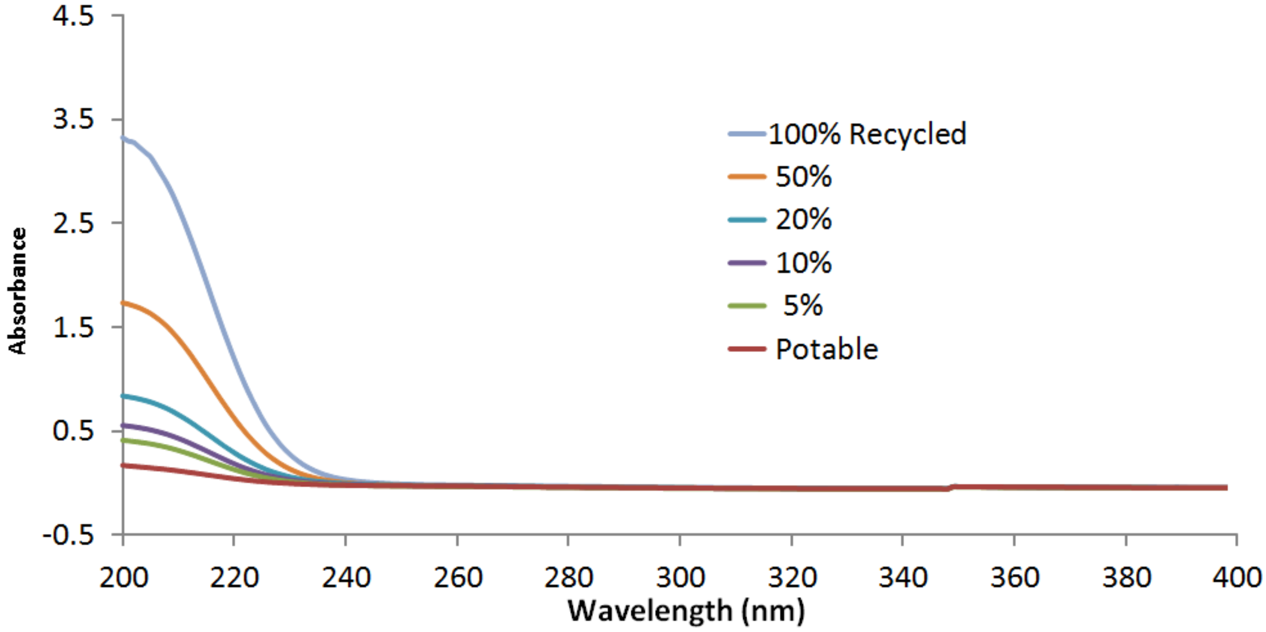

Figure 1. Example of UV-vis absorbance spectra for different concentrations of recycled water.

Despite the absorption data not being capable of providing a clear indication of recycled water contamination, the fluorescence data on the other hand was capable of providing a clear distinction of recycled water from all sites. Fluorescence emission maps for different concentrations of recycled water from each site showed two distinct regions of fluorescence excitation, the first at being in the region of 250-270 nm and the second from 310-370 nm (Figure 2). The 254 nm absorption band is typically a measure of the aromatic character of dissolved organic matter, whereas the aliphatic molecules absorb in the range of 300-370 nm (Hambly, 2013; Table 1).

As a consequence, strong emission signals may be obtained without having the need for expensive and hazardous UV-B (290-320 nm) or UV-C (200-290 nm) excitation sources.

During Milestone 3 and 4, several prototype devices were developed and exhaustively tested in the laboratory to control samples (various concentrations of quinine sulphate or in other cases tonic water) and also to potable and recycled water samples from various sites (Trinchi *et al.*, 2013 and 2014). The ratio of recycled to potable water was varied from 0 to 50% in increments of a fraction of a percent. Several prototype sensors were connected in series as part of a continuous flow testing system and the experiments run continuously for weeks at a time. Laboratory tests revealed that not only could the 10% cross-connection target in the challenge sample[1] be achieved, but the sensors were capable of far exceeding this limit, even for the treatment plant producing recycled water with

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[1] The challenge sample was the collected recycled water that exhibited the most similar fluorescence characteristics to potable water. This recycled water was produced at a facility using ozonation, biological media filtration, ozonation, UV disinfection and chlorination.

the lowest fluorescence signal. Furthermore it was also demonstrated that the sensor was also designed to be affordable with component costs being around $150-200 for a one-off device.

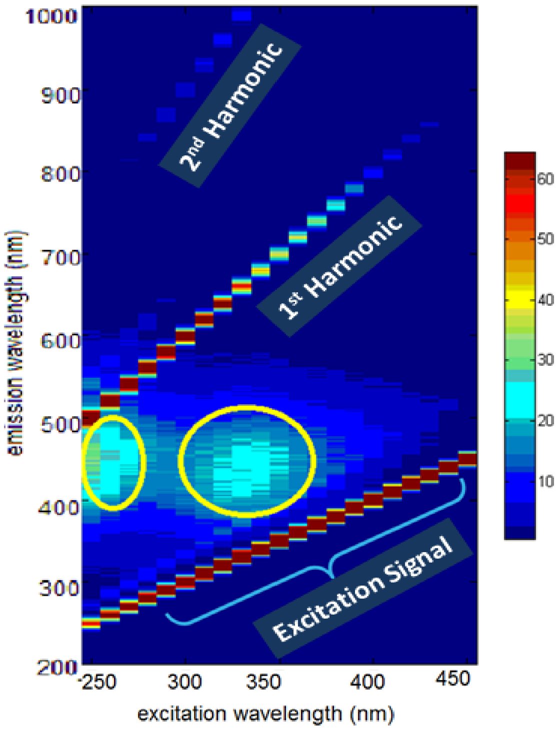


Figure 2. Fluorescence excitation-emission map for a recycled 'Class A' water.

Table 1. Commonly observed fluorescence peaks of natural and artificial water samples (Hambly, 2013).

Peak		Peak Notation	Excitation Wavelength (nm)	Emission Wavelength (nm)
Protein-like	Tyrosine-like	B	225-237	309-321
	Trypophan-like	T1	275	340
		T2	225-237	340-381
Humic-like	Fulvic-like	C1	300-370	400-500
	Humic-like	C2	370-390	460-480
	Humic-like	A	237-260	400-500

Both potable and recycled water exhibit fluorescence, however, owing to the greater presence of organic species in recycled water, its fluorescence signature tends to be significantly greater than that of the potable water. Consequently, the change in the fluorescence properties of both recycled and potable water has been shown to be reliable indicators for the change in quality of the water.

The effect of the water temperature on the sensors response was also investigated (Trinchi *et al.*, 2014) as fluorescence intrinsically has temperature dependence (Hambly, 2013). Analytical tests conducted on samples from water supplies as well as on the control samples revealed the fluorescence intensity exhibited a linear response to temperature in the range of 20-50°C, with increasing temperature resulting in a decrease in the fluorescence intensity (Trinchi *et al.*, 2104). After exhaustive testing, it was established that temperature effects could be compensated for during data acquisition. It should be noted that full temperature compensation is a challenging task in any system, as not only is the fluorescence dependant on temperature, but so too are the electronic circuitry and components, making the matter a complex one. The same also holds true for EC sensing.

In an effort to demonstrate the ability of fluorescence sensors to cope with changing water quality conditions, considerable effort was spent on the development of a portable sensing rig that could facilitate the paired measurement of potable and recycled water (Figure 3).

Figure 3. Photos of the testing chamber developed for field trials.

The portable rig allowed for precise mixing of potable and recycled water for simulating different cross-connection ratios. As outlined in both Milestone 4 and 5 reports, the system consists of waterproof housings for electronics, data logging and external communication to a web server, circuits, mixing tank and flow sensors. The field trial rig accommodates two of the prototype fluorescence sensors: one in line with the potable water and one in line with the mixing tank to measure the fluorescence of the different cross-connection mixtures. The field trial rig also contained an EC sensor, which was supplied courtesy of Hawk Measurement Systems. This EC sensor was placed in line with the mixing tank.

3. Brushy Creek Trial Revisited

As described in the Milestone 5 report, the first field installation was at the Brushy Creek Water Recycling Facility (Yarra Valley Water) and ran from the 2nd March 2015 to 8th April 2015. During this time, the desired cross-connection ratio was achieved by periodically dosing the mixing tank with a known volume of recycled water. Figure 4 provides a sample of the fluorescence signal from two prototypes, one placed in line with mixed recycled and potable water circulated from the mixing tank (CC1) and one placed in the potable water line (CC2). The EC sensor was placed in line with CC1. Figure 4 corresponds to data that is not corrected for temperature changes, however, a linear correction was subsequently applied to all data so that a direct comparison could be made at a constant temperature, which for the current project was chosen to be 22°C. Further details of temperature correction can be found in Milestone 5 report (Best *et al*., 2015).

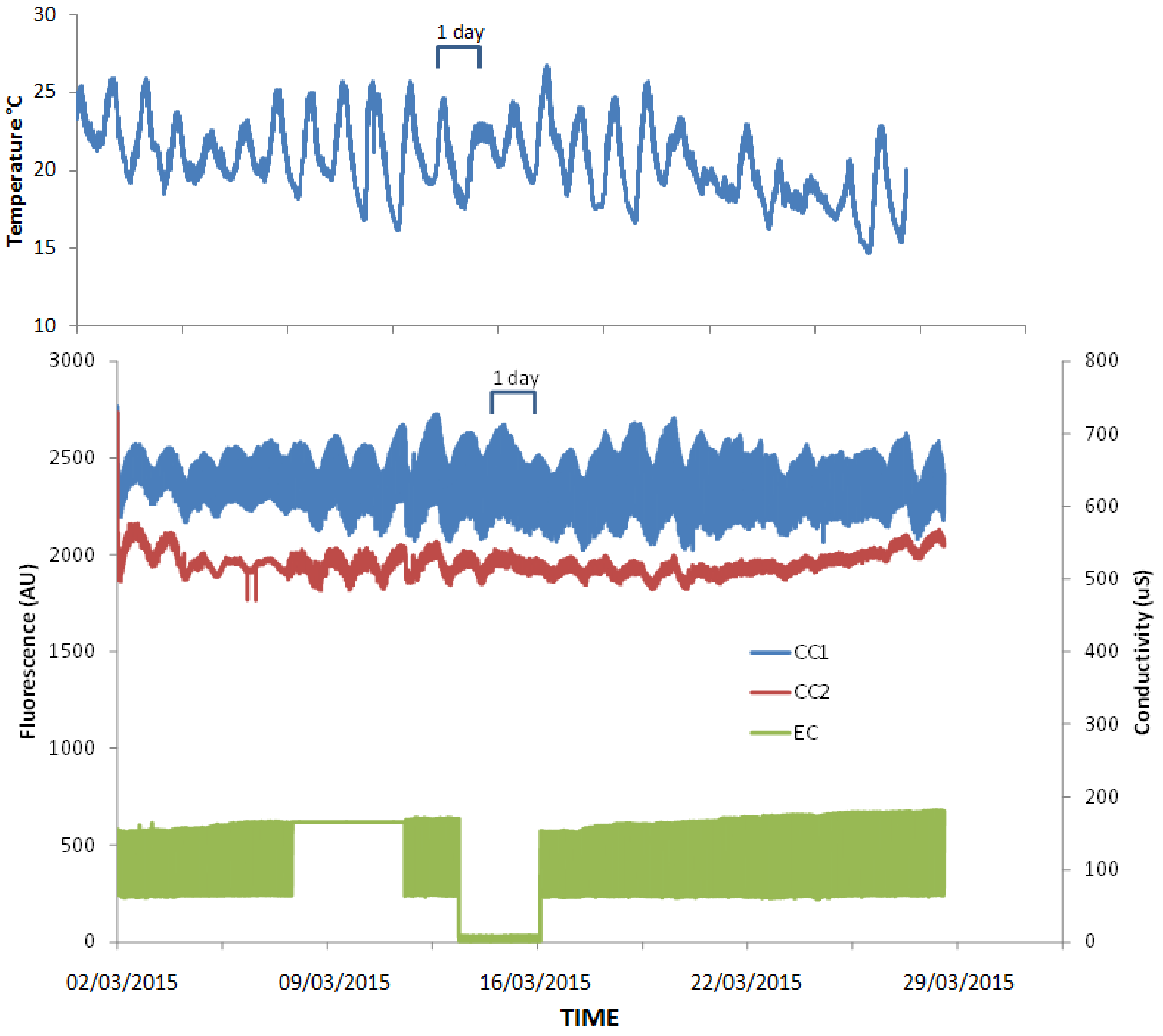


Figure 4. Output from CC1, CC2 and EC (not temperature corrected) in the system during the Brushy Creek trial.

Figure 5 demonstrates typical data recorded during a 30 min cycle where mixtures of recycled water of 2.2, 4.3, 6.3, 8.2, 10.1, 11.9, 13.6, 15.2, 16.8, and 18.3% were created. Aside from two times when the EC sensor failed to respond, the majority of the data was collected without significant drift or complication.

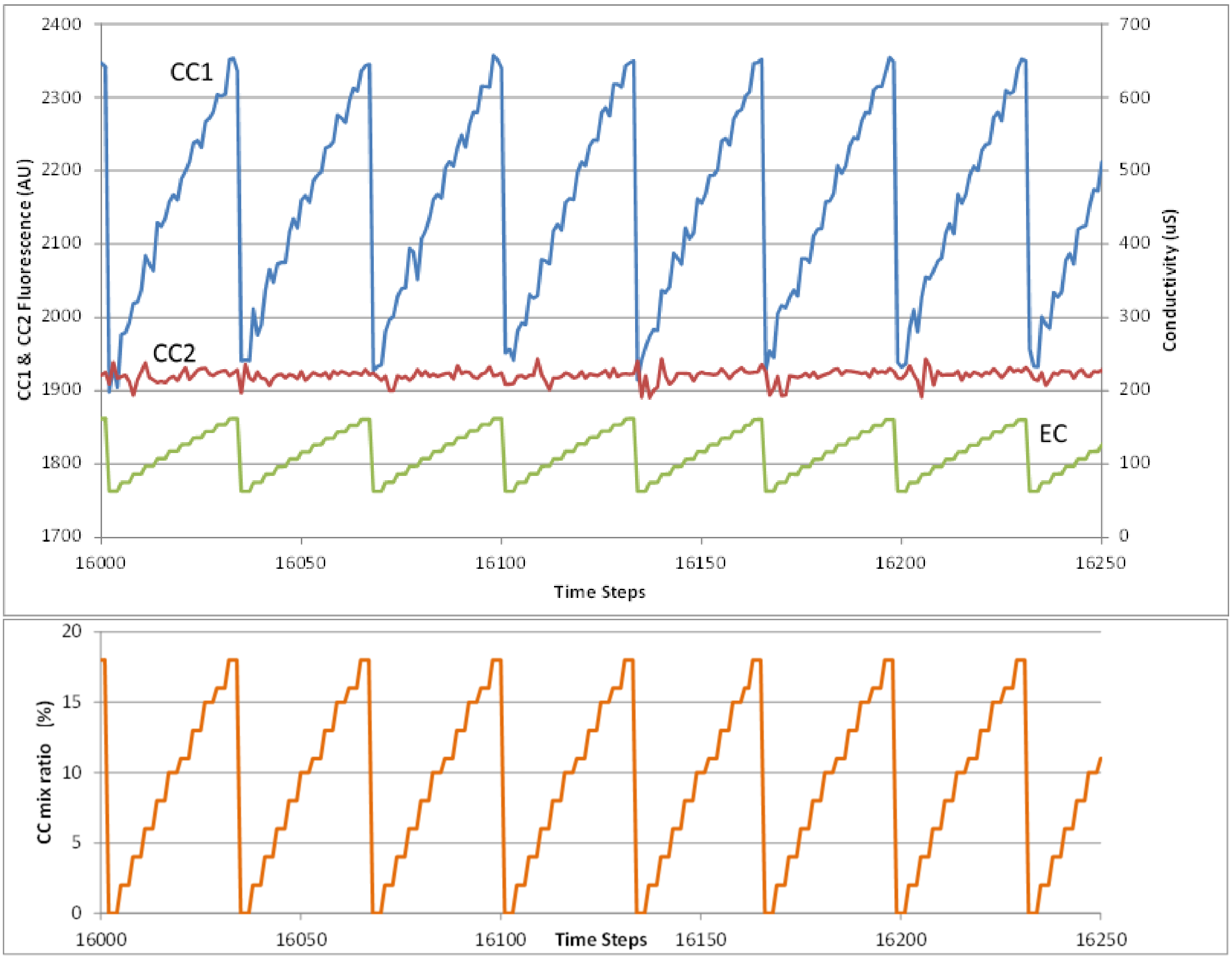


Figure 5. Typical raw data set for mixing cycles at Brushy Creek. CC1 = fluorescence sensor in mixing tank, CC2 = fluorescence sensor in the potable water line, EC = electrical conductivity sensor in mixing tank. Time step = 1 min.

Figure 6 shows water quality data measured by Yarra Valley Water during the period of the test. In comparison to the use of real-time sensors, there is a relatively lean amount of data collected using existing industry practice. That said, Figure 6 indicates that most of the commonly measured parameters were consistent over the period of the trial, although there were considerable fluctuations in the pH of the potable water from pH 6.7 to 9.1. Differences in EC were large for the system at Yarra Valley Water, with potable water possessing a conductivity of less than 100 µS/cm and recycled water being as high as 670 µS/cm. From the data in Figure 6, there is no clear distinction in the turbidity of both water types, however, there is sufficient difference in the presence of small organic molecules that lead to a differentiation based upon fluorescence signal. Observing the changes in the cross-connection ratio in Figure 5 demonstrates that both EC and fluorescence have a similar ability to distinguish between water quality types, with the EC sensor appearing to provide a signal with a mildly increased stability for the Brushy Creek system.

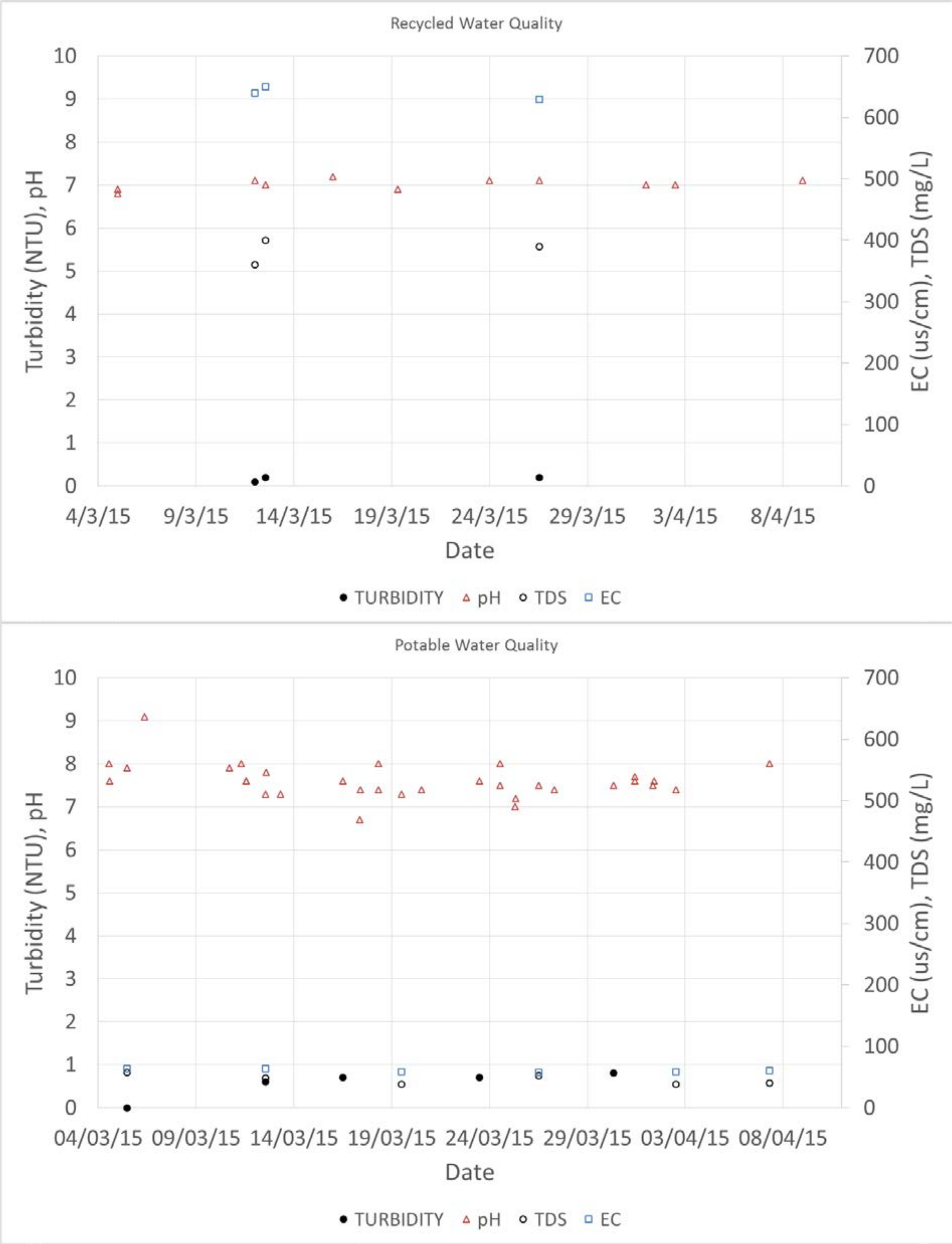
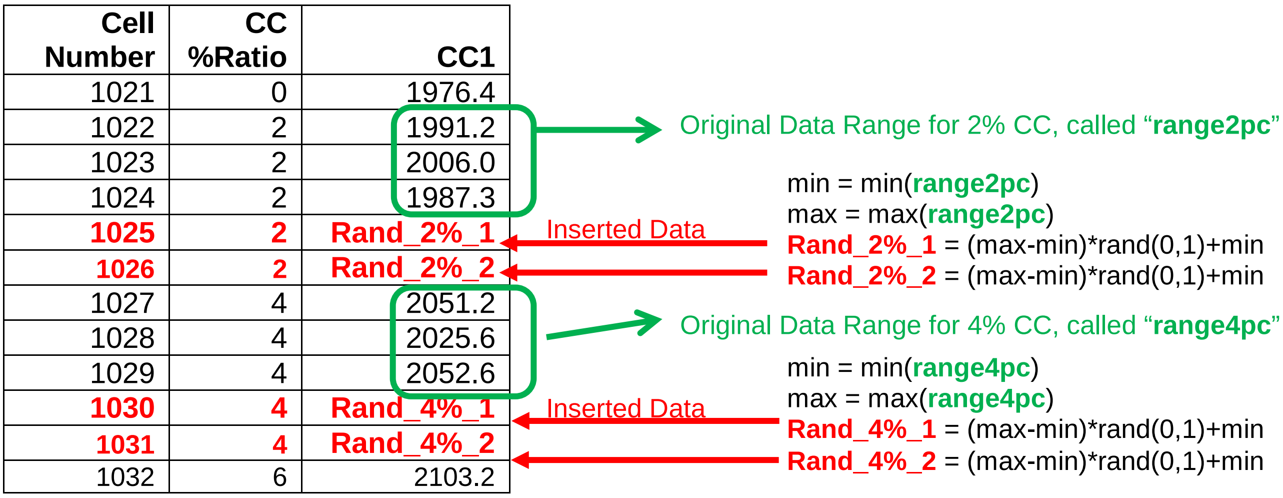


Figure 6. Water quality data from YVW during the period of the trial. Recycled water data is a combination of measurements taken at the Brushy Creek Water Recycling Facility and various locations within the local area of Croydon, Victoria. Potable water quality data is collected from numerous locations throughout the YVW reticulation system.

Within the portable rig, the two prototype sensors are operated in a paired configuration for monitoring the fluorescence of both potable and recycled water (i.e. data is collected simultaneously from both CC1 and CC2). This approach lends itself to the utilisation of a paired T-test, which can provide a continuously updated statistical evaluation as to whether the readings from the two sensors are correlated. In practice, this would be akin to one sensor operating within a potable reticulation system and having the other sensor located within a premises where the presence of a cross-connection was a possibility.

The ability of the T-test to more accurately determine a cross-connection was demonstrated in Milestone Report 2a using the fluorescence dataset collected by Hambly *et al*. (2010) for Rouse Hill, Sydney, which had been previously assessed as enabling the detection of 45% recycled water in potable water (O'Halloran and Gould, 2013). With the T-test re-evaluation, it was confirmed that 10% recycled water sourced from Rouse Hill in Sydney could be detected 100% of the time, but this was dependent upon a representative number of samples (10 data points) being used in the statistical analysis. The Milestone 5 report demonstrated that the paired T-tests performed on the Brushy Creek data using only three data points could detect a cross-connection at 8% recycled water 100% of the time. Therefore, we investigated the number of sensor readings required to significantly improve the accuracy and detection limit for the field-based readings at Brushy Creek. As illustrated in Figure 7, further simulated data points were added to the field trial data to assess improved differentiation. The original data consisted of three consecutive sensor readings from the same cross-connection ratio, the simulated data points were determined by selecting a random number that was uniformly distributed between the minimum and maximum sensor readings of those three consecutive readings. In doing so, it was possible to add as many of such points as desired to the field trial data. A random portion of the raw field trial data consisting of 12,500 data points was selected for this investigation.



Cell Number	CC %Ratio	CC1
1021	0	1976.4
1022	2	1991.2
1023	2	2006.0
1024	2	1987.3
1025	**2**	**Rand_2%_1**
1026	**2**	**Rand_2%_2**
1027	4	2051.2
1028	4	2025.6
1029	4	2052.6
1030	**4**	**Rand_4%_1**
1031	**4**	**Rand_4%_2**
1032	6	2103.2

Original Data Range for 2% CC, called "**range2pc**"

min = min(**range2pc**)
max = max(**range2pc**)
Rand_2%_1 = (max-min)*rand(0,1)+min
Rand_2%_2 = (max-min)*rand(0,1)+min

Inserted Data

Original Data Range for 4% CC, called "**range4pc**"

min = min(**range4pc**)
max = max(**range4pc**)
Rand_4%_1 = (max-min)*rand(0,1)+min
Rand_4%_2 = (max-min)*rand(0,1)+min

Inserted Data

Figure 7. Example of the method for inserting the simulated data points. The original data is coloured in black and the inserted points in red. The range three consecutive data points acquired from the same CC ratio are analysed to find their minim and maximum value. Then random numbers are selected so that they are uniformly distributed between these minimum and maxim values. Once selected, the desired quantity of such numbers is inserted below each original data range segment.

Figure 8 shows the statistical improvement made in accurately confirming a cross-connection through the use of a greater number of fluorescence (water quality) measurements. The plots show the percentage of cross-connections detected as a function of the number of data points collected during each measurement for different concentrations of recycled water. For the case of 2% cross-connection, there is a clear asymptotic increase in the percentage of cross-connections detected with increasing number of samples, which tends to level out at around 79% for 20 samples per measurement. For a cross-connection ratio of 4%, around 82% of cross-connections are detected for 3 samples which increases asymptotically to around 96% for 20 samples. When the cross-connection ratio was at 6%, the detection limit approaches 100% much more rapidly and once the cross-connection ratio is above this value then virtually all cross-connections are detected regardless of the number of samples acquired. A full list of results can be found in in Table 2. The highlighted cells indicate that more than 99% of cross-connections were detected.

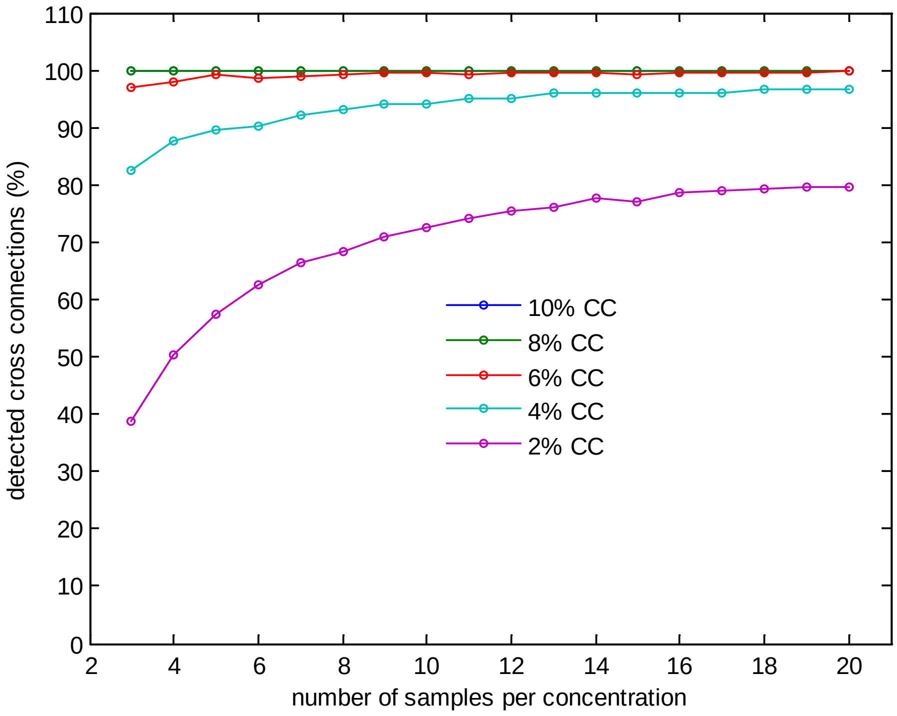


Figure 8. The percentage of cross-connections detected for different concentrations of recycled water vs the number of data points collected during each measurement at Brushy Creek.

Table 2. Sample data from the CSIRO testing rig used in the T-test calculation at Brushy Creek (coloured cells indicate more than cross-connections were detected over 99% of the time).

Number Samples	CC 2.2%	CC 4.3%	CC 6.3%	CC 8.2%	CC 10.1%	CC 11.9%	CC 13.6%	CC 15.2	CC 16.8%	CC 18.3%
3	38.7	82.6	96.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0
4	50.2	87.6	98.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0
5	57.4	89.7	99.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6	62.6	90.4	98.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
7	66.3	92.1	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
8	68.2	93.0	99.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0
9	71.0	94.1	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
10	72.5	94.1	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
11	74.3	94.9	99.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12	75.4	94.9	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
13	76.0	95.9	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
14	77.6	95.9	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
15	77.1	96.1	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16	78.8	96.0	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
17	78.9	96.1	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
18	79.3	96.6	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19	79.6	96.7	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
20	79.8	96.7	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The treatment of the Brushy Creek data appears to reinforce the previous observation in the Milestone 2a report that approximately 10 data points should be used to maximise the accuracy of the paired T-test.

4. Surbiton Park Field Trial

4.1 Raw data and temperature corrected data

As was the case during the Brushy Creek field trial, sensors CC1 and EC were exposed to the different cross-connection ratios in the mixing tank and sensor CC2 was placed in-line with the potable water supply at Surbiton Park.

Figure 9 presents the output data for each of the sensors corrected to a 22°C temperature. The raw temperature of the water tank is also reported for completeness. Again CC2 and EC were exposed to the repetitious blending of waters ranging from potable water to 18.3% cross-connection over a five-week period from April 8 2015 to May 18 2015.

Several observations can be made directly from this figure. Firstly the EC sensor went offline on four occasions. Secondly, the EC value of the potable water at Surbiton Park is almost an order of magnitude greater than that of Brushy Creek, yet the fluorescence baseline value was not significantly changed. An additional point of note is that CC1 experienced a reduction in its baseline value over the duration of the trial (most likely due to the slow burn out of the CC1 excitation source, the reason for which, as well as the significance, will be discussed in subsequent sections). There was also a brief power outage around the 30th of April and hence data is absent for that period.

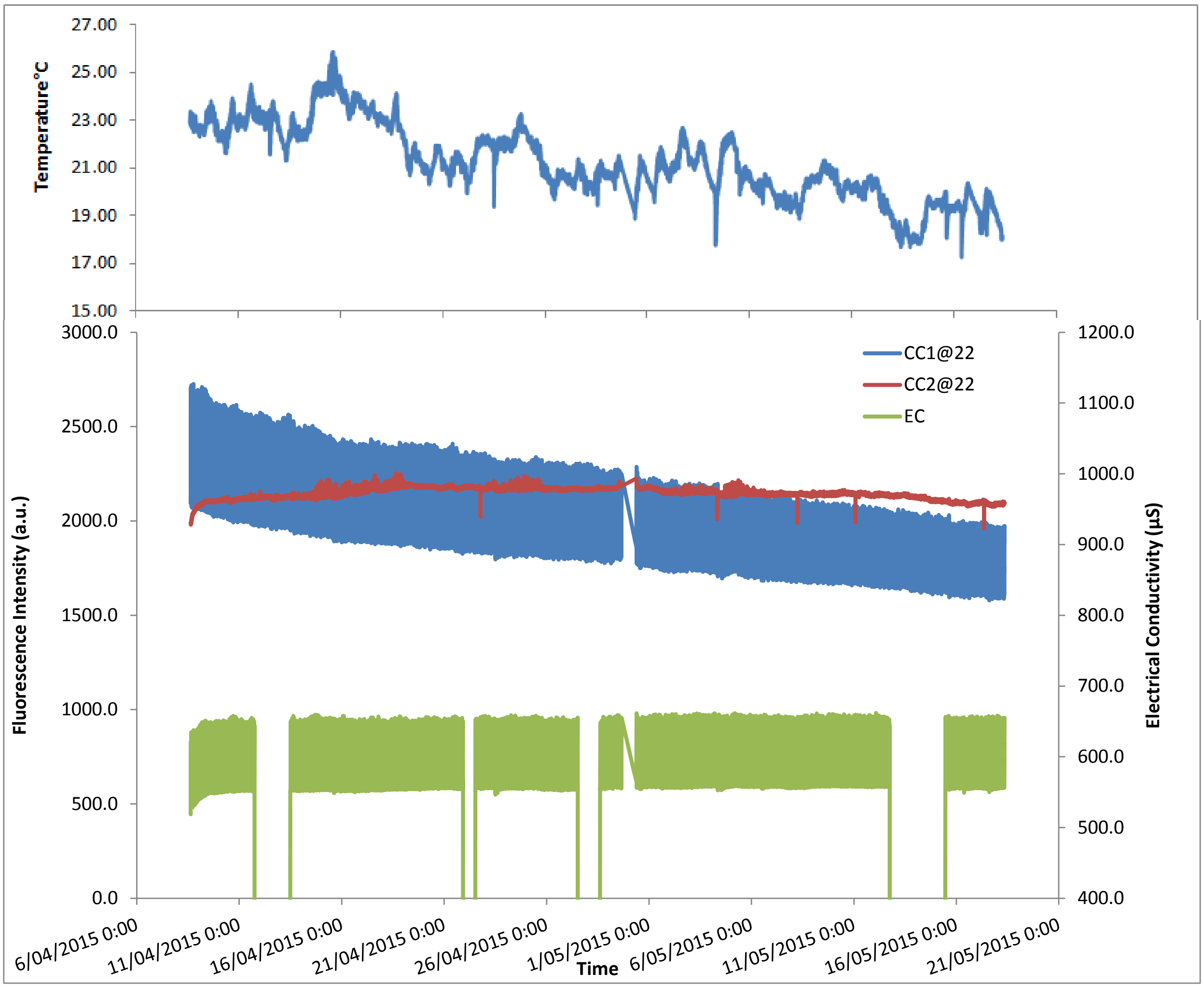


Figure 9. Output from CC1, CC2 and EC for the duration of the field trial at Surbiton Park.

Table 3 and Table 4 provide a summary of water quality measurements from the Water Recycling Facility ('Class A' outlet and at the customer tap) as well as data from the local potable supply, which is fed predominantly from Merrimu Reservoir. The EC readings recorded by the Hawk Measurement

Systems sensor match that of the commercial analytical laboratory that was employed to provide the water quality data in Table 3. It was also noted that the pH of the potable water supply, along with turbidity and total dissolved solids can fluctuate over a yearly cycle, yet appear to do so in a relatively controlled manner as levels did not change significantly during the trial period. There was a notable difference in the colour readings of Class A recycled water and potable water, which is suspected to be related to the organic components of the water such as humic acids. This suggests that fluorescence sensing approaches may be well-suited to detect cross-connections in the system at Surbiton Park.

Table 3. Water quality data from Surbiton Park Water Recycling Facility during the period of the trial and the local reticulation system from Merrimu Reservoir.

Date	BOD_5 (mg/L)	Ca (mg/L)	COD (mg/L)	Mg (mg/L)	EC (μS/cm @ 25^{o}C)	pH	SS (mg/L)	Colour True (PCU)	Turbidity (NTU)	UV Trans.@ 254 nm (%)
Melton Class A Storage Tank (Recycled Water)										
9/4/15	2		32		1100	7.4	2	16	0.3	67
16/4/15	2	22	30	20	1000	7.4	2	16	0.2	66
23/4/15	2		33		1100	7.2	2	18	0.2	67
30/4/15	8		31		1100	7.5	2	15	0.3	67
7/5/15	2		25		1100	7.6	2	14	0.1	66
14/5/15	2		29		1100	7.4	2	14	0.1	68
Potable Water										
01/5/15		18		21	540	7.4		2	0.3	

Table 4. General water quality data from Surbiton Park Water Recycling Facility and the local reticulation system from Merrimu Reservoir.

	Date	pH	COD	EC	Turbidity	TDS
		a.u.	mg/L	μS/cm	NTU	
Recycled Water Quality						
Class A Outlet	2/01/2013	8.3	18	780	0.4	
Customer Tap	2/01/2013	7.2	16	680	0.6	
Class A Outlet	24/04/2014	7.3	27	1000	0.1	
Customer Tap	24/04/2014	7.1	27	1000	0.1	
Potable Water Quality (Merrimu Treatment Facility)						
Annual 95% Upper confidence limit	2014	7.9			0.2	
Annual Maximum	2014	9.3			0.9	
Annual Minimum	2014	6.8			0.1	
Annual 95% Upper confidence limit	2013	7.8			0.9	270
Annual Maximum	2013	9.1			1.6	360
Annual Minimum	2013	7			0.1	180
Annual 95% Upper confidence limit	2012	7.6			0.3	266
Annual Maximum	2012	8.3			2	320
Annual Minimum	2012	7.1			0.1	230

During the field trial the ratio of recycled water to potable water was varied during a repetitive 45 min cycle that consists of a 30 min of testing together with a 15 min of cleaning and mixing. Figure 10 demonstrates corrected data recorded during a 30 min cycle where mixtures of recycled water of 2.2, 4.3, 6.3, 8.2, 10.1, 11.9, 13.6, 15.2, 16.8, and 18.3% were created.

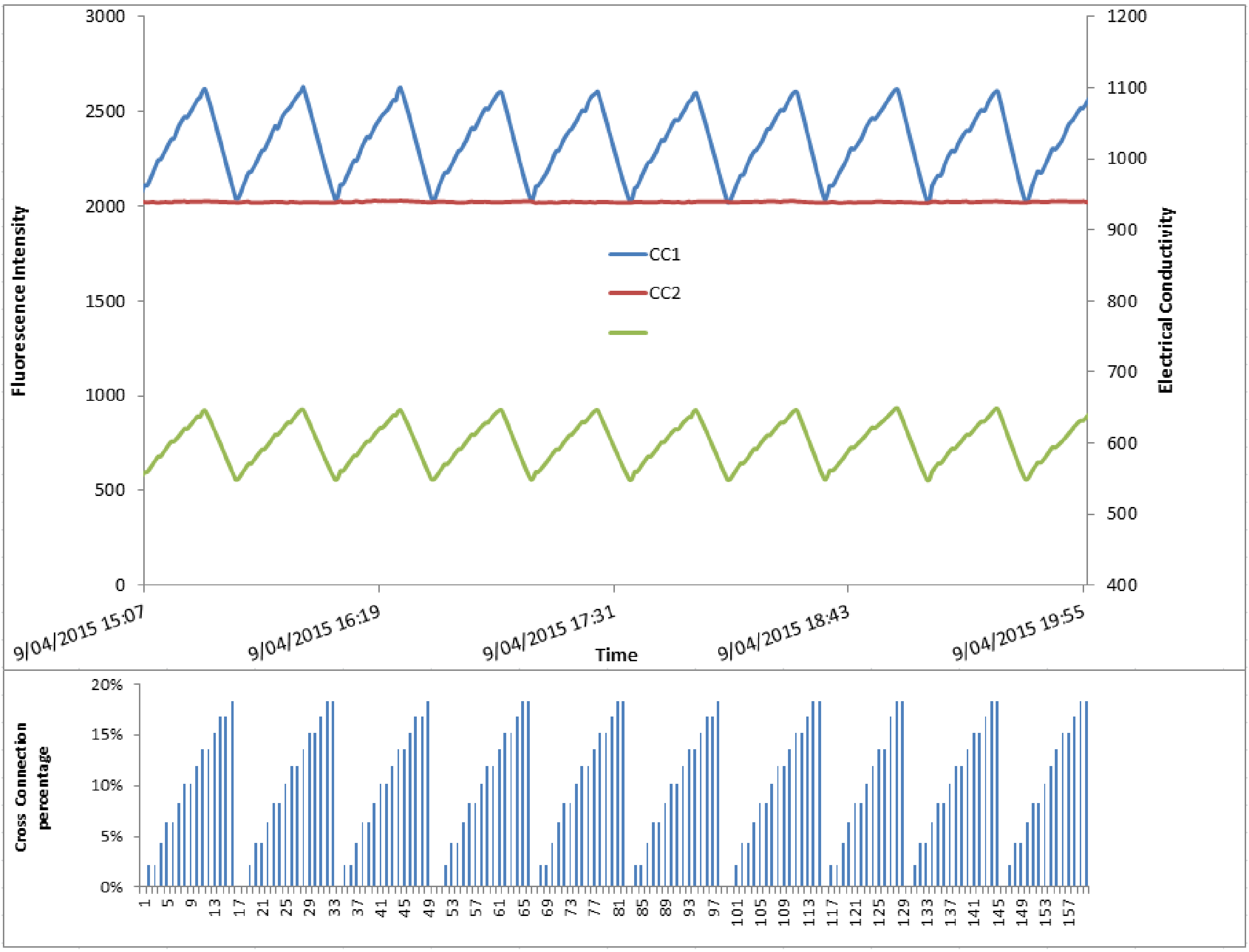


Figure 10. Typical raw data set for mixing cycles.

Figure 11 shows a scatter plot of the of the CC1 fluorescence sensor for different CC1 concentrations for around 8,000 data points, where stability in the signal measured by the sensors was consistent over time for each cross-connection percentage, as indicated by the clustering of the scatterplot.

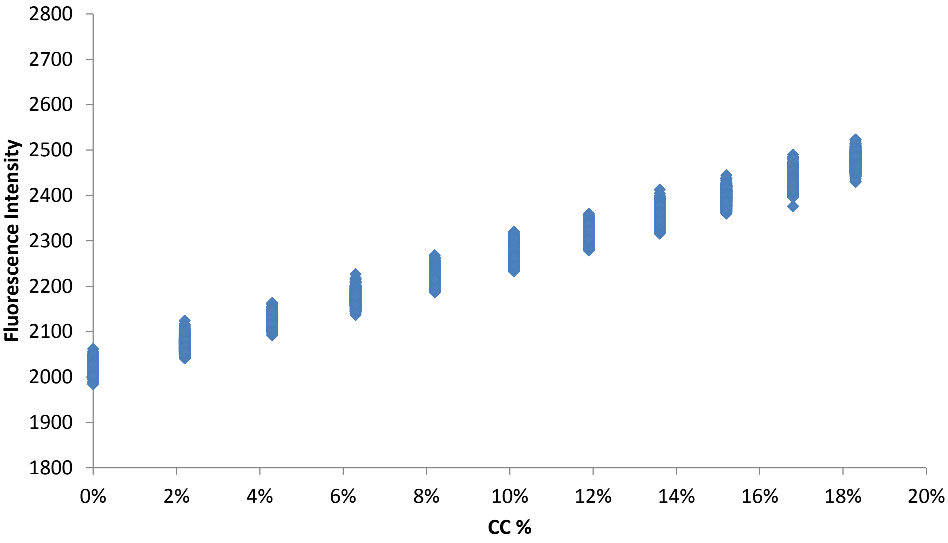


Figure 11. Scatter plot showing the relationship between CC1 and CC2 for potable water over time.

4.2 Cross-connection and paired T-test data

The paired T-test calculation was based on a moving average of the previous three differences in the CC1 and CC2 sensor reading, as per the previous test at Brushy Creek. However, owing to the slow decrease in the background fluorescence for CC1, the data was further corrected to provide an ongoing calibration. In practice, this calibration procedure will not be available for a specific sensor and this will be further discussed below, however for the purpose of demonstrating the best-case scenario, a portion of 10,000 samples, as shown in Figure 12, were used to assess the accuracy of cross-connection detection.

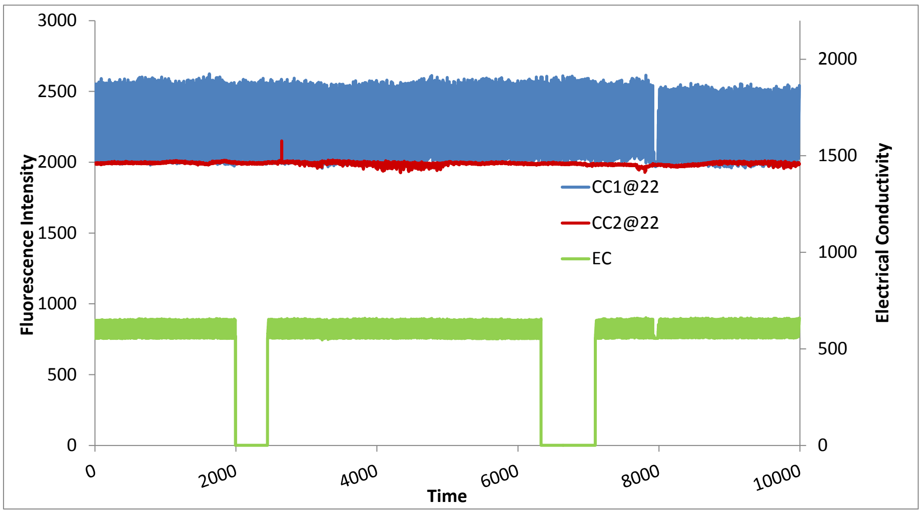


Figure 12. Corrected Surbiton Park CC1 sensor data used for the T-test statistical analyses.

Figure 13 shows a plot of the percentage of cross-connections that were detected for different concentrations of recycled water as a function of the number of sample points acquired. It is seen clearly that for 2% cross-connection, the curve once again increases logarithmically and tends to asymptote to around 90%. For virtually all other scenarios, the cross-connection was virtually always detected, regardless of the number of samples acquired. A full list of results can be found in Table 5. The highlighted cells indicate that more than 99% of cross-connections were detected. This improved ability to detect cross-connections at Surbiton Park, compared to that of Brushy Creek, can be largely attributed to the increased dynamic range of the fluorescence from CC1 sensor data, presumably due to increased organics (colour) in the recycled water.

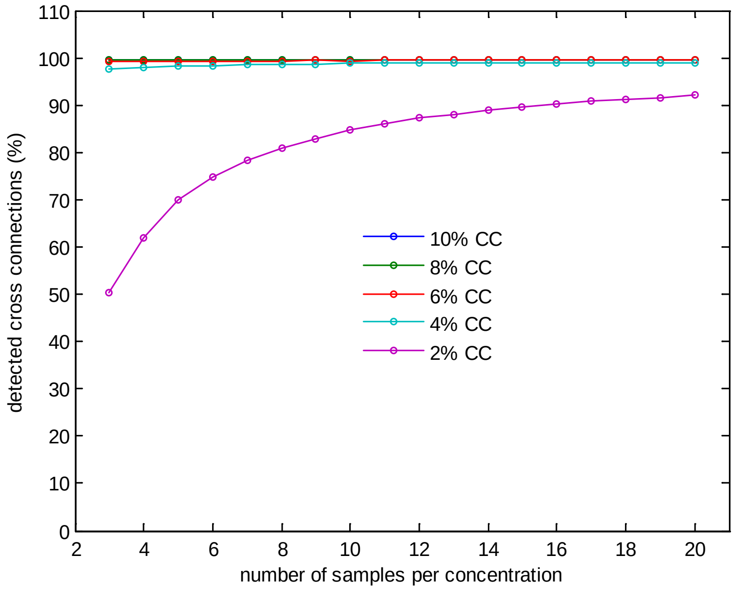
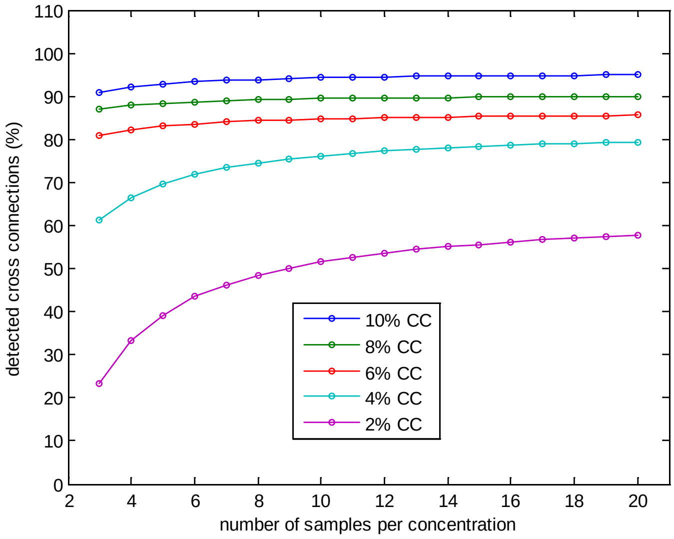


Figure 13. The percentage of cross-connections detected for different concentrations of recycled water plotted against the number of data points collected during each measurement at Surbiton Park.

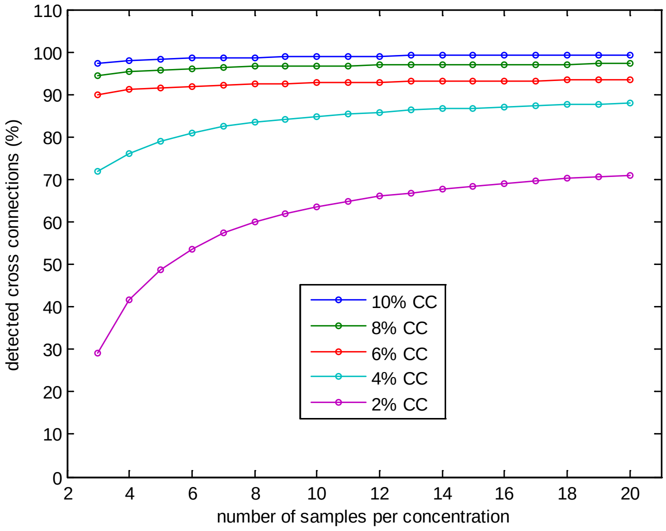
Table 5. Sample data from the CSIRO testing rig used in the T-test calculation at Surbiton Park with an ongoing calibration (coloured cells indicate more than cross-connections were detected over 99% of the time).

Number Samples	CC 2.2%	CC 4.3%	CC 6.3%	CC 8.2%	CC 10.1%	CC 11.9%	CC 13.6%	CC 15.2	CC 16.8%	CC 18.3%
3	50.3	97.5	99.1	99.5	99.5	99.5	99.5	99.6	99.5	99.6
4	62.0	98.0	99.3	99.5	99.5	99.5	99.5	99.7	99.7	99.7
5	70.0	98.3	99.2	99.5	99.5	99.5	99.5	99.6	99.7	99.7
6	74.8	98.3	99.4	99.5	99.6	99.6	99.5	99.7	99.6	99.7
7	78.2	98.6	99.3	99.6	99.7	99.6	99.5	99.6	99.6	99.7
8	80.8	98.6	99.4	99.6	99.7	99.6	99.5	99.7	99.6	99.6
9	83.0	98.7	99.4	99.5	99.7	99.6	99.5	99.7	99.7	99.7
10	84.6	98.8	99.4	99.6	99.6	99.6	99.5	99.7	99.6	99.7
11	86.0	98.8	99.4	99.5	99.6	99.6	99.5	99.8	99.7	99.6
12	87.2	98.8	99.4	99.5	99.6	99.6	99.5	99.8	99.7	99.6
13	88.0	98.8	99.4	99.5	99.6	99.6	99.5	99.8	99.7	99.7
14	88.9	98.9	99.4	99.5	99.6	99.7	99.5	99.8	99.6	99.7
15	89.6	99.0	99.5	99.6	99.7	99.6	99.5	99.8	99.6	99.6
16	90.2	98.9	99.4	99.5	99.6	99.6	99.5	99.7	99.7	99.6
17	90.7	98.9	99.5	99.6	99.7	99.6	99.5	99.7	99.6	99.7
18	91.3	98.9	99.5	99.5	99.6	99.6	99.5	99.8	99.6	99.7
19	91.6	99.0	99.5	99.6	99.6	99.6	99.5	99.8	99.6	99.6
20	92.1	99.0	99.5	99.6	99.7	99.6	99.5	99.8	99.6	99.7

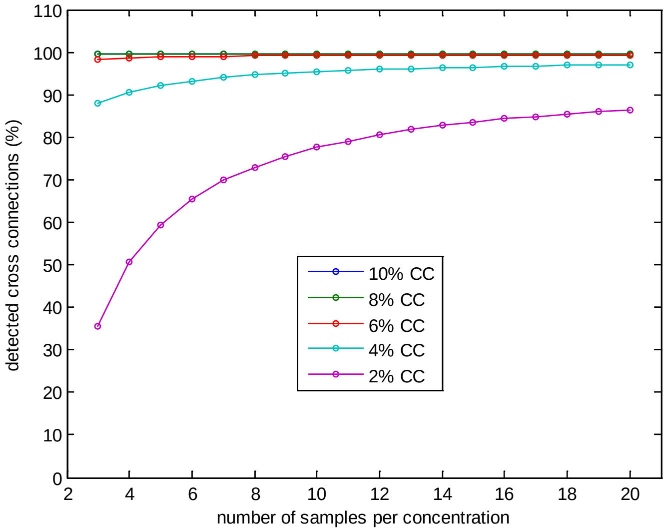
Whilst the assessment above is performed assuming that calibration is not an issue, the following data attempts to outline the periodicity in which calibration should be performed to ensure accuracy. Figure 14(a) provides a summary of the detected cross-connections where the data from the Surbiton Park trial is calibrated every seven days rather than on a continuous basis. In this case, this frequency of calibration is not sufficient to ensure the accurate assessment of a cross-connection of less than 10% recycled water in potable water. Along similar lines, Figure 14 (b and c) demonstrate that a more frequent calibration would be required to enable the successful detection of a cross-connection, which for the data at Surbiton Park, suggests calibration at least every four days as a minimum would be required to achieve a 10% detection. Assuming that degradation of the excitation LED is the main cause of the signal deterioration, this frequency would need to be scaled accordingly to reflect the actual ‘duty time’ of the excitation source. This point is discussed further in subsequent sections.



(a) 7 day



(b) 4 day



(c) 1 day

Figure 14. The percentage of cross-connections detected for different concentrations of recycled water in potable water for Surbiton Park where calibration of CC1 was carried out at 7, 4 and 1 day intervals.

5. Discussion

5.1 Calibration and deterioration of fluorescence signal

As eluded to above, an ongoing calibration of sensors is vital for enabling an accurate assessment of a cross-connection. In conducting a running paired T-test between the readings of any two sensors, the critical factor is the baseline value as it represents the “null-hypothesis” in the T-test (i.e. it responds to the difference between the mean values of two datasets at their respective baseline values).

There are several factors that could affect the baseline value, the main ones being biofouling of optics components and degradation of the sensor component. The calibration is also complicated by the dependence of fluorescence on ongoing temperature and water quality changes. Temperature changes can be accounted for by compensation through its simultaneous measurement, as in the case of the CSIRO developed system and also the Hawk Measurement Systems EC sensor. The degradation of components can in some cases also be accounted for (which is addressed in the following sub-section), yet the change in supplied water can be slightly more challenging.

Throughout the field trials, the portable system was able to observe clear steps and changes in the recorded sensor data for both potable and recycled ‘Class A’ water. Upon noticing this, the water suppliers were contacted and it was found that at the time points in question, the treatment facility had undergone changes. These changes included a change in chlorination regimes in the facility and outages or changes to the purification system. As an aside, it was positive to note that such changes in the water treatment system were spotted directly from the sensor data, but at the same time, such changes result in a step change in either the recycled or potable water, and this change could interfere with an ongoing baseline calibration of the sensors. This is true for any type of sensor that would be installed, not just fluorescence of electrical conductivity.

As a consequence, a method for periodic calibration of the installed sensors is needed in order to ‘reset’ any offset in the ongoing sensitivity of the device such that the ‘null-hypothesis’ for the calculation can be established on precise credentials. One possibility for achieving this is to use the data values themselves as a means for calibration. During the field trials this was relatively straightforward, as a known quantity of each type of water could be dosed to all the sensors, and hence the ‘null-hypothesis’ condition could be reassessed. However achieving this in a real scenario could be quite different. One means of approaching this may be an inbuilt calibration solution that doses a precise amount of a fluorescent compound on demand, or could involve an evacuation of water from the sensor in order to run a periodic baseline check.

From the fluorescence data presented earlier from the Surbiton Park field trial, a slow decay in the baseline value was observed. This decay, although not obvious on a day-to-day basis, could either be attributed to biofouling of the optics or a slow decay in the efficiency of the excitation source. Upon inspection of the optics of CC1 at the completion of the Surbiton Park trial there were no signs of biofouling, nor was there a measured increase in signal following cleaning. Therefore, the slow decay in signal was attributed to a loss in the LED excitation source’s emission intensity over time. This particular excitation source had been used continuously for approximately six month of laboratory experiments and both field trials, hence the following section describes the subtleties of a weakening excitation source.

5.2 Lifetime of the excitation source in the device

Importantly, in a real application scenario, the LED would not be required for continuous 24/7 operation (as was the case here) but rather they would have a much lower duty cycle (i.e. the ratio or time on to time off). For a duty cycle of say 1 minute in 20 minutes (5% duty cycle), the energy consumption drops down to say 75% that it would take the lifetime to over 3 years. This is illustrated graphically in Figure 15.

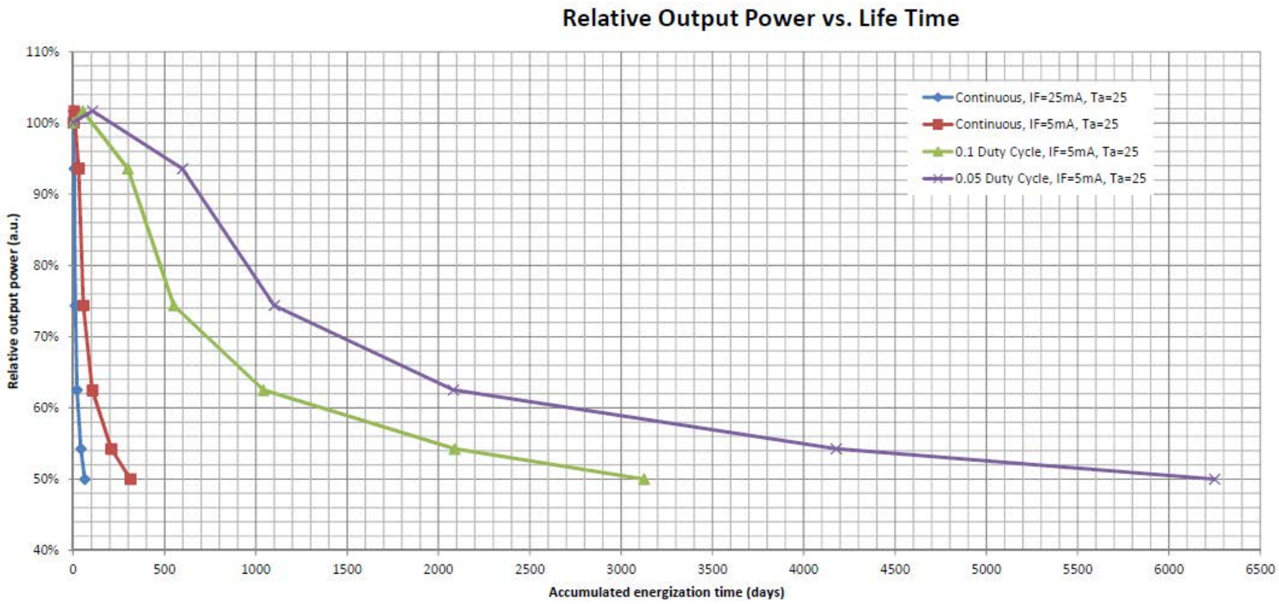


Figure 15. Approximate lifetime of LED for different operating conditions.

The current that flows through the LED can be varied, and thus the power (hence, the output light intensity) depends on the current flowing through it, i.e. the more the current, the brighter the light. During the field and lab trials, the LED excitation sources were operated in a constant current mode, i.e. the electrical current passing through the LED is maintained at a constant level, in a continuous manner 24 hours per day. As per the manufacturers data sheets, the upper level for the current flow is around 25 mA, which results in a high output emission (beyond that required for this project). Decreasing to the current from 25 mA to a more appropriate value of around 5 mA would see the lifetime increase from 63 days to 313 days. Realistically, the full-time utilisation of the LED excitation source in the present work would equate to a 10-year lifetime at 5% duty and as such calibration may be required on an annual or six-monthly basis. On these timeframes, it may be biofouling or other materials degradation issues that may lead to concern, rather than LED degradation.

In order to compensate for the slow burn out and decay in the LED excitation source, which was assumed to be the major contribution to error in the present work, a strategy would be to place a secondary light detector (photodiode) in the vicinity of the excitation source. This detector could monitor the LED's emission and then provide feedback to the driving circuits. Should the LED's output decrease, the feedback detector could initiate a response to appropriately adjust the current levels through the LED to ensure a constant excitation intensity. Ultimately, this would be achieved through the utilisation of an LED excitation source with a built-in photodiode that is capable of assessing its own UV intensity, though this may add to the cost of the device assembly.

5.3 A comparison of fluorescence and EC measurement approaches

Work carried out in parallel to the current project through Hawk Measurement Systems and the Smart Water Fund has demonstrated that EC is able to detect cross-connections down to 2% in selected recycling/potable water systems (Jayaratne *et al*., 2015). When undertaking similar measurements in the current project, the fluorescence prototypes have been demonstrated to achieve similar detection levels, <1% in the laboratory under controlled conditions and <4% in field conditions. Both EC and fluorescence are able to easily distinguish between difference potable water types and can therefore be used to provide information on mixing regimes within potable reticulation systems. The work undertaken within the current project has however highlighted that the key to ensuring these high levels of assessment are maintained is to develop a means for calibration of the sensors, both fluorescence and EC.

The complementary nature of EC and fluorescence sensors is demonstrated in Table 6; where the ratio of sensor outputs in recycled and potable water are presented. At Brushy Creek, there is a significant difference in the EC levels in recycled and potable water (10.5 : 1), as opposed to fluorescence differences of approximately 2.2 : 1. Hence in this situation, using an EC sensor to detect cross-connections will be more accurate than fluorescence sensors. In contrast, the system at Surbiton Park shows that fluorescence sensors are likely to be more accurate due to an increased ratio in signal from recycled water when compared to potable (2.6 : 1); and EC measurements, whilst being higher at Surbiton Park only have a two-fold difference between recycled and potable supplies.

It follows that a combination of sensing principles is expected to be powerful for the construction of a robust cross-connection unit that could work in almost any potable and recycled water type. EC is determined by dissolved salt concentrations whereas fluorescence is dependent almost independently on organic carbon contents within the water. A device that is flexible enough to work in a larger number of water quality types would offer many benefits in allowing a water retailer to confidently change treatment, blend or supplement potable water. A dual detection would also enable a more robust detection whereby a cross-connection alert from one sensing element could be either supported or challenged by the second independent sensing element.

Table 6. Summary of the ratio of EC and fluorescence measurements for two recycled water schemes where water quality characteristics determine the sensitivity of the two sensing approaches.

Recycled Water Facility	EC ratio (Recycled : Potable)	Fluorescence ratio (Recycled : Potable)
Brushy Creek	10.5	2.2
Surbiton Park	2.0	2.6

In comparing the two sensing elements, one key differentiator is the power consumption levels for the two techniques. EC can typically be achieved using nano or microampere currents whereas the excitation of the UV LED (5 mA), whilst not excessively high, would benefit from access to mains power or may require more costly batteries. At the outset of the project, it was expected that such a cross-connections device may be located under the kitchen sink, in which there is typically easy access to mains power.

5.4 Application

During the project, various discussions were had with industry representatives as to how the developed sensing technology may find application within the water sector. Considerable detail was collected and reported in the Milestone 4 report (Trinchi *et al*., 2014), the major points are summarised below.

- Water service providers (WSP) and water regulators from NSW, SA and VIC were consulted. The potential for cross-connections to occur between potable and recycled water remain a concern for the water industry.
- Public perception and public confidence in water utilities to manage and provide water that is safe and fit for purpose can be severely affected if cross-connections are detected. This would undoubtedly become an even bigger issue if any illnesses could be attributed to the consumption of recycled water.
- Water utilities continue to invest considerable money and effort into ensuring that such events do not occur. With an increasing number of households being connected to recycled water schemes each year, the ability to monitor all these with labour-intensive inspections and reliance upon laboratory analyses is increasingly difficult.
- Water utilities currently focus on checking the plumbing connections of new dwellings (connected to a recycled water scheme) and an ongoing inspection program that inspects the plumbing of 5-20% of properties connected to recycled water annually. In this, there is a need to ensure that homeowners are present in order for the inspection to occur. There is a significant inefficiency in labour due to homeowner absence or mis-timed visitation by auditors. Whilst inspections methods are currently a workable solution, with the anticipated increases in numbers of customers with recycled water connections over the next decade, auditing targets may become difficult to achieve. Inline sensors could be used in the demonstration of safe operation in both new infrastructure and ongoing operation.

- The water industry continues to seek new and emerging technologies to provide a solution to the ongoing potential issues of cross-connections.
- Whilst an in-house sensor will be able to detect cross-connections, concerns have been raised on several occasions (by water utilities and technology manufacturers) around difficulties interfacing with households, monitoring and maintenance issues and the potential for customers to turn the sensor off for various reasons.
- The advantage of having a device akin to a “fuse box” implemented within a house is that this may ensure correct water use of all plumbing such as potable, recycled water, rainwater and grey water.
- One of the key challenges in developing a new technology is the cost. They must be ‘affordable’.
- Some of the difficulties interfacing with households would remain a challenge regardless of the cost and ability of the sensor developed. The issues related to sensor maintenance are not dissimilar to other household safety devices (e.g. smoke alarms require bi-annual battery replacement and working check, safety switches that keep tripping may require an electrician to assess the problem). If the sensors are robust and reliable and have undergone significant field testing to thoroughly understand their ability and limitations, then a pre-determined maintenance schedule with few deviations should be possible.
- It is expected that initially any monitoring of the device would be done by the water utility or other responsible authority rather than the homeowner.
- Some WSPs saw increasing difficulty in using these units as an in-house/under sink sensor. For instance, Yarra Valley Water (YVW) anticipates that 90,000 customers will have recycled water connections by 2020, and it is expected that there would be considerable maintenance issues if rolled out within individual households.
- Therefore, it may be beneficial to consider a sensor suitable for installation at the water meter. In doing this, the technology could be kept within the water utility’s jurisdiction.
- In further developing the technology it will be important to keep a regular dialogue with water health regulators as there is a possible movement to implement a new practice for a certified plumber to carry out inspections on all properties supplied with recycled water when there is a change in ownership or tenancy at a property (i.e. through section 32 or similar).
- Water regulators suggested that existing systems do have a low failure rate, and it was suggested that a cost-benefit analysis would be required before inline sensing units would be further trialled for commercial uptake.
- It was suggested that this analysis should explore their deployment initially for larger buildings and facilities such as high-rise unit complexes and hospitals, public facilities etc.
- There are likely to be opportunities to assist in the privatisation of recycled water schemes and reporting of their operation. It would seem to be worthwhile exploring this space as there may be an increased need to ensure safety and provide additional evidence of auditing to governing bodies.

6. Conclusions and Further Work

This project has delivered a ‘low-cost’ fluorescence-based sensor that can measure the mixing of relatively clean waters such as potable and recycled water.

Throughout this project, there has been a focus on the development of a universal cross-connections device that utilises changes in fluorescence and EC properties of recycled water parameters for ultimate use within consumer premises. For instance, the resultant device could compare water quality between the point of supply (e.g. smart water meter) and point of use (e.g. kitchen sink), with the intention of communicating the finding and thus detect cross-connections.

Prior to conducting our laboratory tests, sensor development, and statistical analyses, the CSIRO team initially used the statistical results published in a 2010 paper by Hambly of the UNSW to construct a matrix of water mixtures as a test of the validity of our proposed methodology. According to Hambly’s results, where recycled water and drinking water grab samples were collected weekly from the dual distribution systems at a domestic property in Rouse Hill and whose fluorescence was monitored over 12 weeks, it was reported that fluorescence measurements could detect 45% contamination of recycled water in drinking water with a signal-to-noise ratio > 3 for more than 95% of individual random sample pairs. The authors also stated that greater sensitivity could be obtained by averaging numerous samples. It followed that the application of a T-test to the data, demonstrating that 10% contamination with recycled water could be readily detected 99% of the time provided that 5 samples points were used in the calculation, and that 10% contamination with recycled water was detected 100% of the time when using 10 sample points.

Subsequently, the work within this project set about characterising various potable and recycled ‘Class A’ recycled waters sourced from different suppliers. The ability of spectroscopic methods to distinguish between water quality types was evaluated. It was found that UV fluorescence, as opposed to UV absorbance, was considerably more sensitive in being able to distinguish between potable and recycled water.

The sensor prototypes were developed with the view of being affordable in-home devices, as opposed to expensive, analytical instruments. The total cost of the components for the prototype device were kept to under AU$200, and with production scaling would be expected to the further reduced in cost. The physical assembly of fluorescence sensor prototypes involved appropriate selection of UV LED excitation, filtering, microprocessor integration, signal amplification and conditioning, and temperature control.

The sensitivity of the fluorescence sensor prototypes was demonstrated in controlled laboratory tests, showing that recycled water contamination less than 1% could be detected. The practical limits of the sensor were subsequently explored in two field trials. From the data acquired during both field trials (refer to Table 2 and Table 5), it is seen that for recycled water contamination ≥ 6.3 %, over 99% of all cross-connections were detected using the paired T-test calculation. The data analysis revealed that the number of sampling points does have an impact on the valuation of the statistical outcomes, particularly for differentiating between waters of different qualities. Consequently, ensuring that a minimum of 10 data sampling points are including in statistical calculations increases the overall efficacy for determining cross-connections, particularly at lower levels of recycled water contaminations.

As hypothesised prior to the outset of the project, EC and fluorescence are complementary detecting cross-connections, as demonstrated by the varying water quality parameters of the potable water from the two different field trial sites. That is, EC was more effective at Brushy Creek whereas fluorescence was more effective at Surbiton Park. It follows that molecules and dissolved organic matter that alter the conductivity and EC will vary in their concentration across different systems, and therefore independent measures are potentially advantageous.

The need to provide ongoing calibration of cross-connection devices (both EC and fluorescence) remains unclear at this stage and will require additional evaluation. This is not to say that either EC or fluorescence have significant issues regarding their drifting of calibration, however, future work is warranted to explore ways to achieve calibration whilst in service. On a positive note, the fluorescence sensors did not experience any catastrophic failures or experience problems associated with biofouling. However, following the use of a fluorescence sensor for over six months of continuous operation, its excitation intensity was found to decrease slowly. In practical scenarios, the sensor would not operate continuously and measures can be input into the device to ensure constant excitation intensity (through a photodiode feedback loop). There are also various means to provide an ongoing calibration to the device if required, including a metered injection of a fluorescent standard or via evaluation of the sensor to provide a regular operational baseline.

Aside from calibration uncertainties, the fluorescence prototype has been demonstrated to provide an excellence means of differentiating water quality over long periods of time at low cost. Commercialisation options for the fluorescence sensor are being evaluated by AWRCE with the support of CSIRO.

References

M. Best M, A. Trinchi, TH Muster (2015). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 5 report. CSIRO Land and Water Flagship, Australia.

M. Best, T.H. Muster, A. Trinchi, M. Toifl, S. Gould, R.O'Halloran. (2015). An inline sensor to detect cross-connections between potable and recycled water systems in real time. Proceedings of OzWater 15, Adelaide, May 2015.

A.C. Hambly, R.K. Henderson, M.V. Storey, A. Baker, R.M. Stuetz, S.J. Khan (2010). Fluorescence monitoring at a recycled water treatment plant and associated dual distribution systems - Implications for cross-connection detection. *Water Research* **44**, pp 5323-5333.

A.C. Hambly (2013). Fluorescence as a portable tool for cross-connection detection within dual reticulation systems. PhD Thesis, University of New South Wales.

K. Murphy, K.D. Butler, R.G.M. Spencer, C.A. Stedmon, J.R. Boehme, G.R. Aiken (2010). Measurement of Dissolved Organic Matter Fluorescence in Aquatic Environments: An Interlaboratory Comparison, *Environmental Science and Technology* **44** (2010), pp. 9405-9412.

J. van den Broeke, G. Langergraber and A. Weingartner (2006). On-line and in-situ UV/vis spectroscopy for multi-parameter measurements: a brief review. *Spectroscopyeurope.com* **18**(4).

G. Gruber, J. Bertrand-Krajewski, J. De beneditis, M. Hochedlinger and W. Lettl (2005). Practical aspects, experiences and strategies by using UV/VIS sensors for long term sewer monitoring. *10th International Conference on Urban Drainage*, Copenhapgen/Denmark, 21-26 August.

A. Jayaratne, L. Richards, R. Vivekanantham, J.Yeung, T. Muster, M. Toifl (2015). Real time monitoring for cross-connection detection. Proceedings of OzWater 15, Adelaide, May 2015.

R. O'Halloran and M. Toifl. (2008). Detection of cross-connection to potable water distribution systems - Stage 1: Development of contamination signatures. Water for a Healthy Country Flagship Report for CRC for Water Quality and Treatment. November 2008.

R. O'Halloran, M. Toifl, R. Taylor and M. Winnel (2010). Detection of cross-connection to potable water systems – Stage 2: Field trials of recommended detection parameters. *Water for a Healthy Country Flagship report.*

R. O'Halloran (2012). Installation of prototype conductivity sensors at Brushy Creek – Technical Report. CSIRO Australia, November 2012.

R. O'Halloran, S. Gould (2013). An inline sensor to detect cross-connections between potable and recycled water systems in real-time. Milestone 2a: demonstration of lower detection limits. *Water for a Healthy Country Flagship*. July.

M. Pouet, F. Theraulaz, V. Mesnage and O. Thomas (2007). *Natural Water*. In UV-visible Spectrophotometry of water and wastewater. Eds, O.Thomas and C. Burgess.

J. Radcliffe (2010). Evolution of water recycling in Australia. *Water Science and Technology*, 62(4), 792-802.

O. Thomas, F. Teraulaz, S. Vaillant and M. Pouet (2007). *Urban wastewater*. In UV-visible Spectrophotometry of water and wastewater. Eds, O.Thomas and C. Burgess.

J. Weishaar, G. Aiken, B. Bergamaschi, M. Fram, R. Fujii and K. Mopper (2003). Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon. *Environ. Sci. Technol.* **37**, pp 4702-4708.

R.J. O'Halloran and S. Gould (2013). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 2a report. CSIRO Water for a Healthy Country Flagship, Australia.

A. Trinchi, M. Toifl, S. Gould, M. Best, R. O'Halloran, T. Muster (2013). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 3 report. CSIRO Water for a Healthy Country Flagship, Australia.

A. Trinchi, M.Best, S. Gould, M. Toifl, T. Muster (2014). An inline sensor to detect cross-connections between potable and recycled water systems in real-time: AWRCOE Milestone 4 report. CSIRO Water for a Healthy Country Flagship, Australia.