

## A reliable sewage quality abnormal event monitoring system



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### ABSTRACT

With closing water loop through purified recycled water, wastewater becomes a part of source water, requiring reliable wastewater quality monitoring system (WQMS) to manage wastewater source and mitigate potential health risks. However, the development of reliable WQMS is fatally constrained by severe contamination and biofouling of sensors due to the hostile analytical environment of wastewaters, especially raw sewages, that challenges the limit of existing sensing technologies. In this work, we report a technological solution to enable the development of WQMS for real-time abnormal event detection with high reliability and practicality. A vectored high flow hydrodynamic self-cleaning approach and a dual-sensor self-diagnostic concept are adopted for WQMS to effectively encounter vital sensor failing issues caused by contamination and biofouling and ensure the integrity of sensing data. The performance of the WQMS has been evaluated over a 3-year trial period at different sewage catchment sites across three Australian states. It has demonstrated that the developed WQMS is capable of continuously operating in raw sewage for a prolonged period up to 24 months without maintenance and failure, signifying the high reliability and practicality. The demonstrated WQMS capability to reliably acquire real-time wastewater quality information leaps forward the development of effective wastewater source management system. The reported self-cleaning and self-diagnostic concepts should be applicable to other online water quality monitoring systems, opening a new way to encounter the common reliability and stability issues caused by sensor contamination and biofouling.

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### 1. Introduction

In order to ensure the security and sustainability of water supply, alternative water sources such as storm water, desalinated seawater and recycled wastewater have been vigorously exploited (Page et al., 2015; Radcliffe, 2015). In this regard, purified recycled

water (PRW) has been widely recognized as a viable alternative water source (Radcliffe, 2015), especially for large cities, leading to significant investments in PRW infrastructures by Australia, Singapore, USA and European countries (Raso, 2013; USEPA, 2005). However, the introduction of PRW, both potable and non-potable, dramatically changes the traditional view of wastewater quality control as what was once a waste stream is now a part of source water, giving a rise to potential water quality risks from possible contaminants in PRW (Fielding and Roiko, 2014; Onyango et al., 2015; USEPA, 2005). Consequently, to adopt PRW as a servicing option, the wastewater, PRW and drinking water must be cohesively managed to ensure the risk to public health is minimized (Onyango et al., 2015). To this end, the effective wastewater source

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management is crucial to mitigate potential risks at the earliest stage. There is, however, a major shortfall in wastewater quality monitoring techniques to address such needs (Wang et al., 2015). The current wastewater monitoring regime typically relies on taking discrete samples, which lacks the space and time resolutions to adequately describe wastewater quality, capture illegal discharges or detect industry spill events (Wang et al., 2015). It is therefore a necessity to develop a new wastewater management system (WMS) capable of alerting operators in real-time of abnormal wastewater quality changes that could potentially impact downstream operations and PRW quality, enabling rapid response capabilities to mitigate risks in an operationally relevant timeframe. This can be achieved by incorporating an effective abnormal event detection algorithm into a wastewater quality monitoring system (WQMS) (Loureiro et al., 2015; Perelman et al., 2012). To date, although numerous event detection algorithms have been developed (Arad et al., 2011; Liu et al., 2015; Loureiro et al., 2015; Perelman et al., 2012), the development of WMS has been hindered by the lack of robust WQMS capable of reliably operating over a prolonged period without the need for maintenance. This can be attributed to the highly hostile analytical environment of wastewaters, especially raw sewages, that challenges the limit of existing sensing technologies.

In practice, the reliability of WQMS has been fatally constrained by contamination and biofouling of sensors (Flemming et al., 1998; Nguyen et al., 2012). As a result, only a limited number of sensors have been found to meet the reliability requirements of WQMS (Liu et al., 2014; Rieger et al., 2005). A USA Water Environment Research Foundation study compared over 50 commercially available online sensors and revealed that only one met specified wastewater quality monitoring criteria (Rakesh Bahadur and Samuels, 2009). The results obtained from our extensive field trial of commercial sensors during the Urban Water Security Research Alliance project (Huijun Zhao et al., 2012; UWSRA, 2012) suggested that only temperature and few purposely designed pH, conductivity, redox potential, dissolved oxygen and turbidity sensors could potentially be used for WQMS. Although these surrogate sensors are incapable of directly determining specific contaminants, the combined water quality data from multiple surrogate sensors could be collectively used to indicate the general characteristics of a wastewater matrix (Cook et al., 2005; Hall et al., 2007). In fact, it has been reported that the changes in drinking water characteristics causing by different containments (e.g. secondary effluent from a wastewater treatment plant, pesticide, herbicide, drugs and heavy metals) can be indicated by multiple surrogate sensors (Hall et al., 2007).

In order to make a WQMS reliably functioning over a prolonged period, the severe contamination and biofouling of sensors under operational conditions must be prevented (Flemming et al., 1998; Lynggaard-Jensen, 1999; Weerasekara et al., 2014). To tackle such vital issues, numerous strategies such as periodic calibration, chemical cleaning, mechanical wiping and the use of protective membranes, have been proposed and tested (Campisano et al., 2013; Lynggaard-Jensen, 1999). The results suggested that these approaches not only increase the system complexity and costs, disrupt the continuous monitoring and consume large quantities of chemical reagents, but also make the system requiring frequent maintenance (Byrne and Diamond, 2006; Janasek et al., 2006). More importantly, these approaches are incapable of *in situ*, real-time preventing the biofilm formation (Campisano et al., 2013). As a result, barely any available online WQMS can reliably and continuously operate over a period of a month or even a week without calibration/maintenance (Vanrolleghem and Lee, 2003).

An ability to confirm whether a sensor is functioning and if so, the acquired sensor response is truly responding to the targeted water quality parameter, is a basic quality assurance requirement of

any analytical system. For laboratory analyses, such quality assurance requirements can be readily provided by a classic analytical calibration procedure under artificially manipulated measurement conditions. However, for a real-time online WQMS, performing classic analytical calibration under artificially manipulated measurement conditions in real-time become impractical (Bourgeois et al., 2001). This adding to other uncertainties occurred under operational conditions make difficult to confirm whether a WQMS sensor is correctly functioning. Although online and offline classic quantitative analytical calibration approaches have been almost exclusively used to address the issue, they are incapable of real-time validating the acquired data and detecting sensor fault. Recently, Vanrolleghem and co-workers reported a new approach that utilizes Principle Component Analysis combined with Q-Statistic Test to validate water quality data collected from two identical sensors for fault detection (Alferes et al., 2013a, 2012, 2013b; Alferes and Vanrolleghem, 2014). Such an innovative approach opens a new means to achieve real-time water quality data validation and fault detection.

In Australia, a millennium drought during 2006–2010 led to storage shortages of all major dams in Southeast Queensland being below the absolute alarm levels, seriously threatening the sustainable water supply to the region. To secure the water supply, the Queensland Government built a world largest PRW system as a part of the Southeast Queensland Water Grid. An Urban Water Security Research Alliance (UWSRA, 2012) was established to ensure the integrity of PRW system and serve the needs of water utilities, regulatory bodies and governmental agencies. As a part of the UWSRA, we developed a real-time, online Wastewater Quality Information Acquisition System, which was further developed into a WMS (Fig. S1) with the support of Australia Research Council and major Australian water utilities. Other than real-time wastewater quality information acquisition, the developed WMS is also capable of real-time detecting abnormal wastewater quality changing events and informing operators the potential impact of the detected events to their downstream operation and PRW system. This work reports a WQMS that is purposely developed as the sensing platform of WMS for abnormal event detection. Other aspects of the system, such as development of real-time event detection algorithms based on collective input of real-time data of multiple sensors, Ontology (OntoWQ, Ontology for Water Quality) based event impact prediction and effectiveness of WMS when apply to different sewage catchments, will be sequentially reported in future communications. The reported WQMS consists of four-pairs of identical temperature (Temp), conductivity (EC), turbidity (TB) and pH sensors. The sensing platform design and sensor selection are revealed in detail. The design and fabrication of suitable EC and TB sensors are also discussed because no commercially available EC and TB sensors could meet the requirements of WQMS. Importantly, a vectored high flow hydrodynamic approach and a dual-sensor design are implemented to achieve self-cleaning and self-diagnostic functions, enabling WQMS to work reliably in wastewater environment. The performance of WQMS has been evaluated over a 3-year trial period at different sewage catchment sites in Australian states of New South Wales, Victoria, Queensland and Western Australia. The obtained results demonstrated that the developed WQMS can reliably and continuously acquire real-time wastewater quality data over a period of 6–24 months without the need for calibration and maintenance.

## 2. Experimental section

### 2.1. WQMS assembly

The WQMS system consists of dual-sensor wall-jet and U-

shaped flow cells, an on-board computer and a telecommunication modem as shown in Fig. 1. A pair of Temp, EC and TB sensors was respectively incorporated into the wall-jet cell, and a pair of pH sensors was built into the specially designed U-shape cell. Table 1 summarizes the specifications of adopted sensors.

The control electronics of all sensors are directly mounted onto the back of the wall-jet cell and all output signals are digitized by a built-in A/D convertor. The on-board computer is connected to the control electronics and modem for real-time data acquisition, abnormal event detection, communication, reporting and operational controls. The output sensing signals of each sensor are acquired every 10 s and averaged over 1 min period to give 1 data point per min.

## 2.2. Calibration, installation and validation

Before assembling into the flow cells, all sensors were calibrated via standard procedures. The assembled WQMS sensors were calibrated in laboratory against a TPS multi-sensor unit (TPS Pty Ltd, Australia) using a sampling tank containing 0.5 m<sup>3</sup> of synthetic wastewater. The calibration was conducted by circulating the synthetic wastewater through the WQMS sensing unit with a submersible pump (EHEIM compact<sup>+</sup> 3000), while Temp, pH, EC and TB sensors of the TPS unit were immersed in the sampling tank. Suitable amounts of hot/cold tap water, acid/base, salt and milk were added into the sampling tank to impose the changes in Temp, pH, EC and TB. The obtained data by the WQMS sensors were compared with the data acquired by the corresponding TPS sensors to calibrate and confirm the WQMS sensors are functioning correctly. For protective purpose, the sensing unit together with on-board computer and modem were onsite installed into a rain-proof and heat insulated enclosure with a cooling fan. The installed system was fixed above ground on a base or wall near the sampling well (Fig. S2). Before operation, the WQMS sensing unit was onsite calibrated using a similar procedure as that for laboratory calibration. However, a larger sampling tank containing 2.5 m<sup>3</sup> of sewage from the site was used (Fig. S3). After onsite calibration, the WQMS is connected to the sample delivery pump (ABS piranha submersible pump, model 08-110, ABS Pty Ltd, Ireland) ready for operation. It should be mentioned that for quality assurance purpose, during all trials, samples are taken by a predetermined frequency (by a system controlled auto-sampler) and onsite analyzed by a TPS multi-sensing unit.

## 3. Results and discussion

### 3.1. Sensors

The wastewaters, especially raw sewages, are highly diversified in compositions, representing the most complex and hostile sample matrixes. This makes the vast majority of well-performing sensors unsatisfactory for wastewater monitoring applications (Rakesh

Bahadur and Samuels, 2009). A suitable sensor for WQMS needs to meet basic criteria: (i) must be able to physically tolerate the hostile wastewater conditions for a prolonged period; (ii) can rapidly and continuously respond to one or more physical/chemical wastewater parameters; (iii) should possess a configuration favorable for minimizing blockage, surface contamination and biofouling. Ideally, a sensor should also have a self-contained embodiment, consume no reagent and require no on-going calibration. Though employing compound specific sensors to confirmatively determine targeted analytes are highly desirable, however, in reality, it is very difficult to find such sensors that could meet the above criteria (Liu et al., 2014). This is because compound specific sensors are almost exclusively designed for laboratory-based analyses under strictly-defined measurement conditions (Rakesh Bahadur and Samuels, 2009). They work well for laboratory analyses as sample manipulation is allowed, but become problematic for field-based online applications where circumstances do not allow artificial sample manipulation before assay. As such, the surrogate type of sensors becomes the only viable option for WQMS.

Extensive investigations were therefore conducted to trial various commercially available surrogate sensors against the above sensor selection criteria to evaluate their suitability for WQMS. The trial results suggested that certain types of Temp, pH, EC, TB, dissolved oxygen (DO) and redox potential (ORP) can meet the basic sensor selection criteria and could be potentially used for WQMS. These surrogate sensors were therefore incorporated into our 1st generation WQMS for trial. The 1st generation WQMS was subjected to a year-long trial at selected wastewater treatment plants. With real-time data input from the above 6 surrogate sensors, the Event Detection Algorithms (EDA) developed by us detected 5 major abnormal events over the trial period. An investigation was then carried out to simplify the hardware system, further improving the reliability and durability. The data recorded from different sensors during the trial were artificially fed into the EDA in different combinations to evaluate the effect of input data of different sensors on event detection. In short, our investigation revealed that when the input data from the 4 surrogate sensors (pH, Temp, EC and TB) without input data from DO and ORP, the 5 abnormal events detected by the EDA were identical to those detected when the input data from the 6 surrogate sensors were used. This means that for event detection purpose, a WQMS with the 4 surrogate sensors (pH, Temp, EC and TB) is as effective as that with the 6 surrogate sensors. Our investigations also suggested that ORP contributes little to event detection due to its insufficient sensitivity and DO is useful for overflow event detection but such type of events are also strongly associated with conductivity changes, which can be picked up by EC sensor. In addition, we found during the trial that the DO probe needs to be replaced every 3–6 months due to the failure of the gas permeable membrane under high flow rate conditions. On such bases, DO and ORP sensors were made redundant in the new generation WQMS. Subsequent

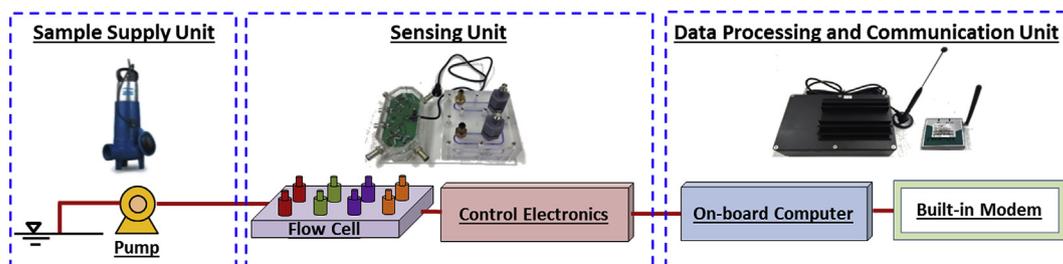


Fig. 1. Schematic illustration of WQMS major components.

**Table 1**  
Specifications of WQMS sensors.

Sensor	Model	Description	Range
Temp	LM335A	Thermocouple sensor	−40 °C to +100 °C
pH	660CD	Gel-filled sensor purchased from Sensorex	0 to 14
EC	Homemade	Four stainless-steel probes	0 to 40,000 $\mu\text{S cm}^{-1}$
TB	Homemade	Consists of a high power infrared emitter (850 nm) LED (Osram SFH 4550) light source and two photodiode detectors (Osram SFH 203 FA) (one located at the opposite of the light input and the other at 90° to detect absorbed and scattered light)	20 to 4000 NTU

trials at different sites confirmed that for event detection purpose, the simplified WQMS (Fig. 1) with the 4 surrogate sensors are as effective as the WQMS with the 6 surrogate sensors but having additional advantages of the reduced cost and improved reliability.

A LM335A thermocouple temperature sensor (Digi-Key Electronics) was chosen because of its advantageous features of suitable linear range (−40–100 °C), small size (4.90 × 3.91 mm) and anti-corrosion stainless steel sensor body. A pH sensor (Model 660CD, Sensorex) was selected due to its fast response (<1 s), excellent pressure stability (highly tolerant to flow rate changes), large area of porous frit (better tolerance to contamination and biofouling) and flat-shaped sensing surface (favorable for minimizing blockage and installation into flow cell).

However, none of the trialed commercial EC and TB sensors could be directly used for WQMS, mainly because: (i) their sizes and geometries make them difficult to be incorporated into a compacted flow cell with minimized blockage, contamination and biofouling; (ii) their sensing responses are unstable and unreliable under high flow rate conditions. Suitable EC and TB sensors were therefore purposely designed and fabricated to meet the needs of WQMS.

Fig. 2a illustrates the configuration of a four-electrode EC sensor. The four stainless steel rods (1.5 mm in diameter) are seamlessly incorporated into a wall-jet flow cell as the sensing electrodes. Although this is probably the simplest configured EC sensor and cheapest to build, it possesses a minimal flow resistance, highly favorable for minimizing blockage, contamination and biofouling as proved by the field-trials (see later for details). The analytical performance of the constructed EC sensor was examined against a commercial EC probe (Amber Science Model 3084). A plot of the conductivity values measured by our EC sensor against those measured by a commercial EC probe gives a linear relationship within a conductivity range of 50–8000  $\mu\text{S cm}^{-1}$  (Fig. S4a). A near unity slope value can be obtained, implying that for a given sample, the measured conductivities by the two sensors are essentially the same. This simple configured EC sensor has never failed over three years of trials at various sewage catchment sites, confirming its superior reliability and applicability for sewage monitoring applications.

Fig. 2b shows the design of the dual-beam TB sensor, consisting of a near infrared LED light source (Osram SFH 4550) and two photodiode detectors (Osram SFH 203 FA). One photodiode is positioned vertically against the LED light beam to detect the scattered light intensity while the other is located opposite to the LED beam to measure the light absorption as reference for light source intensity correction. This dual-beam design can effectively reduce the errors caused by light intensity fluctuation and matrix absorption, critically important for accurate TB measurement of wastewaters. Importantly, the component of the TB sensor can be directly embedded into a wall-jet flow cell with a minimal flow resistance to avoid blockage, contamination and biofouling. The constructed TB sensor was compared against commercial TB analyzer (Hach Model 2100P) using standard ratio optical TB calibration solutions (Labtek Pty Ltd). A linear relationship (up to 4000

NTU) with an almost unity slope value can be obtained when the determined TB values of our TB sensor are plotted against those determined by the commercial TB analyzer, suggesting that for a given sample, the measured TB values by the two sensors are essentially the same (Fig. S4b). The superior performance of this simple TB sensor for sewage monitoring has been proven by over three years of trials at various sewage catchment sites.

Fig. 2c shows the photograph of the flow cell with four pairs of embedded sensors. It should note that the control electronic circuit board of all sensors is directly mounted onto the back of the wall-jet flow cell and fully sealed to reduce electromagnetic interferences on sensor signal output and prevent the electronics from the highly corrosive atmosphere of sewage environment.

### 3.2. Self-cleaning

It is well known that without effective protection/cleaning, severe sensor contamination and biofouling will unavoidably occur when a sensor is in direct contact with wastewaters, especially raw wastewaters, due to the presence of high concentration contaminants, rich nutrients and a variety of bacteria (Nguyen et al., 2012; Weerasekara et al., 2014). This will lead to a rapidly deteriorated sensor performance and eventually sensor failure (Lynggaard-Jensen, 1999). Therefore, an effective sensor protection/cleaning regime must be in place to enable long-term reliable operation of a WQMS. Despite numerous attempts in the past (Campisano et al., 2013; Lynggaard-Jensen, 1999), such vital issues remain as a great challenge, hindering the development of practically applicable WQMS. It has been envisaged that for any continuous real-time online WQMS, an ideal protection/cleaning method needs to be not only capable of effectively preventing sensor contamination and biofouling, but also nondestructive to the continuous data acquisition and system operation. In this work, we propose to achieve such objectives via a vectored high flow hydrodynamic self-cleaning approach.

The presence of solid particles in wastewaters is common and can be innovatively utilized for real-time sensor cleaning to prevent sensors from contamination and biofouling. This is based on that when solid particles are empowered with high velocity and right angles to lash onto sensor surface, their bombardment effects should be more than sufficient to keep sensor surface clean. It is to note that the cleaning power of solid particles is much greater than shearing forces of liquid with the same speed. All existing online monitoring systems are almost exclusively employing flow cells with small cross-section flow channel design (easy blockage) and peristaltic pumps for sample delivery with typical flow rates of few milliliters per minutes (insufficient for sensor cleaning purpose). In order to minimize the blockage and provide solid particles with sufficient cleaning power, the flow cell used in this work is designed with large size major-arc-shape cross-section flow channel ( $r = 7 \text{ mm}$ ;  $\theta = 118^\circ$ ) and an industrial pump is employed to deliver high flow rates of 40–60  $\text{L min}^{-1}$ , equivalent to high velocities of 5–8  $\text{m s}^{-1}$ . It is to note that the flat channel top design is for easy sensor installation with minimized flow resistance.

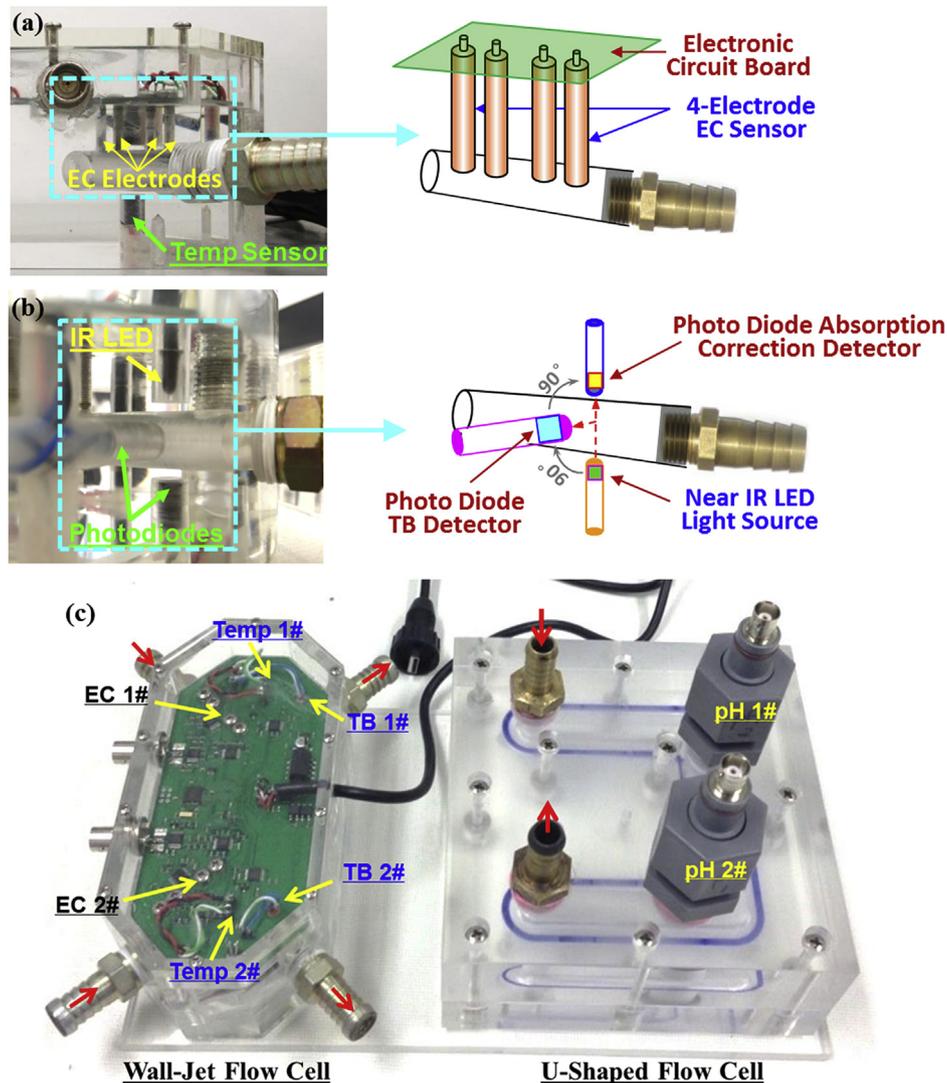
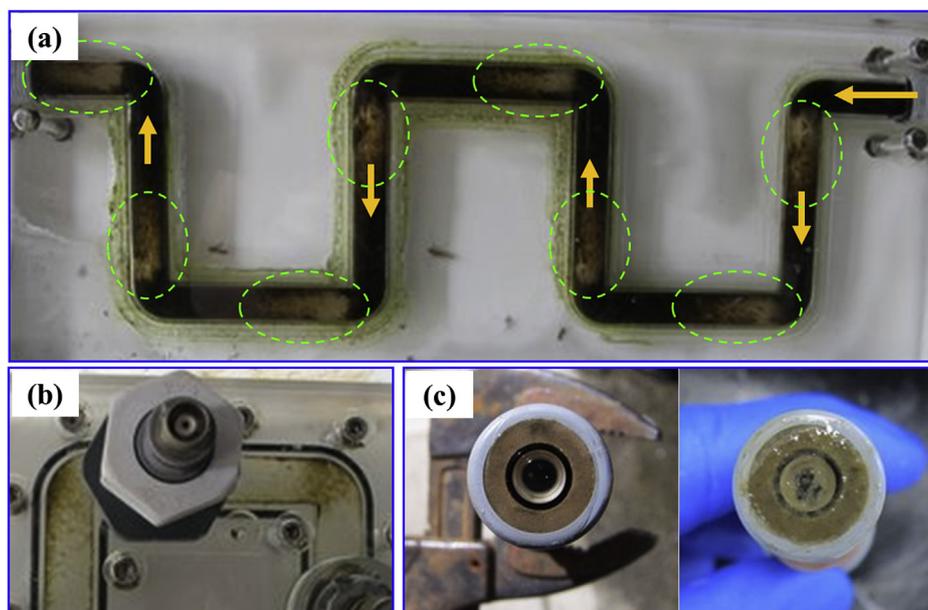


Fig. 2. Configuration of (a) 4-electrode conductivity probes, (b) dual-beam turbidity sensor, (c) flow cell with four pairs of embedded sensors.

As suggested by hydrodynamic studies (Akbarinia and Behzadmehr, 2007; Jarrahi et al., 2010), for a given volume flow rate, the vectored flow velocity of fluid on the surface of different channel wall locations of a curved flow channel can be dramatically different because the centrifugal force at the curved part can change laminar flow into turbulent flow. The hydrodynamic modeling predicts that the highest fluid shearing force to the channel wall can be obtained from a  $90^\circ$  curved channel at locations straight after the curved part (Akbarinia and Behzadmehr, 2007). We therefore designed and constructed  $90^\circ$  curved major-arc-shape cross-section flow channel cells with different channel diameters ( $r = 2\text{--}12$  mm) and a wall-jet flow cell to investigate their effectiveness in preventing the cell blockage and sensor failing. The constructed cells were trialed in a WWTP in Queensland under different flow rates. As the hydrodynamic modeling predicted, the least biofilm formation was observed from all trialed cells on locations straight after the curved channel part (Fig. 3a). For a given flow rate, smaller channels are more effective but channel blockages were observed with the channel diameters smaller than 8 mm. For a given channel size, a higher flow rate leads to a reduced biofilm formation. It was found that under pumping rates between 40 and  $60\text{ L min}^{-1}$ , the flow cell with a channel diameter of 14 mm ( $\theta = 118^\circ$ ) has demonstrated to sustain a 12-month continuous trial

without blockage and significant biofilm formation (Fig. 3b). The effectiveness of such a vectored high flow hydrodynamic self-cleaning approach can be further demonstrated by the photograph shown in Fig. 3c, where no biofilm formation can be observed from a pH sensor being continuously used over 6 months in raw sewage under a pumping rate of  $60\text{ L min}^{-1}$ . In strong contrast, the biofilm were grown over the entire surface of a same type pH sensor after only 7 days of usage in raw sewage at a low pumping rate of  $0.2\text{ L min}^{-1}$ . It should be mentioned that for fifteen WQMSs being trialed since 2013 at different sewage catchment sites in Australian states of New South Wales, Victoria, Queensland and Western Australia, none of the observed sensor failures were due to sensor contamination or biofouling, which should be sufficient to confirm the effectiveness and practicality of the vectored high flow hydrodynamic self-cleaning approach.

The presence of large-sized rags in wastewaters, especially for raw sewage at locations prior to the bar debris screens of the WWTP makes the continuous wastewater sampling a very challenging practical issue as large-sized rags can easily cause cell blockage and pump damage. In order to ensure a long-term, nondestructive continuous high flow rate sample delivery, an ABS Piranha submersible pump with built-in stainless steel blade capable of breaking rags was employed (Fig. S5). The pump was



**Fig. 3.** (a) Biofilm formation profile in the 90° curved flow channel; (b) a U-shaped flow cell after 12-month trial in raw sewage; (c) photographs of pH sensors after 6 months continuous operation in raw sewage with a pumping rate of 60 L min<sup>-1</sup> (left) and after 7 days operation in raw sewage with a pumping rate of 0.2 L min<sup>-1</sup> (right).

fixed inside of a stainless steel mesh sampling cage (Inset in Fig. S5) that only allows small-sized rags to be sampled by the pump, further preventing the cell blockage and pump damage.

### 3.3. Self-diagnosis

For online wastewater quality monitoring, the occurrence of sensor contamination and biofilm formation, physical damage to sensor and other interferences can seriously compromise the accuracy and integrity of the acquired sensing signals, and even lead to total malfunction of sensors. This is especially true for online raw sewage quality monitoring where the above mentioned interferences are much severer (Campisano et al., 2013; Liu et al., 2014). As such, the development of a practically implementable method capable of real-time confirming the faith of the acquired sensing signals and diagnosing malfunction sensors is a necessity for a viable WQMS.

Inspired by Vanrolleghem and co-workers' approach (Alferes et al., 2013a, 2012, 2013b; Alferes and Vanrolleghem, 2016; Alferes and Vanrolleghem, 2014), we propose to tackle this critical issue by a novel dual-sensor self-diagnostic approach. For a given water quality parameter, this approach employs two identical sensors to allow real-time cross-referencing the consistency of sensing signals acquired from the sensor pair. The Minkowski Distance is employed to real-time determine the similarity of the acquired sensing signals ( $X\{x_1, x_2, \dots, x_i, \dots, x_n\}$  and  $Y\{y_1, y_2, \dots, y_i, \dots, y_n\}$ ) from a dual-sensor pair. The Minkowski Distance ( $d$ ) of order  $p$  between  $X$  and  $Y$  can be calculated according to:

$$d = \left( \sum_{i=1}^n |x_i - y_i|^p \right)^{1/p} \quad (1)$$

where, dataset  $X$  and  $Y$  are the running windows of the sensor pair,  $n$  is the dataset length,  $x_i$  and  $y_i$  represents the  $i$ -th element inside dataset  $X$  and  $Y$ , respectively. In this work, for each sensor pair, a threshold vector value ( $T$ ) is predetermined by historic data of the sensor pair. The determined  $T$  values when  $n = 240$  and  $p = 2$  for Temp, pH, EC and TB are 30, 10, 2000 and 1600, respectively. The

sensor pair is deemed to be functioning similarly when  $d < T$ . Under the circumstance, although the absolute signal values of the sensor pair may differ slightly from each other, the trend of sensing signal changes should be synchronized as shown in Fig. 4a. Considering the probability of both sensors fail at the same time and fail in the same manner is very slim, therefore both sensors can be considered to be functioning normally when  $d < T$ . Therefore, the determined deviation in the trend of the signal changes of the sensor pair when  $d > T$  can be used to infer that at least one sensor of the pair is failing. The operator will be notified in real-time once such inconsistency is determined. The operator can then stop the system and offline calibrate the problematic sensors, if it is deemed necessary. Fig. 4b shows a typical example where unsynchronized trend changes of pH sensing signals were determined. The offline examination at the time confirmed that one of the pH sensors was functioning abnormally due to the blockage of porous frit of the sensor. Fig. 4c and d shows the unsynchronized trend changes of sensing signals recorded from two different TB sensor pairs. A malfunctioned TB sensor was confirmed for both cases, one (Fig. 4c) was due to the entrapped air bubbles in the vaseline layer used to fill the gap between the photodiode and optical window, and another (Fig. 4d) was due to the completely failed photodiode. Over the past 3 years, the effectiveness of the dual-sensor self-diagnosis approach was trialed at 5 different sewage catchment sites in different Australian states. During these trials, 7 unsynchronized trend changes of dual-sensor signals were recorded for pH, Temp and TB sensors (see Fig. S6 for four additional examples of unsynchronized trend changes). All recorded cases were confirmed to cause by at least one malfunctioned sensor, suggesting the dual-sensor self-diagnosis approach can be used to effectively and reliably diagnose the sensor failure of online WQMS in real-time.

### 3.4. Performance

For abnormal event detection performance evaluation, we have installed fifteen WQMSs since 2013 at 8 different sewage catchment sites across different Australian states. For demonstration purpose, we only report the performance of WQMSs installed at

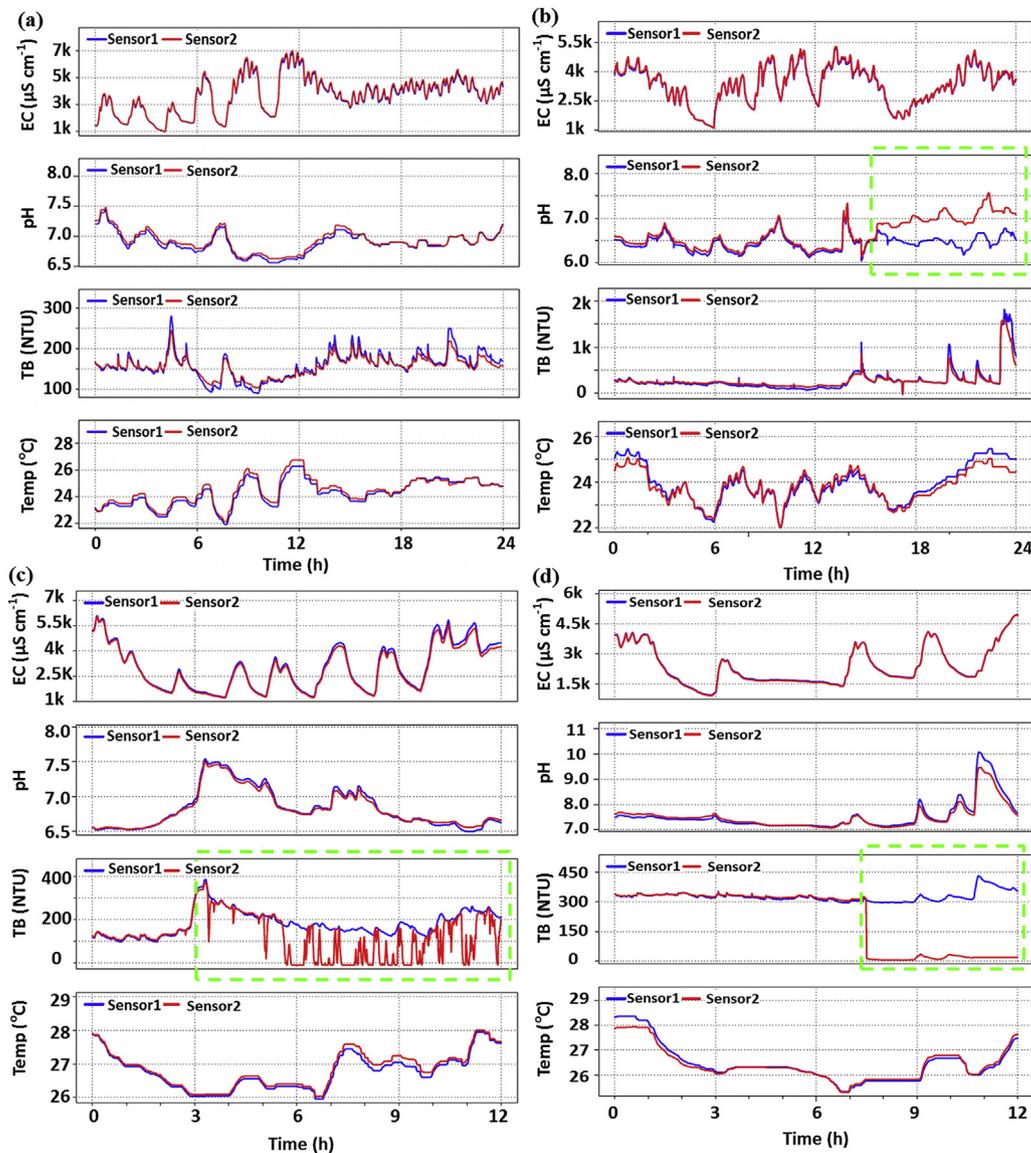


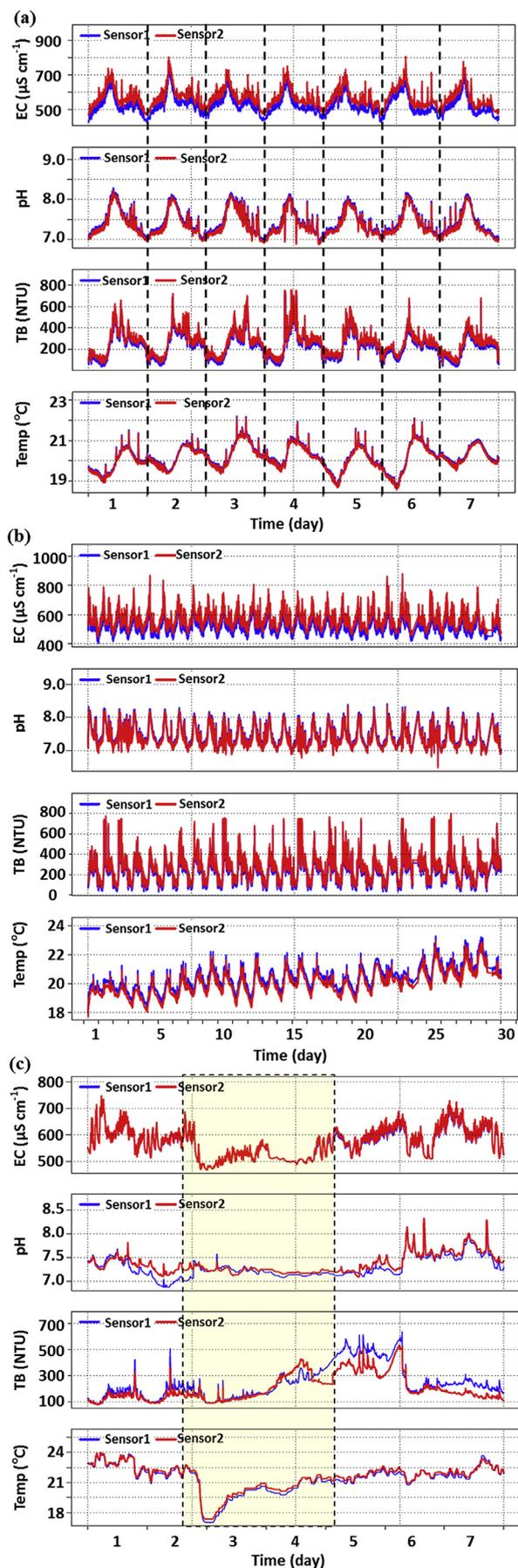
Fig. 4. (a) A typical consistent and (b)–(d) inconsistent dual sensor data profiles.

two selected trial sites in two different sewage catchment networks of New South Wales. For both sites, the WQMSs were installed on the wells of the sewage pump stations. These sites were selected to represent typical residential and industrial predominant sewage catchments. Prior to the field installation, all sensors of WQMS were calibrated in laboratory and recalibrated onsite. A set of typical sensing responses from onsite calibration can be found in Fig. S7.

For quality assurance, during these trials, hourly samples were taken over a 10 h period one day every fortnight and analyzed by TPS multi-sensor unit. Fig. S8 shows a representative set of comparative data during one sampling period from both trial sites. It can be seen that linear relationships can be obtained for all case investigated when the data obtained from the grabbed samples analyzed by TPS multi-sensor unit were plotted against the corresponding sensing data obtained from WQMS. As can be seen, the slopes and  $R^2$  of these straight lines obtained from different parameters are within the ranges of 0.93–1.04 and 0.93–0.99, respectively. These results suggest that the data obtained from both methods are essentially the same and with high precision. The

slopes and  $R^2$  obtained from 10 sampling cycles over a 20-week period at both trial sites are found to be within the ranges of 0.93–1.07 and 0.92–0.99, respectively. These results confirm the high accuracy and reliability of WQMS.

The trial site S1# represents typical residential predominant sewage catchments located at a relatively large pump station with a pumping capacity of  $\sim 2300 \text{ L s}^{-1}$ . Except interruptions by power failures, the installed WQMS was continuously operated for more than 18 months without maintenance and failure. Fig. 5a and b shows a set of typical weekly and monthly sewage quality data obtained from the trial site. Very clear daily patterns can be observed from monitored parameters. The observed daily temperature changes are the reflection of the daily ambient temperature changes. The daily EC, pH and TB are fluctuated between 450 and  $800 \mu\text{S cm}^{-1}$ , 7–8.3 and 100–600 NTU, respectively. These observed regular daily changes directly reflect the sewage discharge characteristics resulting from people's regular daily activities. Throughout the entire 18 months trial period, no significant irregular industrial discharge was detected at the site S1#. This is not a surprise finding when consider that this is a residential



predominant catchment site with large buffering capacity. However, a number of noticeable abnormal sewage quality changes directly correlating to heavy rainfall weather conditions were detected. Fig. 5c shows a typical weather event recorded during a heavy storm period, resulting from the storm water infiltration into the sewage network. The signals of all sensors were concurrently changed during the event. The sharp drop in temperature and EC is due to temperature and EC of storm water being lower than that of the bulk sewage. The slightly decreased pH was due to the rain-water being saturated with  $\text{CO}_2$ . It should be mentioned that similar daily patterns and rainfall weather events were also observed across all residential predominant catchment trial sites in other Australian states, suggesting that clear daily patterns and rainfall weather events are a general characteristic of such type of catchments with relatively large buffering capacities. It should also be noted that the WQMS was still fully functioning at end of the trial, confirming the robustness of sensors design and effectiveness of the vectored high flow hydrodynamic self-cleaning approach.

The trial site S2# is a typical industrial predominant sewage catchment site located at a relatively small pump station (with a pumping capacity of  $\sim 170 \text{ L s}^{-1}$ ) near a large number of commercial wastewater discharge points of various industries such as dairy, juice, soft drink, condiment/seasoning manufactures and other light industries. Other than 3 interruptions due to power outages, the installed WQMS at this site was continuously operated for 24 months without maintenance and failure. Fig. 6a and b shows a set of typical weekly and monthly sewage quality data obtained from this site. Although daily patterns can be observed from all water quality parameters, but with higher variation and less regular cycle patterns when compared to those shown in Fig. 5 from the residential predominant sewage catchment site, suggesting a weaker underlying seasonal trend. In particular, daily EC readings were found to be fluctuated between 1000–3500 and 1000–6000  $\mu\text{S cm}^{-1}$ . Also, pH and TB data revealed irregularly occurred large spikes (see data of 2nd and 3rd days in Fig. 6a), resulting from irregular discharge activities of certain customers. The daily temperature patterns were very unclear and no longer reflecting the daily ambient temperature changes. These observed characteristics are due to that the discharge behaviors of industrial customers are dictated by their operational processes, differing markedly from those residential predominant sewage catchment sites where daily discharge characteristics are determined by relatively regular daily life patterns of people. Also, differing markedly from the site S1#, during the 24 months trial period, a number of abnormal sewage matrix changing events were observed from site S2#. Three of such examples are shown in Fig. 6c–e. Fig. 6c shows sudden and concurrent changes of sensing signals of all sensors, confirming a noticeable sewage matrix change caused by a problematic sewage discharge. The sharp increased EC, pH and TB values suggest that the problematic sewage has high salt, base and solid particle contents. An increased temperature was also observed during the event. The determined sewage matrix change characteristics, especially the high pH, suggest that this inappropriate discharge action was likely carried out by condiment/seasoning manufactures. The event was continued for  $\sim 3.5$  h. Based on the pump rate of  $170 \text{ L s}^{-1}$ , this event involves an approximately  $2000 \text{ m}^3$  of the problematic sewage. Considering the very high pH (up to 11) of the problematic sewage, such an abnormal event could seriously affect the performance of a small size WWTP. Fig. 6d shows a typical TB dominated sewage matrix

Fig. 5. (a) A typical weekly and (b) monthly real-time sewage data profiles of site S1#; (c) a typical weather event resulting from storm water infiltration recorded from site S1#.

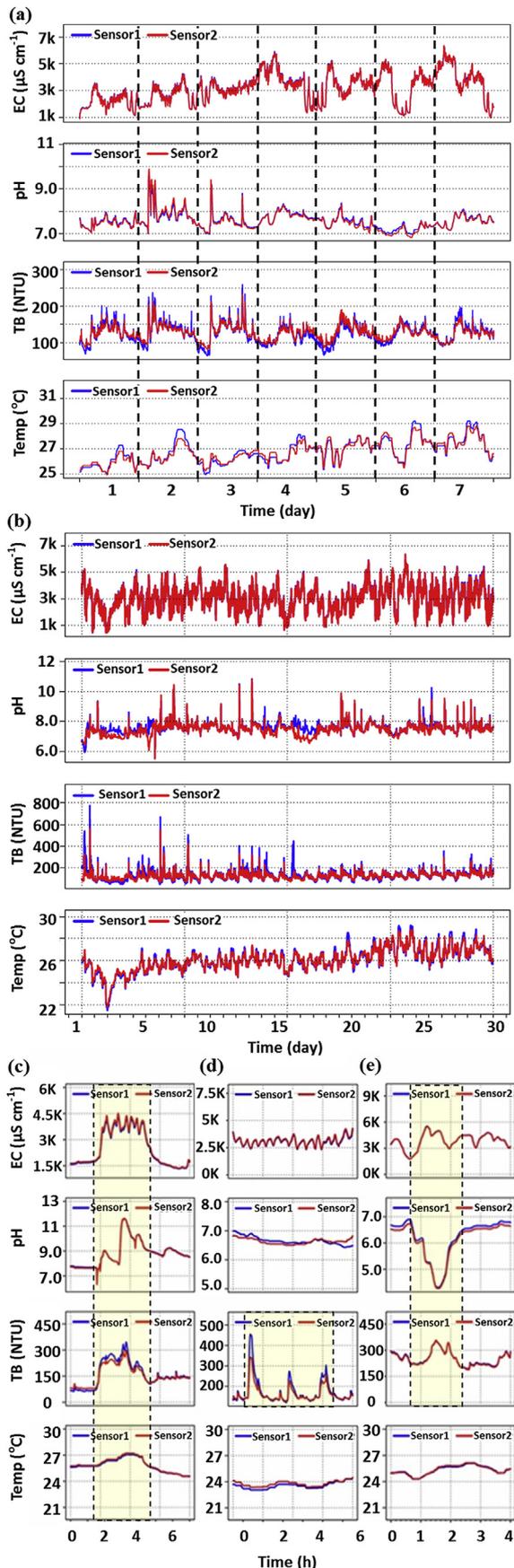


Fig. 6. (a) A typical weekly and (b) monthly real-time sewage data profiles of site S2#; (c)–(e) typical abnormal discharge events recorded from site S2#.

change event that was likely caused by discharge actions of dairy factories. Fig. 6e shows an event resulting from an improper discharge of acid containing sewage as confirmed by the sudden and concurrent sensing signal changes of all sensors. The characteristics of low pH accompanied by an increased EC and TB suggest that soft drink factories were likely responsible. It should be noted that an auto-sampler (Fig. S9) was installed to all WQMSs used for trials. The auto-sampler will be triggered to collect samples for laboratory conformational analysis once an abnormal event is detected. It should also be noted that all events reported above were confirmed with laboratory analysis of the collected samples by the auto-sampler.

In order to identify water utilities' needs, we conducted a survey at the early stage of Urban Water Security Research Alliance project, involving the top 4 largest Australian water utilities to gather historic information on the causes of major failures of their wastewater treatment plants and types of events that may affect their wastewater treatment plants and advanced membrane treatment-based wastewater recycling facilities. The survey revealed that the vast majority of major failures had been caused by illegal trade waste dumping and irregular manufacture discharges that are mostly associated with long-lasting significant wastewater matrix changes in pH, conductivity and turbidity. Over three years of trials at different sewer catchments across different Australian states, indeed, all detected abnormal events by WQMS resulting from illegal trade waste dumping and irregular industrial discharges were found to be associated with long-lasting significant changes in pH, conductivity and turbidity, while the detected overflow events were normally associated with a slightly decreased pH, significantly decreased conductivity and noticeably increased turbidity. This means that the reported WQMS are capable of detecting the above described events.

#### 4. Conclusion

We presented a suite of practically implementable technological solutions to effectively tackle the severe reliability and stability issues, enabling the development of robust online WQMS. Suitable sensor and flow cell designs are innovatively combined with a vectored high flow hydrodynamic self-cleaning approach to prevent sensors from contamination and biofouling under operational conditions. A dual-sensor self-diagnostic approach is employed to real-time detect malfunctioned sensors. The superior reliability and excellent practicality of the developed WQMS are confirmed by multiple long-term trials in different sewage catchment sites. For the first time, a WQMS has demonstrated a capability of continuously operating in raw sewage for a prolonged period up to 24 months without maintenance and failure. The approaches reported here should be applicable to encounter the common reliability and stability issues of other online water quality monitoring systems. Furthermore, the demonstrated capability of WQMS to reliably acquire real-time wastewater quality information sets a firm foundation for development of reliable wastewater quality abnormal event detection, potential impact prediction and early warning systems that can be used as effective tools for wastewater source control and management.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.watres.2017.05.040>.

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