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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.

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; Alfreres 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-