Water Quality Monitoring Using Wireless Sensor Networks: Current Trends and Future Research Directions

KOFI SARPONG ADU-MANU, CRISTIANO TAPPARELLO, and WENDI HEINZELMAN, University of Rochester
FERDINAND APIETU KATSRIKU and JAMAL-DEEN ABDULAI, University of Ghana

Water is essential for human survival. Although approximately 71% of the world is covered in water, only 2.5% of this is fresh water; hence, fresh water is a valuable resource that must be carefully monitored and maintained. In developing countries, 80% of people are without access to potable water. Cholera is still reported in more than 50 countries. In Africa, 75% of the drinking water comes from underground sources, which makes water monitoring an issue of key concern, as water monitoring can be used to track water quality changes over time, identify existing or emerging problems, and design effective intervention programs to remedy water pollution. It is important to have detailed knowledge of potable water quality to enable proper treatment and also prevent contamination. In this article, we review methods for water quality monitoring (WQM) from traditional manual methods to more technologically advanced methods employing wireless networks (WSNs) for in situ WQM. In particular, we highlight recent developments in the sensor devices, data acquisition procedures, communication and network architectures, and power management schemes to maintain a long-lived operational WQM system. Finally, we discuss open issues that need to be addressed to further advance automatic WQM using WSNs.

4

CCS Concepts: • **General and reference** → **Surveys and overviews**; • **Computer systems organization** → *Sensor networks*; *Sensors and actuators;*

Additional Key Words and Phrases: Wireless sensor networks, environmental monitoring, water quality

ACM Reference Format:
Kofi Sarpong Adu-Manu, Cristiano Tapparello, Wendi Heinzelman, Ferdinand Apietu Katsriku, and Jamal-Deen Abdulai. 2017. Water quality monitoring using wireless sensor networks: Current trends and future research directions. ACM Trans. Sen. Netw. 13, 1, Article 4 (January 2017), 41 pages.
DOI: http://dx.doi.org/10.1145/3005719

1. INTRODUCTION

The increase in human activity over the past century is having a devastating impact on our environment, directly resulting in a cost to human health [Panayiotou et al. 2005]. Particularly in developing countries, the growth in slum cities, lack of sanitation facilities, and activities of mining companies all contribute to negative impacts on the environment. To ensure environmental sustainability, it is critical to have effective monitoring systems. Environmental monitoring systems have been developed for monitoring air quality [Cordova-Lopez et al. 2007; Khedo et al. 2010; Bhattacharya et al. 2012], water quality [Sanders 1983; Chapman 1996; Farrell-Poe 2005; Strobl and Robillard 2008], animal tracking [Szewczyk et al. 2004; Pereira et al. 2008; Amundson

This work was funded in part by the National Science Foundation under research grant CNS-1239423.
Authors' addresses: K. S. Adu-Manu, C. Tapparello, and W. Heinzelman, Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY 14627; emails: kadumanu@ur.Rochester.edu, ctappare@ece.rochester.edu, wheinzel@ece.rochester.edu; F. A. Katsriku and J.-D. Abdulai, Department of Computer Science, University of Ghana, Legon, Accra, Ghana; emails: {fkatsriku, jabdulai}@ug.edu.gh.

DOI: http://dx.doi.org/10.1145/3005719

and Koutsoukos 2009], and earthquake monitoring [Estrin et al. 2002; Akyildiz and Stuntebeck 2006].

Of particular importance in environmental monitoring is water quality monitoring (WQM). Every living creature needs water to survive [WHO 2011]. About 71% of the earth's surface is covered by water, whereas the remaining 29% is made up of land mass [Alkandari et al. 2011; Universe Today 2015]. Although water is abundant on earth, only 2.5% of the available water is fresh water [USGS 2015], and approximately 20% of the world's population does not have access to safe drinking water [Yue and Ying 2011]. Currently, modernization in major areas in the world and urban cities with concentrated human activity are responsible for severe water pollution, which is considered one of the major problems affecting the environment [Derbew and Libsie 2014]. As a result, observing and detecting pollutants in water is vital.

Water quality describes the general composition of water with reference to its chemical, physical, and biological properties. WQM can be described as a method for periodically sampling and analyzing water conditions and characteristics [Farrell-Poe 2005]. WQM typically involves monitoring freshwater sources such as rivers, streams, lakes, ponds, springs, reservoirs, shallow or deep groundwaters, cave water, flood plains, wells, and wetlands to ensure that the water source is providing safe water for drinking and other human and animal activities [Jiang et al. 2009; Zhu et al. 2010; Nasirudin et al. 2011]. The WHO has determined different water quality targets that specify the safe amounts of certain chemicals that may be found in water [WHO 2011], and different WQM systems aim to test the water regularly to ensure that the concentrations of these chemicals remain within safe limits and to raise alarms should they fall outside of the safe limits. WQM is also used in reference to monitoring water for industrial utilization [Zhou et al. 2012b]. WQM projects focus on applications such as monitoring of drinking water, waste water treatment, and aquaculture administration [Jadhav et al. 2016]. The main difference among the various types of water monitoring is seen through the nature of the freshwater body (i.e., moving or static) and the depth to which the monitoring is performed (i.e., surface or deep, e.g., wells and underground water).

From the 1960s to 2000, WQM mainly relied on a manual approach for water sampling and analysis, where a human user would travel to a water source, take one or more samples of the water, and transport these samples to a laboratory for subsequent analysis. During this period, the focus of the research on WQM was related to the general framework, including identification of the objectives and strategies and specific techniques to be used for water analysis, as well as on the network design, including selecting the water quality variables to be measured, the sampling sites, and the sample frequencies [Sanders 1983]. Some researchers have emphasized the need to create fixed sampling stations for easy access to the water body and consistency of the sample collection [Strobl and Robillard 2008]. Other works focused on how to efficiently utilize the generated data, considering, for example, techniques for conversion of the data into a format that facilitates decision making [Sanders 1983; WHO 2011; Strobl and Robillard 2008; Chapman 1996]. These traditional WQM systems have several limitations due to the high spatiotemporal variability of the water physiochemical and/or microbial parameters [Katsriku et al. 2015]. Additionally, there are several sources of errors that can affect this traditional manual water monitoring approach. These include human errors during the sample collection (e.g., sample cross contamination or misidentification) as well as during the subsequent analysis and data recording, errors introduced by the sample collection and transportation apparatus (e.g., the type of container used for sample collection and transportation, the presence of reagents and other environmental contaminants, and other variables like the temperature), and error introduced by the laboratory equipment (e.g., instrument malfunction and miscalibration). Additional errors can be introduced during the data manipulation and reporting stages due to, for example, statistical errors, round-off errors, or omission of values [van Niekerk 2004].

Starting from the late 2000s, new technologies were introduced to address some of these limitations. In particular, new sensors were developed that utilize fiber optics, laser technology, biosensors, optical sensors, and microelectronic mechanical systems (MEMS) to detect different water quality parameters in situ [Bhardwaj et al. 2015; Sawaya et al. 2003], whereas computing and telemetry technologies were introduced to support the data acquisition and monitoring processes. Moreover, new methodologies like satellite image acquisition to remotely estimate some water quality parameters [Sawaya et al. 2003] and architectures for visualizing the water quality parameters through the Internet were introduced to monitor lakes, rivers, and other water bodies [Hall et al. 2007]. The purpose of these systems was to further improve on the manual water sample collection from fixed sampling stations by introducing automatic monitoring points where water samples could be continuously or periodically captured and analyzed [Glasgow et al. 2004; Bourgeois et al. 2001; Noble and Weisberg 2005; Sawaya et al. 2003].

A further improvement for WQM systems came with the advent of wireless sensor networks (WSNs), which began to be used for WQM in early 2000 but have gained increasing attention in recent years as the devices and communication techniques have improved. WSNs have proven to be very effective in supporting the capture, analysis, and transmission of environmental data. The use of WSNs for WQM is particularly appealing due to the low cost of the sensor nodes and hence the cost effectiveness of this solution, the ability to acquire and process data at several distributed sampling points, and the ability to communicate the data using low-power wireless communication techniques, which enables decision makers to receive data from multiple remote sensor devices in a timely manner.

In the past 10 years, several researchers have proposed and deployed WSNs for WQM (e.g., Zennaro et al. [2009], Wang et al. [2009], Yang and Pan [2010], and Alkandari et al. [2011]). The use of online platforms for the purposes of automatically analyzing the water quality data to detect water quality problems has also gained popularity [Bourgeois et al. 2001; Hall et al. 2007; U.S. EPA 2015a]. Moreover, several researchers have shown that using WSNs for WQM can overcome some of the pitfalls of the traditional WQM techniques that have been used throughout the years. These include the ability to replace expensive laboratory equipment that may be old (if not obsolete) with the lower-cost distributed sensor nodes and the ability to perform the analysis on site, thus removing the need to transport the samples from the monitoring sites to the laboratory for analysis, saving large amounts of human time and cost. Additionally, using WSNs for WQM has been shown to reduce the time and costs required to train staff for the collection and transportation of the samples, as well as for the laboratory analysis and the data recording, as required by the traditional manual approach for sampling water [Wang et al. 2009, 2010; Silva et al. 2011; Adamo et al. 2015]. To design and deploy WSNs to monitor freshwater sources, different factors are considered, including the sensing capabilities of the sensor nodes, the type of communication (radio or acoustic), signal processing, and network topology. WSN systems are employed to monitor freshwater sources and to measure water quality parameters such as temperature, pH, turbidity, and dissolved oxygen (DO) [Rasin and Abdullah 2009; Chaamwe 2010; Nasser et al. 2013]. In WQM, sensor nodes communicate using radio communication technologies for surface water monitoring and acoustic communication for underwater monitoring, either locally or remotely. Examples of WQM systems include SmartCoast, a multisensor system for WQM [O'Flyrm et al. 2007], and LakeNet, an embedded WSN deployed at St. Mary's Lake on the Notre Dame campus [Seders et al. 2007].

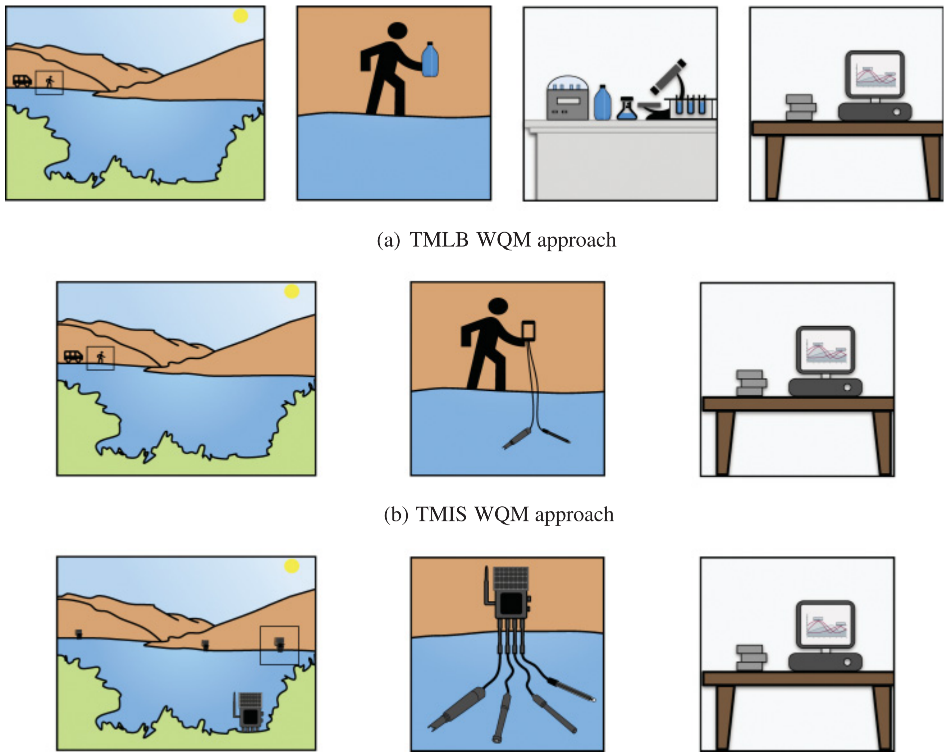
In this article, we provide an in-depth survey of WSN-based WQM systems for freshwater sources (e.g., rivers, lakes, ponds, or wells). There have been a few literature reviews on the use of WSNs for marine environment monitoring (MEM) and sensing [Albaladejo et al. 2010; Xu et al. 2014], water-level sensing [Loizou and Koutroulis 2016], water pipeline monitoring [BenSaleh et al. 2013], fish farming monitoring [Carroll et al. 2003], and residential water management [Carboni et al. 2016]. The attributes/factors that differentiate the different water monitoring applications relate mainly to the objective of the monitoring system and the size of the water source. These translate into the adoption of different network topologies and node densities, adoption of different devices and sensors for monitoring different parameters, and the inclusion of specialized treatment technologies. To the best of our knowledge, there is currently no survey in the literature that presents the current state of the art on WSN-based systems for WQM of freshwater sources.

The rest of the article is organized as follows. In Section 2, we overview the evolution of WQM systems from the manual, lab-based approaches to current state-of-the-art WSN-based WQM systems. In Section 3, we describe the general water monitoring framework used prior to the introduction of WSNs, as these traditional systems form the basis for current WSN-based WQM systems. In Section 4, we present current water quality parameters that are typically measured and the in situ sensor devices that are capable of sensing these parameters. Building on the availability of these sensor devices, WSNs for potable WQM are presented in Section 5. In particular, we develop a general framework for WSN-based WQM and describe the various network and communication techniques, energy management schemes, and data processing techniques presented in the literature for ensuring long lifetime WSN-based WQM systems. In Section 6, we present a comprehensive review of the current state of the art in WQM using WSNs, highlighting the key design choices that characterize the different implementations. In Section 7, we discuss the current open issues and future research directions to enhance existing WSN-based WQM systems. Finally, Section 8 concludes the article.

2. EVOLUTION OF WQM SYSTEMS

In this section, we describe how WQM systems evolved from the traditional manual lab-based (TMLB) monitoring approach to the traditional manual in situ (TMIS) monitoring approach, and finally to more recent WSN-based solutions.

For many years, the procedure for testing the quality of water followed a simple work flow that involved manually collecting samples of the water and then transporting these samples to a laboratory for analysis to detect chemicals and microbial contaminants [Sanders 1983; Strobl and Robillard 2008; Bhardwaj et al. 2015]. Although this TMLB approach, illustrated in Figure 1(a), was able to provide adequate WQM and has been used for many years, it also presents several limitations. First, it requires the use of specialized apparatus and trained personnel for the quality assessment of the samples collected from the water source. Second, quality control measures may be lost and this approach is time consuming due to the dependence on human interactions and the need for transportation of the samples from the water source to the laboratory for analysis. Third, the sample analysis is oftentimes based on outdated or obsolete equipment [van Niekerk 2004; Bhardwaj et al. 2015]. Fourth, this approach has a high cost in terms of time, effort, and resource investment in the design and implementation of these systems as well as the cost of building the fixed platforms for data collection, the cost of the lab-based sensor hardware, and the cost of the subsequent system maintenance [United Nations 2005]. Fifth, there is an inability to conduct trend analysis based on historic data, as data may not be sampled frequently enough for some analyses, and additionally data can be lost at any given time due to the manual processes



(a) TMLB WQM approach

(b) TMIS WQM approach

(c) Wireless sensor network-based WQM approach

Fig. 1. Evolution of WQM systems.

involved in data collection and recording. Sixth, it is very difficult to determine changes in the water conditions over time, as the samples cannot be collected and tested within short intervals [Strobl and Robillard 2008]. These limitations led to a shift toward a more reliable approach for capturing water parameters to measure water quality.

In particular, to address some of the limitations of the TMLB WQM approach, new in situ sensors were developed to measure water quality parameters in the field and in real time, thus leading to the development of the TMIS WQM approach. In this process, illustrated in Figure 1(b), human users bring the in situ sensors to the water source to measure certain parameters on-site. More recent techniques adapting TMIS have considered different forms of remote water sensing, such as the use of aircraft or satellites to capture images for analysis, optical sensors for monitoring the aquatic environment in situ [Murphy et al. 2015], and MEMS sensors for capturing water quality parameters at the water site [Bhardwaj et al. 2015]. Although these techniques enable the capture of water quality parameters on-site, they still do not address the need for continuous monitoring of the water source. Additionally, most of the time they do not allow for feedback control such that new data can be obtained in response to the results of the initial analysis.

A modern approach to WQM should overcome the shortcomings of both the TMLB and TMIS WQM approaches and should meet the following goals: (1) achieve high sensitivity and selectivity, (2) be able to detect water quality parameters in real time and on-site, (3) provide distributed sensing of the water body and support local analysis of the data from the distributed sensors, and (4) provide a long operational lifetime.

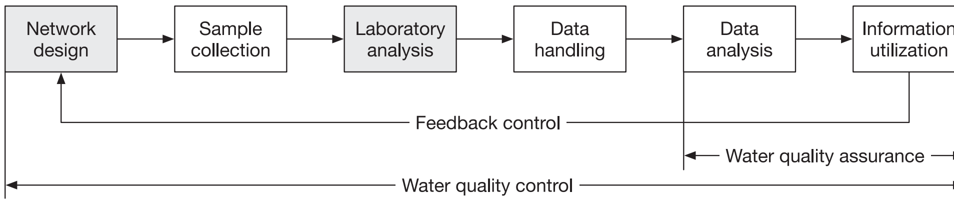


Fig. 2. Traditional WQM framework [Sanders 1983].

For all of these reasons, researchers have started considering WSNs as an alternative solution to WQM. In Figure 1(c), we illustrate the WSN-based monitoring approach for WQM.

In recent years, low-power sensor devices with wireless communication capabilities have become widely used for environmental sensing and monitoring, as they can capture data from distributed sensors in real time; perform local processing of the data; are robust; and are able to self-configure, self-power. and operate autonomously [Estrin et al. 2001; Yadav et al. 2015; Chung and Yoo 2015]. A main advantage of using WSNs for environmental monitoring is that they do not require human presence or intervention to operate [O'Flyrm et al. 2007; Zhang and Zhang 2011], so the sensors can be deployed in areas or regions where human accessibility is difficult or inconvenient. A requirement, however, is that the network should provide and transfer data in a timely manner [Chen et al. 2011].

In the following sections, we discuss the state-of-the-art WSN-based WQM systems, starting from an overview of the TMLB approach to WQM, then moving on to the development of approaches that use in situ sensors (TMIS), and finally to WSN-based systems that provide real-time, continuous monitoring of water quality parameters.

3. TMLB WQM

To capture and utilize measurable and meaningful information on the general characteristics of water quality, as shown in Figure 2, the design of TMLB WQM systems is often divided into six phases: network design, sample collection, laboratory analysis, data handling, data analysis, and information utilization [Sanders 1983; Strobl and Robillard 2008].

The *network design* consists of three main activities: identification of the sampling sites, selection of the water quality parameters (or variables) to monitor and the lab-based sensors to measure these parameters, and the sampling frequency with which to gather water samples to guarantee a certain detection accuracy. Thus, during the network design phase, the main goal is to identify what is to be detected from the water samples, as well as to identify where, when, and how often these water samples are to be collected [Bartram and Ballance 1996].

The *sample collection* phase consists of determining the specific sampling technique, the eventual measurements that can be done at the sampling point, and the techniques to be used for storing and preserving the samples during transport to the laboratory for analysis. It is important to note that each water quality parameter requires selecting a sampling method that may or may not differ from the sampling method used for other variables, or may differ from that of the same parameter at a different location [United Nations 2005].

The *laboratory analysis* is the core activity of the water monitoring process. This is a complex task that involves several physical, chemical, and biological procedures to determine the water quality variables defined during the network design using the water samples collected during the sample collection phase. Moreover, operational procedures, quality control and assurance, and data recording are other important operations that are part of the laboratory analysis phase.

The last three phases within the WQM framework deal with the data handling, data analysis, and the final information utilization. During the *data handling* phase, the received data are screened, verified, and stored for later use and/or reported to management for decision making. In *data analysis*, basic summary statistics, regression analysis, water quality indices, quality control interpretation, time series analysis, and water quality models are used to analyze the data. Finally, in the *information utilization* phase, the appropriate data formats and operation procedures are defined to utilize the information generated from analyzing the data [Sanders 1983; Strobl and Robillard 2008].

To achieve the objectives of the monitoring program, the general guidelines must be followed carefully in the first three phases (i.e., network design, sample collection, and laboratory analysis). This is extremely important because the last three phases largely depend on what happened in the first three phases of the monitoring framework. In essence, WQM is designed to capture data from the water source, to extract specific information from this data, and finally to use this information for efficiently managing the water resources [Strobl and Robillard 2008].

WQM has historically been viewed as a set of operational activities that aim to assess whether water sample parameters conform to specific values that have been shown to signify healthy/safe water quality. Over the years, several guidelines and standards have been proposed to support WQM. For example, extensive guidelines for WQM are provided in Chapman [1996], with a particular focus on the data processing, data quality control, and data transfer from the sampling location to the laboratory for analysis. Moreover, different types of water bodies (e.g., rivers, lakes, reservoirs, and groundwater) are described, taking into account their particular physical, chemical, and biological characteristics.

Similarly, Bartram and Ballance [1996] specify that the requirements for WQM should consist of a clear identification of the purpose and objectives of the water analysis, followed by a determination of the sampling site(s) and sampling rate(s) to meet these objectives. In addition, the details of the laboratory analysis, storage, and safety of the water samples gathered are discussed in this work. The authors also propose some guidelines on the various testing methods and the quality assurance procedures that should be followed when dealing with the acquired water samples. Following these guidelines, it is possible to determine the physical, chemical, and biological characteristics of the water samples and ensure satisfactory results from the WQM process.

Additional guidelines on site selection, field operation, calibration, record computation, and reporting to facilitate the design of the WQM process are provided in Wagner et al. [2006].

As seen in the preceding discussion of research on TMLB WQM systems, these works mainly focus on the network design (e.g., sample frequencies and timing); sample collection; the procedures for data processing, retrieval, and transfer; and the storage of the data. In this regard, we note that the design phase is mainly influenced by the number of parameters to be analyzed and by the frequency with which samples must be collected. In addition, both the parameters to be sampled and the sample frequency are dependent on the equipment available at the laboratory for analysis.

4. SENSORS FOR MEASURING WATER QUALITY PARAMETERS

There has been much research aimed at identifying the different parameters that should be measured to determine water quality, as well as the sensors that can measure these parameters. This section highlights the various parameters that have been

Table I. Water Quality Parameters and the WHO Values for Safe Drinking Water

Measurement Parameter	Definition	WHO Standard (Drinking Water)	References
pH	Effective hydrogen-ion concentration (i.e., $pH = -\log[H+]$)	7–8.5 (preferably ≤ 8)	WHO [2011], Yue and Ying [2011], and Wagner et al. [2006]
Turbidity	Amount of solid matter (particles or colloids) suspended in water that obstruct light transmission	1–5 NTU	WHO [2011], Yue and Ying [2011], and Wagner et al. [2006]
Dissolved oxygen (DO)	Amount of DO	5–6mg/l	Yue and Ying [2011] and Wagner et al. [2006]
Residual chlorine detection (RCD)	Amount of chlorine (residual after chlorine-based water disinfection)	2–3mg/l	WHO [2011]
Conductivity (also Salinity)	Ability of an aqueous solution to transfer an electrical current (measure for salinity)	25°C	Wagner et al. [2006]
Temperature	Temperature impacts DO content	Drinking water supply (15°C)	Eckenfelder [2001], Wagner et al. [2006], and WHO [2011]
Fluoride	Salts that form when fluorine combines with minerals in soil or rocks	4mg/l (or 2mg/l, secondary standard)	WHO [2011] and Analytical Technology, Inc. [2015]
Calcium hardness	Amount of calcium salts (reacts with most detergents and can reduce the effectiveness of the cleaning process)	75–100mg/l	WHO [2011] and Cotruvo [2011]
Total dissolved solids (TDS)	Amount of inorganic salts and small organic matter	600–1,000mg/l	WHO [2003, 2011]
Magnesium hardness	Amount of magnesium salts (causes an undesirable taste and stains laundry)	50–100mg/l	WHO [2011] and Cotruvo [2011]
Manganese	Mineral that naturally occurs in rocks and soil and is a normal constituent of the human diet	<0.1mg/l	WHO [2011] and Connecticut Department of Public Health [2015]
Sodium	Essential mineral that is commonly found in the form of sodium chloride (salt)	~200mg/l	WHO [2011] and WA Health [2012]
Hydrogen sulfide	Formed by sulfur and sulfate-reducing bacteria that can occur naturally in water	0.05–0.1mg/l	McFarland and Provin [1999] and WHO [2011]
Oxidation reduction potential (ORP)	Capacity to either release or accept electrons from chemical reactions; influences the life span of bacteria in water	650–700mV	Suslow [2004]

proposed for measurement and describes different sensors that can be used to measure these parameters.

Table I provides a summary of water quality parameters that may be measured, along with references to works that utilize these parameters in their WQM systems. In addition, Table I presents the threshold values for the various WQM parameters to

Table II. Guidelines for Data Processing in a WQM System [Wagner et al. 2006]

Data Processing Procedures	Explanation
Initial data evaluation	The initial data evaluation is conducted to verify the accurate transfer of raw field data (instrument readings) to the database and to evaluate and identify erroneous data. A variety of formats is available to store raw field data, depending on the recording equipment and the means of downloading data from the recording equipment.
Application of data corrections	The application of data corrections allows recorded data to be adjusted for instrument calibration drift and sensor fouling errors that occurred between subsequent servicing visits. These are due to environmental or instrumentation effects and other factors such as cross-section variability or calculated parameters.
Application and evaluation of cross-section corrections	If the measurement point is not representative of the stream, the measurement point should be relocated to a more representative measuring point in the cross section.
Final data evaluation	Final data evaluation consists of reviewing the data record, checking data corrections, and making any needed final corrections. When review is completed, the data are verified for publication and rated for quality.
Record computation	The record computation process verifies the data and overall report quality. Accurate field notes and calibration logs are essential in processing the record.
Final record review	Review of a continuous water quality record involves analysis of the tables of the measured field parameters.

ensure that water quality remains within safe limits, as determined by researchers at the World Health Organization (WHO) [Wagner et al. 2006]. If the water parameters are sensed to be outside of these safe limits, trigger warnings/alarms should be raised.

4.1. Evolution of Sensor Devices

Sensor devices for WQM have evolved from the traditional lab-based sensors, such as potentiometric, conductometric, mass spectrometry, ion-sensitive electrodes, and amperometric sensors, to in situ sensors capable of real-time measurement of water quality parameters on site, such as biosensors, fiber optic sensors, lab-on-a-chip sensors, electromagnetic wave sensors, fluorescence detection, and infrared (IR) sensors [Korostynska et al. 2013; Storey et al. 2011]. The current generation of sensor devices for monitoring water quality parameters are referred to as wireless sensor nodes and have the ability to not only measure water parameters in-situ but also to locally process and transmit the measured data.

In situ sensors used for WQM must be calibrated in the laboratory before installation at a monitoring station/site. Ideally, these sensors should be easy to calibrate in the field as well. Data from these sensors must be processed following a set of standard guidelines to ensure an acceptable quality, as outlined in Table II. Hence, the sensors ideally should provide a standard and user-friendly format for data reporting to facilitate verifying and publishing the data in a format that is readily accessible for public use or analysis [Wagner et al. 2006]. Two notable organizations that have published water quality data for public use are the U.S. Geological Survey (USGS) [USGS 2015] and the United Nations Global Environment Monitoring System (GEMS) [United Nations 2005].

Standard sensors for measuring the different water quality parameters are commercially available from several manufacturers (e.g., ATI Analytic Technologies [2016], CENSAR Technologies [2016], Hach [2016], In-Situ [2016], Libelium [2016], S::can [2016], Technical Associates [2016], YSI [2016], and Zap Technologies [2016]). A list of common commercially available water quality sensors and their capabilities is

Table III. Common Commercially Available Water Quality Sensors and Their Capabilities for Measuring the Water Quality Parameters

Single Parameter		
Sensor Model	Water Quality Parameter	References
ATI	Free chlorine	Hall et al. [2007]
Hach A-15 Cl-17	Free/Total chlorine	Hall et al. [2007]
Hach 1720 D, WQ730, WQ720	Turbidity	Hall et al. [2007] and Xylem Inc. [2015b]
GLI PHD, WQ201, WQ101	pH	Hall et al. [2007] and Xylem Inc. [2015b]
GLI 3422, WQ-Cond	Specific conductance	Hall et al. [2007] and Xylem Inc. [2015b]
Hach Astro TOC Ultraviolet/Process Analyzer	Total organic carbon	Hall et al. [2007]
WQ401	Dissolved oxygen (DO)	Xylem Inc. [2015b]
WQ600	Oxidation reduction potential (ORP)	Xylem Inc. [2015b]
Multiple Parameters		
Sensor Model	Water Quality Parameters	References
Dascore Six-Sense Sonde	Specific conductance, DO, ORP, temperature, free chlorine	Hall et al. [2007]
YSI 6600 Sonde, 6820 V2, 600XL, WQMS	Specific conductance, DO, ORP, pH, temperature, free chlorine, ammonia-nitrogen, chloride, nitrate-oxygen, turbidity	Hall et al. [2007] and Xylem Inc. [2015b]
Hydrolab Data Sonde 4a	Specific conductance, DO, ORP, pH, temperature, free chlorine, ammonia-nitrogen, chloride, nitrate-oxygen, turbidity	Hall et al. [2007]
Smart Water (Libelium)	Conductivity, DO, ORP, pH, temperature, turbidity, nitrates, dissolved ions	Libelium [2014]

provided in Table III. Nevertheless, several researchers have focused on improving the sensors for water quality measurements. For example, Bhardwaj et al. [2015] provide an overview of modern sensor devices used for monitoring water quality, such as optical sensors, MEMS, and biosensors, and they discuss the advantages of these current, in situ sensor technologies over the traditional lab-based sensors. Although these modern sensors present several advantages such as high sensitivity, high selectivity, good response time, lack of need for a reference sensor, insensitivity to electromagnetic interference, and the possibility of real-time analysis, they also have some direct shortcomings. In particular, when compared to traditional methods such as UV, spectrometry, and ion sensitive electrodes, these modern sensors require substantial additional power, they need to be equipped with an individual electronic transducer unit, and they require regular maintenance visits to ensure their correct operation. These shortcomings make it difficult to achieve concurrent detection of different water parameters [Bhardwaj et al. 2015].

Recently, Murphy et al. [2015] designed a low-cost autonomous optical sensor for monitoring a range of water quality parameters. The optical sensor designed by the authors is robust, easily deployable, and simple to operate. This sensor consists of a multiwavelength light source with two photodiode detectors. This sensor is capable of measuring the transmission and side scattering of the light in the detector head, which contains five LEDs of different wavelengths. The detector head forms part of the sensor head, which covers the optics and controls the detection abilities of the sensor.

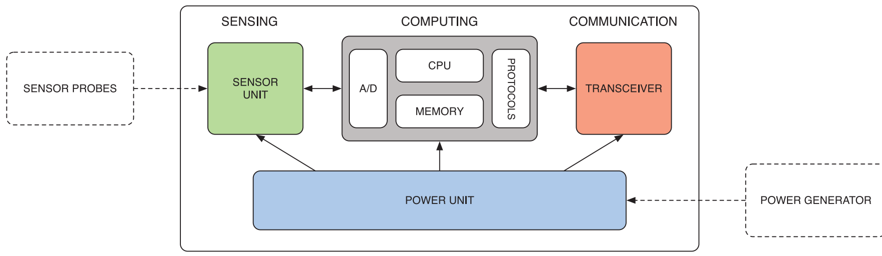


Fig. 3. Generic wireless sensor node hardware architecture.

The sensor head is covered with copper to protect it against corrosion. The detector head enables the sensor to provide quantitative data on the changes in the optical opacity of the water.

4.2. Wireless Sensor Nodes

WSNs extend the capabilities of in situ monitoring systems. Although traditional in situ systems enable analysis on-site, they require that the data collected be transported manually to remote offices or control centers for further analysis and action. WSNs enable the automatic transfer of this data, as well as provide a feedback mechanism in some instances, to refine the granularity of data collection. Typically, a wireless sensor node consists of the sensor unit, the interface circuitry, a processor, a transceiver system, and a power supply unit [Yang et al. 2002; Yang and Pan 2010; Wang et al. 2010], as shown in Figure 3.

There are several commercially available wireless sensor nodes for measuring water quality parameters. These wireless sensor nodes are designed to accommodate a variety of situations ranging from short-term or spot sampling of the water quality parameters to long-term, unattended monitoring and analysis. Additionally, there are other sensors that are designed to float on water, such as buoys that come with flow controls and mini wet labs to collect water samples for analysis [Burke and Allenby 2014].

Different types of commercial sensors are presented in Table III. The sensors are classified into single and multiple parameters, depending on the number of water quality parameters that the sensor is able to detect. Several studies also proposed the use of specialized hardware devices to support the wireless sensor nodes for measuring water quality parameters. These include, for example, autonomous underwater vehicles (AUVs) [Zhan et al. 2009], fish robots [Shin et al. 2007], unmanned airboats [Kaizu et al. 2011], mini-boats [Tuna et al. 2013], and digital cameras [Goddijn and White 2006]. The characteristics of these specialized hardware technologies, as well as some details about their advantages and disadvantages, are summarized in Table IV.

5. WSN-BASED WQM

In this section, we present an overview of WSN-based WQM systems. We start by identifying a common functional framework for WQM systems that utilize WSNs, derived from the TMLB framework presented in Figure 2. We then discuss different techniques that have been proposed in the literature for enabling communication, energy management, and data processing in WSN-based WQM systems.

5.1. WSN Framework

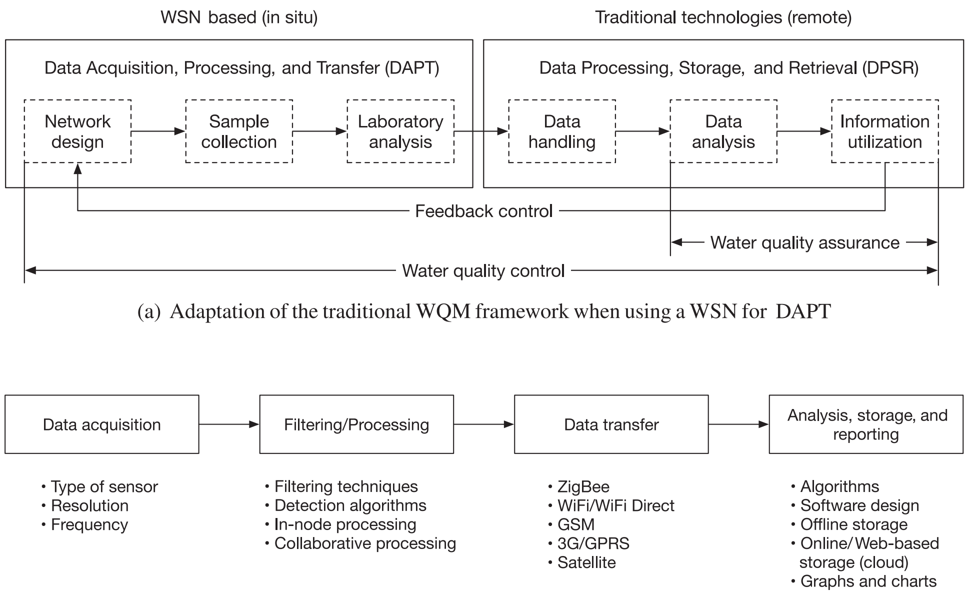
When considering the use of WSNs for WQM, the traditional WQM framework presented in Figure 2 can be divided into two main activities, as shown in Figure 4(a). The first activity is performed in situ by the WSN and comprises the functions *data*

Table IV. Specialized Hardware Devices for Supporting Wireless Sensor Nodes

Device	Communication	Implementation	Advantages	Disadvantages	Reference
Digital videos	ZigBee and CDMA	Three monitoring points along a river	Multihop, ability to monitor large area, flexible and easy to extend three-layer architecture	Data acquisition not clearly defined	Peng [2009]
Automatic underwater vehicles	GPRS (multihop routing)	3D grid of sensors	Proposed algorithm showed high performance	AUV navigates only in one direction	Zhan et al. [2009]
Fish robots	ZigBee, IR, and GPS	Swimming pool testing with sonar localization	Sonar localization proved to be more efficient than GPS, autonomous system	Battery operating devices with short lifetime	Shin et al. [2007]
Battery-operated mini-boat	Wireless link (type not specified)	Simulation studies	Cheap to implement and maintain	Performance depends on several parameters; battery operating devices with short lifetime	Tuna et al. [2013]
Buoys mounted with probes	Wireless and wired links (type not specified)	Simulation studies	Cheap to implement and maintain	Performance depends on several parameters	Tuna et al. [2013]
Air boat	GPS	Experiments on a mire pool	Using grid sampling, the boat was able to obtain fine-resolution water quality distribution maps	Design of the boat can be improved to reduce side to side oscillation; complex to determine the optimal control parameters	Kaizu et al. [2011]

acquisition, processing, and transfer (DAPT). DAPT is viewed as a unified process when a WSN is employed. To support DAPT, sensor devices are distributed around the water body (e.g., river, lake, or groundwater), thereby enabling sampling at different spatial locations at regular time intervals. The data collected are potentially processed locally on the sensor nodes and then transmitted to a local monitoring station close by the sensor nodes, where further processing of all data from the multiple distributed sensor nodes may be performed. Processing the data locally at the node does have implications for energy consumption. At the local monitoring station (or base station), the processed data is either transmitted through a long-range communication technology (e.g., cellular, WiMax, satellite) to an end user at a remote monitoring station or is stored in a local database at the local monitoring station for eventual collection by a user who travels to the site to gather the data. Other systems that exist for data transfer include the use of automatic vehicles and satellite. The next stage is the *data processing, storage, and retrieval* (DPSR) operations, which in WSN-based systems is normally fully automated. An example of a WSN-based WQM system that follows this framework is illustrated in Figure 5.

Alternatively, it is possible to describe the WSN-based WQM framework represented previously by focusing on the different building blocks that compose the system. To



(a) Adaptation of the traditional WQM framework when using a WSN for DAPT

(b) WSN pipeline for water quality monitoring

Fig. 4. WSN-based WQM framework and relative sequence of operations, with examples of operation-specific techniques.

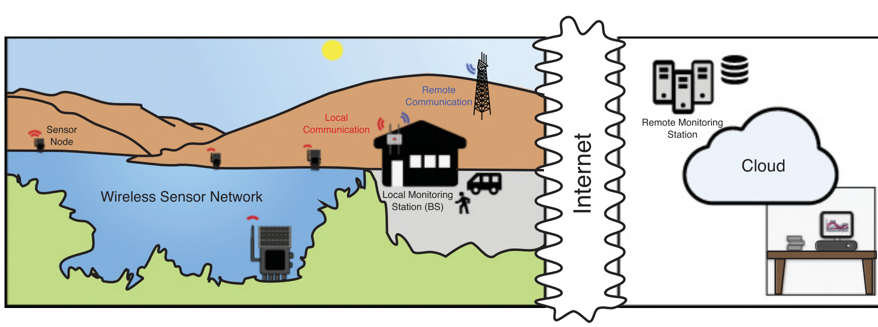


Fig. 5. WQM system using a WSN for data acquisition and transfer.

this end, Figure 4(b) presents the WSN pipeline as composed of four building blocks, which represent the main operations that need to be performed by the system, namely data acquisition, filtering/processing, data transfer, and final analysis, storage, and reporting. In the first block, *data acquisition*, the spatially distributed wireless sensor nodes acquire samples from the water source at periodic intervals. Using multiple distributed sensors for acquiring data increases the level of accuracy since data from different sensors (and samples taken from spatially distributed areas) can be used for analysis. Additionally, the frequency of gathering data from the sensors can be set to meet the WQM goals.

In the second block, *filtering/processing*, the samples collected during the acquisition phase are processed. This phase requires specialized computation and benefits from devices that are able to perform computationally intensive operations locally. Filtering techniques and efficient algorithms for detecting the required water quality parameters are implemented. For processing the data, two main approaches are proposed: in-node processing (InP) and collaborative task processing (CTP). InP is when a node processes its own samples, either individually or over time. CTP, on the other hand, is when nearby nodes share data with each other, and the processing considers the spatially distributed samples from the different nodes. A WSN can utilize both InP and CTP so that the individual nodes process their data locally and then share this processed data with their neighbors for additional CTP. Often when one needs to know the condition of the water body, CTP provides a general or average value, whereas values obtained from InP give an indication of the water condition at particular points, hence the ability to detect the source of contamination.

The next functional block is represented by the *data transfer*, which describes the way in which the data is moved from the source to the final destination. The data transfer is largely dependent on the architecture of the network. The choice of routing protocol and their efficiency becomes an important consideration. Several technologies are available for this, including ZigBee, WiFi, WiFi-Direct, LTE, GSM, or WiMAX.

The final block of the WSN-based WQM pipeline consists of the *data analysis, storage, and reporting*. In this phase, the system performs some additional computations, and organizes and classifies the data collected by the WSN. Data can also be stored using offline storage media, online storage media, and/or the cloud. The data is then presented to the user in the form of graphs, charts, and tables.

Utilizing a WSN infrastructure within a WQM system overcomes the limitations of traditional, manual WQM systems, as (1) WSNs enable the sensors to be fixed in place for gathering consistent samples, (2) water quality can be sampled as frequently as desired, (3) the water quality measurements can be transmitted to an end user for real-time analysis of the water quality, and (4) feedback from the end user can change the sampling frequency on demand in case additional or fewer measurements are required [Bartram and Ballance 1996; Wagner et al. 2006; Strobl and Robillard 2008; WHO 2011].

5.2. Network Communication

The design of the communication network is an important aspect of WSN-based WQM systems. The network architecture can be separated into two main parts: (1) *local network communication*, which is transmission of the data from the sensor nodes to a local monitoring station (or base station), and (2) *remote network communication*, which is transmission of the data from the local monitoring station to a remote monitoring station that enables users to access the data.

In the local network communication, wireless communication techniques such as ZigBee, WiFi, and WiFi-Direct are often used. Depending on the spatial location of the sensors and the local monitoring station, either direct communication from the sensor nodes to the local monitoring station or multihop communication (transmitting the data from a sensor through one of its neighbors to the local monitoring station) may be employed. When multihop communication is utilized, a cluster-based approach may be employed, where the sensor nodes form local clusters with a cluster head and transmit their data to their cluster head, and then the cluster head transmits the data individually or aggregated to the local monitoring station. Many different local network communication systems have been proposed [Nasirudin et al. 2011; Chen et al. 2011].

In the remote network communication, long-range communication techniques, such as cellular (LTE, 3G, GSM, GPRS) and WiMax are used to transmit the data from the local monitoring station to a remote monitoring center or the cloud (see Figure 5). The use of remote network communication systems have been proposed in several studies (e.g., Peng [2009], Yang and Pan [2010], Yue and Ying [2011], Alkandari et al. [2011], Capella et al. [2013], and Katsriku et al. [2015]).

Table V. Wireless Network Technologies

Local Communication						
Technology	Coverage	Frequency	Speed	Advantages	Disadvantages	References
ZigBee	50m	2.4–2.48GHz	20/40/250 Kbps	Low cost, low power consumption, ad hoc, potential to support large number of users	Does not penetrate buildings well, low speed	Ho et al. [2013] and Sidhu et al. [2007]
WiFi (a/b/g/n)	200m	2.4 and 5GHz	Up to 150Mbps	Low cost, high speed, wide distribution, common standard	High power consumption, requires central access point, scalability	Ho et al. [2013] and Dhawan [2007]
WiFi Direct	200m	2.4 and 5GHz	Up to 150Mbps	Ad hoc, low cost, high speed, easy to set up	High power consumption, limited platform support, scalability	Feng et al. [2014] and WiFi Direct [2015]
Remote Communication						
Technology	Coverage	Frequency	Speed	Advantages	Disadvantages	References
RF Module	8Km	2.4GHz	250KBs	Resilient to noise and variations in signal strength	Requires complex demodulator, low speed	Laird Technologies [2012]
GSM	10Km	900–1, 800GHz	9.6Kbps	Wide distribution, 2-factor authentication, support for roaming	Low speed, high energy consumption, needs special processing to handle handoffs	Rahnema [1993] and Ho et al. [2013]
WiMAX	5–100Km	2–11GHz; 10–66GHz	Up to 80Mbps	Relative low cost to deploy, secure and reliable, high speed and coverage	Trade-off between bit rate and coverage, limited access to spectrum, limited diffusion	Ho et al. [2013] and Dhawan [2007]
LTE	100Km	698–960MHz	300Mbps DL; 75Mbps UL	Low latency, high capacity, high speed, backward compatible	Equipment expensive, high energy consumption	Lee and Wong [2010] and Ho et al. [2013]

Table V shows the features of various wireless technologies that have been used for both the local communication (WiFi, ZigBee, and WiFi-Direct) as well as the remote communication (RF Module, WiMAX, LTE, and GSM). Terrestrial communication standards such as WiMax, GSM, and LTE cover between 5 and 100Km, which is desirable for remote monitoring in WQM environments. For local monitoring, ZigBee, WiFi, and

Table VI. Comparison of Network Architectures

Communication Technology / Protocol	Network Design	Routing	Sensor Overlay	Network Type	Reference
ZigBee	Sensors send data to local monitoring center through ZigBee network	Multihop	None	Local	Chen et al. [2011]
Hierarchical WSN	Sensors connected to central fusion center via local fusion centers	Multihop	Clustering	Local	Karami et al. [2012]
ZigBee	Sensors transmit data through base station to data center	Not specified	Not specified	Local	Amruta and Satish [2013]
ZigBee	Sensors connected to local host computer through ZigBee/Ethernet gateway	Not specified	Not specified	Local	Postolache et al. [2014]
ZigBee	Sensors connect to gateway and then to field servers	Multihop	Clustering	Local	Chung and Yoo [2015]
ZigBee, CDMA	Sensors transfer data to local base station (ZigBee/CDMA gateway)	Multihop	Three layers	Local and remote	Peng [2009]
ZigBee, CDMA	Sensor nodes connected to remote monitoring center through cluster head that acts as ZigBee/CDMA gateway	Single hop	Clustering	Local and remote	Wang et al. [2010]
ZigBee, WiMAX	Sensors connected to remote station through local ZigBee/WiMAX gateway	Single hop	Star topology	Local and remote	Silva et al. [2011]
ZigBee, GPRS/GSM	Sensors transfer data to local base station (ZigBee/GPRS gateway)	Single hop	Clustering	Local and remote	Katsriku et al. [2015]
GSM	Sensors connected to remote monitoring center via GSM	Direct connection	None	Remote	Mo et al. [2012]

WiFi Direct, are typically used for shorter distances, range from 50 to 200m. Additionally, Table VI provides an overview of several different communication and networking architectures that have been proposed specifically for WSN-based WQM systems. Other technologies that have not been fully explored in WQM are underwater communication technologies such as acoustic communication and optical communication. These technologies can support high performance in WQM communications. For example, acoustic communication provides long-range communication distances with low rates, whereas underwater optical communication has a very high rate over a few meters [Ge and Wang 2016; Akyildiz et al. 2016]. The communication range for radio in freshwater sources is greater than 10m, whereas the communication range for radio in marine sources is between 10 and 100m. Acoustic communication spans across several kilometers, whereas optical communication ranges between 10 and 100m [Ge and Wang 2016].

Currently, to the best of our knowledge, little has been reported on WQM quality of service (QoS) performance metrics such as throughput, delay, and security, as far as the actual network is concerned. Work done over the past 10 years, and recent research in the area of WSNs for WQM, has focused primarily on collecting data from sensor nodes and storing them in a database.

One such work is the design and deployment of a smart system for gathering data in estuaries using WSNs in which a server is used to request and collect data from several nodes and store them in a database [Parra et al. 2015]. Similarly, Nguyen et al. [2015] presented a design of an energy-efficient environment monitoring station and data collection network based on ubiquitous WSNs. In this work, different climatic parameters from the sensor nodes were sent through the sensor network to the base station. The base station receives the data from the sensors, performs data processing, and transmits data packets to the remote monitoring center via a GPRS/3G data network. Another related work is found in th work of Ge and Wang [2016], who provided an energy-efficient network for WQM in a subterranean river in China. In their work, the authors evaluate the network communication architecture by placing emphasis on the node energy consumption in the network building stage, the data acquisition stage, and the transmission stage. Different node numbers were assigned to each node in the network, and their results indicated that the maximum energy consumed in the data acquisition and transmission phases takes place in the node with the largest node number.

5.3. Energy Management

An issue of key concern in the design of a WSN-based WQM system is how to power the devices and the technique used to manage the power consumption over time. In particular, the goal is to realize a system that can remain continuously operational without needing to constantly replace batteries. There are two main design approaches to support the continuous operation of a WSN-based WQM system: (1) increase the energy available to the wireless sensor nodes, through renewable energy sources, by harvesting energy from solar, wind, RF, and hydro (running water) energy, and (2) reduce the energy draw of the wireless sensor node, through techniques such as duty cycling, power control, use of energy-efficient routing protocols, wake-up radios, and low-contention communication.

Energy harvesting is a key technology to enable the implementation of long-lived WSN-based systems. Many approaches have been proposed for harvesting ambient energy and combining this harvested energy with local energy stored in both fixed and rechargeable batteries as well as supercapacitors. In addition, several researchers have proposed using hybrid systems that harvest renewable energy sources, such as solar energy and RF energy, in addition to traditional battery technologies, to power the sensors in WSN-based WQM systems [Wang et al. 2010; Chung and Yoo 2015; Amruta and Satish 2013]. Supporting the energy needs of the sensor nodes in WQM systems is particularly challenging due to the harsh environment in which the sensors are deployed. A summary of the various energy harvesting systems that have been proposed for powering the sensor nodes used in WSN-based WQM systems, as well

Table VII. Energy Sources and Power Management Schemes

Power Source(s)	Power Management Scheme	Network Performance	Reference
Solar panel and rechargeable batteries	Small sampling rate (once a day)	System works continuously throughout the year	Wang et al. [2010]
Solar panel and rechargeable batteries	Alternates between solar panel and rechargeable batteries, depending on amount of sunlight	Not specified	Amruta and Satish [2013]
Solar panel and rechargeable batteries	Not specified	System works continuously for about 100 hours during cloudy days and about 30 days in sunshine	Mo et al. [2012]
Solar panel and rechargeable batteries	Duty cycling that puts sensors into deep sleep if there are no background processes	Not specified	Yue and Ying [2011]
Solar panel and rechargeable batteries	Local processing (time average) to reduce data transmissions	Local processing substantially increases system lifetimes	Chung and Yoo [2015]
Solar panel and rechargeable batteries	Four sensor modes of operation: active, sleeping, transmitting, and receiving	Batteries fully charged most of the time, hence increasing network performance	Capella et al. [2013]

as the power management schemes and network configurations that were selected to achieve the desired performance goals, is presented in Table VII.

In addition to developing energy harvesting techniques to recharge the batteries of the sensor nodes, researchers have also focused their efforts on reducing the energy consumption of the nodes. One method of reducing the energy dissipation for the sensor nodes is to utilize duty cycling, whereby the sensor nodes are put into a very low power sleep mode when they are not sensing or transmitting data [Yue and Ying 2011]. Various techniques have been proposed to support the wake-up of the sensor nodes, including periodic wake-up as well as on-demand wake-up.

Power-aware protocols and communication techniques are used to ensure long-lifetime WSN-based WQM systems. For example, to ensure minimum power usage by the sensor devices, the system described in Alkandari et al. [2011] organizes the network into clusters, where the cluster head nodes are powered through Sphelar EIPV solar energy–harvesting modules. Using these modules, the cluster heads are able to harvest from the environment enough energy to support their onerous role in the network (e.g., receiving, retransmitting, and processing data for the entire cluster). To maximize the lifetime of the network and increase performance, a fixed or stationary cluster-based network topology is utilized.

Power management schemes for WSN-based WQM environments are discussed in Shu [2016]. Here, the author proposes to adapt the power consumption by dynamically changing the sensor sampling rate with the use of reinforcement-learning techniques (i.e., self-aware scheduling). The sleep and wake-up strategies presented in this work were proposed to be implemented either at the single node or for the entire network. At the node level, the proposed include the battery state awareness, data standard deviation, and hybrid. When considering the entire network, the proposed techniques focus on energy-efficient routing and topology control.

An aggregation routing algorithm, called tnderwater aggregation routing algorithm (UARA), was proposed by Zhan et al. [2009] to prolong the lifetime of AUVs. These AUVs are used to collect the sensor data, as well as to prolong the lifetime of the sensor nodes, as both the sensor nodes and the AUVs have limited battery power (underwater, the batteries cannot be recharged via energy harvesting). The proposed routing protocol utilizes information about the current location of the AUV to optimize the routes from the sensors to the AUVs to minimize the total energy dissipation of the data communication. It has been shown that significant gains can be obtained through the proposed protocol when compared to traditional static routing protocols that do not utilize the current location of the AUVs [Zhan et al. 2009].

In the work of Capella et al. [2013], the development of a WSN for the continuous in situ monitoring of the nitrates in River Turia, Spain, is presented. In this real-world application, ion-selective electrode (ISE) transducers and solar panels for energy harvesting were used. To reduce energy drain, the authors proposed the use of data fusion (or aggregation). To determine the energy used by the system, the authors performed an experiment at the River Turia. In this experiment, the sensor nodes remain in a low-energy consumption mode until 6 PM to enable their batteries to be completely charged (if possible) by means of the corresponding solar panels during the period of most intense solar radiation (during the day). At the aforementioned time, the sensor node is woken up by the real-time clock (RTC) to perform the nitrate measurement and to communicate the data to a neighbor sensor node in the chain (or to the gateway in case there is a direct link). An acknowledgement of the data is then expected. Once this process is over, the sensor nodes revert into the low energy consumption mode until the next operation cycle (on the following day) [Capella et al. 2013]. The authors provide a description of the solar energy–harvesting module that they developed to provide enough energy to power the sensor nodes perpetually without human intervention. In their experiment, the sensor nodes were placed under different operation modes (active, sleeping, transmitting, and receiving) of the ISE sensor and the RTC. The solar panel that they adapted was small in size with a double buffer to store power both in rechargeable batteries and supercapacitors. The authors tested the module experimentally to confirm the energy provision of this solar panel, and they validated the energy harvesting system module during the sampling period. The experiments revealed that before transmission, the battery was charged to around 100%, even on days with scarce solar radiation. Battery measurements in another scenario (right after transmission) showed that in the case of required retransmissions, the charge of the supercapacitor was not always high enough to provide the necessary energy for a retransmission, and therefore the sensor nodes had to use the energy stored in the rechargeable batteries. However, battery charge remained above 95% in all of the measurements obtained [Capella et al. 2013].

In WSN-based WQM systems, energy drain still remains a key issue. As described in Xu et al. [2014], a WSN for water monitoring should intelligently manage the batteries, harvest energy from the environment, and implement energy management schemes at the node level. However, only a few references present details about the energy management schemes [Xu et al. 2014], and as described earlier for WQM systems, most of the existing works have used duty cycling, wake-up radios, and data fusion approaches to reduce the energy drain.

5.4. Data Processing, Storage, and Retrieval

The data collected by the wireless sensor nodes may be processed in several places: locally on the wireless sensor node, at the local monitoring station, and finally at the remote monitoring station. The processing algorithms depend on the types of parameters collected. Additionally, it is important to enable data to be stored and retrieved for further processing or analysis to support the goals of the WQM system.

5.4.1. Data Processing. In WQM, the concept of real-time sensing of water quality parameters has gained popularity around the world. From a data management point of view, this practice allows continuous monitoring of water quality parameters (physical, chemical, and biological) within a reasonable time, thereby opening new opportunities to devise strategies for data processing and validation of the raw data to convert them into useful information. However, current research on data processing for WSN-based WQM systems typically does not focus on specific algorithms but instead focuses on answering the following questions:

(1) Why is the water quality parameter being collected?
(2) What type of data is sensed and transmitted?
(3) How often is the data sensed and transmitted, and when does this data require usage?
(4) How do we process and secure the data?
(5) Which data-sensing techniques and algorithms are appropriate for the data collection for optimal performance?
(6) Where do the data reside?

Sensors deployed for WQM are energy constrained, which has necessitated the development of energy-efficient data aggregation/ processing schemes to prolong the network lifetime. Several different energy-efficient schemes have been proposed for data aggregation/processing. For example, Wang et al. [2016] present a distributed compressed sensing theory for a cluster-based underwater acoustic sensor network that considered spatial and temporal correlations to minimize the total energy consumed by the sensor nodes during data collection. A similar data fusion algorithm has been proposed in Capella et al. [2013].

In the past, prior to the introduction of WSNs for WQM and online monitoring of the water quality parameters, data were manually recorded and interpreted by technicians [Storey et al. 2011]. Calculations were also performed manually, which meant that there was no quick response to pollutants in the water, and no real-time information was available for public health protection agencies. The water quality process depends largely on the time relevance of the collected data. Therefore, appropriate and timely response in detecting water quality problems from the data in real time is crucial in WQM [Storey et al. 2011]. Advances in computer hardware, software, and networks have been introduced in the WQM process to support data processing with proper analysis, documentation, and reporting. In particular, cloud computing techniques can be successfully used to perform the water quality data processing because of their ability to easily support report generation. These reports can then even be directly published by the WSN management system, thus helping policy makers to quickly develop proper strategies to maintain the water quality.

The sensed data may be processed at three different levels [Yang and Pan 2010; Yue and Ying 2011]. The first level is at the sensor node, followed by the local monitoring station and finally at the remote monitoring station. The essence of these levels of computation is to support trend analysis and to be able to determine the source of the contamination by looking at the parts of the water body that have the higher concentration of contaminants. This is possible because the sensor nodes are distributed across different parts of the water, and hence each of these sensor nodes will collect measurement parameters at different intervals for processing. For example, finite element analysis (FEA) is used at the sensor nodes to process the gathered data and to make informed decisions about the pollution level of the water [Alkandari et al. 2011]. The local monitoring station and the remote monitoring station processing are used to complete the data processing cycle and the trend analysis.

5.4.2. Data Storage and Retrieval. Several authors have provided different schemes for data storage and retrieval within WSN-based WQM systems. This task tends to be one of the most important aspects of the WQM process, as the amount of energy consumed by the devices greatly depends on the amount of data to be acquired and the frequency of data acquisition, as does the quality of the WQM process. Many existing implementations rely on memory cards for data storage on the local node, whereas remote reporting is triggered by specialized commands transmitted from the local monitoring station [O'Flyrm et al. 2007; Regan et al. 2009; Jiang et al. 2009; Ritter et al. 2014]. Although this delay-tolerant data collection does not allow for real-time access to the water quality measurements, in some cases it is considered more convenient due to its cost effectiveness [Ritter et al. 2014]. To reduce the energy consumption of the data transmission, Yang and Pan [2010] present a data fusion technique that enables a reduction in the amount of data that need to be transmitted to the remote monitoring station.

The remote monitoring center relies on a database management system for storing the water quality data. In current implementations, these databases are mostly national databases, which are most of the time available online. For example, the GEMS program is dedicated to providing environmental water quality data and information of the highest integrity, accessibility, and interoperability through its database, referred to as Global Water Quality Data and Statistics (GEMStat) [United Nations 2005]. An additional dataset is operated by the USGS [2015]. It is important to note that these databases are only repositories for storing the acquired data, and as a recent study points out, the data become less actively accessed over time [Dong et al. 2015]. Hence, there is a need to explore ways to perform real-time trend analysis of the data collected and compare it continuously to the previous data collected and stored in repositories over the years. In this perspective, a common platform that integrates historical and real-time water quality data has recently been proposed in Sandha et al. [2016].

6. IMPLEMENTATIONS OF WSN-BASED WQM SYSTEMS

The idea of using WSNs for WQM started in early 2000, and there has been an increasing number of WSN-based WQM implementations since then. Most of the proposed systems represent more of a laboratory feasibility test rather than a fully functional deployment in the environment. Nevertheless, the current body of work on the topic provides a complete overview of the different building blocks and limitations of an automatic WQM system. In what follows, we highlight the key design choices that characterize the different implementations and then describe the details and limitations of four selected implementations that follow the WSN-based framework described in Section 5.1.

There have been several implementations of WSN-based WQM systems that have been tested or deployed in Australia [Silva et al. 2011; Rao et al. 2013], China [Jiang et al. 2009; Jin et al. 2010; Wang et al. 2011; Yue and Ying 2011], Cyprus [Hadjimitsis et al. 2009], Kuwait [Alkandari et al. 2011], Greece [Rapousis et al. 2015], India [Verma and Prachi 2012; Amruta and Satish 2013; Wagh and Rao 2014; Moon et al. 2015], Indonesia [Wiranto et al. 2015], Ireland [O'Flyrm et al. 2007; Regan et al. 2009; O'Connor et al. 2012; Garcia et al. 2012; Murphy et al. 2015], Malawi [Zennaro et al. 2009], Malaysia [Rasin and Abdullah 2009], Mexico [Curiel et al. 2016], Peru [Ritter et al. 2014], Portugal [Postolache et al. 2014], Tanzania [Faustine et al. 2014], Turkey [Tuna et al. 2014], and the United States [Yang et al. 2002; Seders et al. 2007; Burke and Allenby 2014; Sun et al. 2016]. Details of these systems are summarized in Tables VIII and IX.

In addition to these implementations, researchers in China [Yang and Pan 2010; Chen et al. 2011], India [Verma and Prachi 2012], the kingdom of Saudi Arabia [Aleisa 2013], and Zambia [Chaamwe 2010] describe the limitations of the current WQM

Table VIII. Existing Implementations of WSN-Based WQM Systems

Reference	Measured Parameters	Communication Technology	Main Contributions	Location
Yang et al. [2002]	Temperature, pH	RF and acoustic transducer	Description of aqueous sensor network with hybrid terrestrial/underwater communications	Pennsylvania, USA
Seders et al. [2007]	Temperature, pH, dissolved oxygen (DO)	RF	System allowed in-network computation to detect change points in data stream	Indiana, USA
O'Flyrm et al. [2007] and Regan et al. [2009]	Temperature, pH, phosphate, DO, conductivity, turbidity, water level	ZigBee	Plug-and-play multisensor system	Ireland
Rasin and Abdullah [2009]	Temperature, pH, turbidity	ZigBee	Design and implementation of low-cost system based on ZigBee	Malaysia
Zennaro et al. [2009]	Turbidity, pH, DO	ZigBee	Adaptation of SunSPOT in three-layer architecture	Malawi
Hadjimitsis et al. [2009]	Temperature, pressure, salinity, turbidity	GPRS	Integration of satellite imaging and WSN-based monitoring	Cyprus
Jiang et al. [2009]	Temperature, pH	ZigBee, GPRS	Present design of hardware and software of sensors, base station, and remote monitoring center	China
Jin et al. [2010]	Temperature, pH, DO, salinity	ZigBee, 3G/GPRS	Design of multiparameter sensor system with hybrid ZigBee/GPRS communications	China
Wang et al. [2011]	pH, nitrate, phosphate	ZigBee, GPRS	System based on TinyOS, LabVIEW, and MySQL	China
Silva et al. [2011]	Temperature, pH, DO, conductivity	ZigBee, Ethernet, WiMax	Hybrid ZigBee/WiMax network	Australia
Yue and Ying [2011]	pH, turbidity, DO	Ethernet	Hierarchical network architecture	China
Alkandari et al. [2011]	Temperature, pH, DO, nitrate, ammonia, carbon dioxide, chlorine	ZigBee, 3G	Radio-to-shore, cellular, satellite, and RFID communications; finite element analysis of gathered data	Kuwait
O'Connor et al. [2012]	Temperature, conductivity, depth	ZigBee, 3G	Multimodal approach that combines visual sensors and context information to support conventional WSN	Ireland
Garcia et al. [2012]	Temperature, depth, flow, turbidity	ZigBee, GPRS/GSM	Use of in-network data aggregation algorithms for WQM and prediction	Ireland
Rao et al. [2013]	Temperature, pH, light, conductivity, DO, oxidation reduction potential	4G	Design of low-cost WQM system based on open-source hardware (Arduino)	Australia
Amruta and Satish [2013]	pH, DO, turbidity	ZigBee	Design and implementation of prototype sensor node powered by solar panel	India
Capella et al. [2013]	Nitrate	ZigBee, GPRS/GSM	Deployment of energy harvesting WSN for continuous in-line monitoring of river	Spain

practice adopted in their region, and they propose the idea and present the benefit of automating WQM through the adoption of WSN technologies.

These different implementations agree on a general WSN-based WQM framework, which includes the use of WSNs, a local monitoring station (or BS), and a remote monitoring station, as described is Section 5.1. However, most of the existing solutions only focus on the design and implementation of the local monitoring network (i.e., a WSN and local monitoring station), either through laboratory feasibility testing [Chaamwe 2010; Wang et al. 2011; Chen et al. 2011] or field deployment [Seders et al. 2007;

Table IX. Existing Implementations of WSN-Based WQM Systems (Continued)

Reference	Measured Parameters	Communication Technology	Main Contributions	Location
Ritter et al. [2014]	Temperature, pH, DO, ORP, conductivity	ZigBee	Continuos in-sensor data collection with on demand access to data	Peru
Wagh and Rao [2014]	pH, water level	ZigBee	Design of simple sensor for river monitoring powered by solar panel	India
Faustine et al. [2014]	Temperature, DO, pH, conductivity	ZigBee, GSM/GPRS (SMS)	WQM system prototype based on Arduino microcontroller and powered by solar panel	Tanzania
Postolache et al. [2014]	Temperature, conductivity, turbidity	ZigBee	Design of low-cost WQM system based on off-the-shelf components	Portugal
Tuna et al. [2014]	Temperature, pH, DO, conductivity, turbidity, nitrate	ZigBee	Design of buoy-mounted wireless sensor nodes with Web-based data visualization	Turkey
Burke and Allenby [2014]	Temperature, pH, DO, conductivity, salinity, specific conductance, resistivity, water level, ORP, TDS	Not specified	Use of multiparameter sensor with integrated display and data logger system	Maryland, USA
Murphy et al. [2015]	Temperature, pH, conductivity, DO, water level, chlorophyll, turbidity, blue-green algae concentration	WiFi	Use of optical sensor for monitoring aquatic environment	Ireland
Wiranto et al. [2015]	Temperature, pH, DO	ZigBee	Design of continuous WQM system withautomatic sample collection unit	Indonesia
Rapousis et al. [2015]	Temperature, pH, conductivity, ORP, chlorine	WiFi	Combination of WSN and crowd-sourced information (user feedback)	Greece
Moon et al. [2015]	Temperature, pH, DO, conductivity, ORP, turbidity	RF	Design and implementation of WQM system with security functionalities (authentication and encryption)	India
Sun et al. [2016]	Temperature, pH, DO	ZigBee, GSM/GPRS	Combination of specialized data logger (STORM 3) with prototype WSN	Texas, USA
Curiel et al. [2016]	Temperature, pH	ZigBee	Design and implementation of WQM prototype based on Arduino Uno	Mexico

O'Flyrm et al. 2007; Sun et al. 2016], and some of the references actually include the final interconnection with the remote monitoring station [Yang and Pan 2010; Silva et al. 2011; Alkandari et al. 2011; O'Connor et al. 2012; Faustine et al. 2014]. Several works provide automated warning signals displayed on computer screens or communicated to decision makers via text or email.

Almost all of the authors describe the design of the hardware of the sensor (i.e., microcontroller, communication interface, water quality parameter probe), gateway and remote center (e.g., PC), and the software used by each component. For some of the implementations, additional details about the design of the communication architecture and protocol [Jiang et al. 2009; Wang et al. 2011; Chen et al. 2011], power management scheme [Regan et al. 2009], data processing and visualization at the monitoring center [Alkandari et al. 2011; Rao et al. 2013; Amruta and Satish 2013], and how to adapt the system to different testing/deployment conditions [Seders et al. 2007] are also provided. Regarding the hardware used at the sensor nodes, it is interesting to note that starting from the early 2010s, there has been a substantial shift from hardware that was traditionally used by the WSN community, such as MICA2 motes [Seders et al. 2007; Wang et al. 2011], the Sun SPOT platform [Zennaro et al. 2009], Libelium Waspmote [Rapousis et al. 2015], or custom-made architectures [Jiang et al. 2009; Wang et al. 2011], to Arduino-based architectures, such as Arduino Uno [Curiel et al. 2016] and Arduino Mega [Rao et al. 2013].

The primary communication technology used for networking data within the WSN is ZigBee (or sometimes simply IEEE 802.15.4), and several researchers describe the benefit and ease of use of ZigBee when compared to other communication technologies. Nevertheless, some implementations rely on underwater acoustic communications [Yang et al. 2002] or WiFi [Rapousis et al. 2015], or consider direct connection between each individual sensor and the remote monitoring station through GSM/GPRS communications [Zhou et al. 2012a; Hadjimitsis et al. 2009; Rao et al. 2013]. Reporting the acquired data from the local to the remote monitoring station is done through cellular communications, either using GPRS [Hadjimitsis et al. 2009; Jiang et al. 2009; Wang et al. 2011; Garcia et al. 2012; Capella et al. 2013; Faustine et al. 2014; Sun et al. 2016], 3G [Alkandari et al. 2011; O'Connor et al. 2012], or 4G [Rao et al. 2013]. Additional details about the communication technologies used by the different implementations are provided in Section 5.2.

Regarding the measured parameters, almost all implementations include temperature and pH. Additionally, many implementations also reported information about DO, conductivity, and turbidity, whereas a few specialized implementations also looked at the oxidation reduction potential (ORP) [Rao et al. 2013; Ritter et al. 2014; Burke and Allenby 2014; Moon et al. 2015], and salinity [Jin et al. 2010; Burke and Allenby 2014] or the concentration of chlorine [Alkandari et al. 2011; Rapousis et al. 2015], phosphate [O'Flyrm et al. 2007; Wang et al. 2011], nitrate [Wang et al. 2011; Tuna et al. 2014], or blue-green algae [Murphy et al. 2015].

To relate the architecture shown in Figure 5 with the existing implementations, we highlight four key implementations of WSN-based WQM systems deployed in Indiana (USA) [Seders et al. 2007], Malawi [Zennaro et al. 2009], China [Yang and Pan 2010], and Texas (USA) [Sun et al. 2016]. For these implementations, we examine how the authors developed the various components of the WSN-based WQM framework described in Section 5.1. In particular, we present the water quality parameters selected for measurement, the approaches used in determining the sampling frequency and sample size, the network architecture and data communication methods used, the type of data analysis performed, how the data were evaluated and presented (e.g., in the form of maps, charts, and graphs), and finally the methods used for storing the data to be accessed by the end users.

6.1. LakeNet (Indiana, USA)

The first implementation is the work presented in Seders et al. [2007]. LakeNet, an integrated sensor network for environmental sensing in lakes and wetlands that focuses on lake water quality, was deployed at St. Mary's Lake on the Notre Dame campus in the fall of 2005 to detect changes in temperature, pH, and DO.

Data samples were collected using a MICA2/MDA300 (the MDA300 is a small data acquisition module that is connected to the three sensor probes, whereas the MICA2 is a radio/processor that is interfaced with the MDA300) sensor module that transmitted the data through radio waves at a frequency of 433MHz. In this implementation, a gateway node was connected to a laptop and transported to the field daily to retrieve the sampled data. When a command was issued from the gateway attached to the laptop, that command was propagated through the ad hoc network. Sensor data were then routed back from the WSN to the gateway node. According to this approach, when a sensor is unable to communicate directly with the gateway node, a multihop network is formed to relay data from sensor to sensor before reaching the gateway (i.e., the laptop).

Two D-cell batteries (providing 2,000mA-h of current at 5V) were used to power the MICA2/MDA300, and a 12V battery was used to power the three sensor probes. In this implementation, the WSN autonomously collects data, but the researchers have to visit the site to access and process the measurements.

A test with 18 sensor probes was conducted for a 10-day period to collect data on pH, DO, and temperature. Sensor data was gathered in 10- to 15-minute intervals, which allowed for continuous battery operation (additional tests showed a maximum lifetime of about 2 weeks). In this implementation, the nodes were deployed in two rows. Within each row, the sensors were roughly 2m apart, with about 1m between the two rows. The communication distance between the sensor nodes deployed in the water and the gateway (the laptop) was approximately 30m. Data collected from the different sensors was aggregated at the gateway node and presented to the user in the form of plots.

6.2. Water Quality WAN (Malawi)

In the second implementation, the Zennaro et al. [2009] presented their implementation of an integrated WSN for WQM deployed in Malawi. The network architecture was designed with a three-layer approach, consisting of the water sensor board layer (data gathering), the wireless sensor node layer (data transfer), and the wireless gateway layer (data storage). The authors adapted the Sun Small Programmable Object Technology (SPOT) architecture and extended it with an additional component referred to as the gateway layer. The Sun SPOT hardware platform is made up of Java-based wireless sensor nodes. It uses off-the-shelf components, is small in size, and has a modular architecture. The Sun SPOT kit comes with two free-ranged Sun SPOT units and one base station unit (which does not have a battery board). The base station unit communicates wirelessly with the free-ranged units and streams the data via a USB connection [Sun Microsystems 2007]. The general workflow of the system design consists of taking water quality samples at a predefined time of the day, a subsequent transmission of the data to the gateway, and the final storage of the data at the gateway layer. After this cycle, all elements of the system go to sleep until the next day, when the system wakes up and performs the entire cycle again (i.e., sampling, transmission, and storage). These processes were mapped onto the three-layer architecture.

As water quality sensors, the system uses 90-FLT (water sensor board layer). The 90-FLT is a single-unit portable water quality logger, and it combines sensors for dissolved oxygen, conductivity, total dissolved solids (TDS), pH, mV, turbidity and temperature [TPS Pty Ltd. 2008], with the Sun SPOT architecture, thus allowing for easy implementation of all system functionalities.

The sensor nodes were powered through rechargeable lithium-ion batteries. The architecture proposed in Zennaro et al. [2009] relies on a wake-up mechanism to prolong the system lifetime by turning off the devices when they are not in use. The Sun SPOT switches to a power-saving mode (shallow sleep) for power reduction whenever it detects that all running threads are idle. In addition, an external eSerial board was used to switch off the 90-FLT sensor when the device was not reading data. To turn the 90-FLT on and off, a string was sent through the serial port from the eSerial board to the 90-FLT sensor. The eSerial board was also powered down when not communicating with the sensor. The wake-up mechanism (from shallow sleep or deep sleep mode) was tested by supplying power to the Sun SPOT architecture by connecting it to a computer. In their experiments, for each acquired measurement, the free-range Sun SPOT nodes and the 90-FLT were in the active state for 50 seconds to transfer the current measurement through the serial connection and then switched to the deep sleep mode. The authors concluded that the wake-up mechanism is able to provide significant energy savings.

To further extend the lifetime of the system, the authors performed other experiments using different power control mechanisms. Using this approach, the node dynamically adjusts its transmission power based on the distance of its neighbors. However, their experimental results showed that the Sun SPOT consumed almost the same amount of power even when communicating with nodes at different distances. Therefore, the energy-saving technique implemented in their deployed system only included the adaptation of the shallow and deep sleep modes.

6.3. Monitoring of Fushun Reach River (China)

An implementation similar to the one presented in Zennaro et al. [2009] has been presented in Yang and Pan [2010]. Here, the authors present a WSN-based WQM architecture to monitor the quality of water at the point where the Hunhe River reaches the industrial city of Fushun (Liaoning Province, China). The architecture is composed of several sensor nodes and a base station (local monitoring station) connected to the Internet through a GPRS cellular connection, which is used to upload and store the data to a remote database server. In this implementation, the authors deployed sensor nodes in the Hunhe river to detect physical and chemical water quality parameters such as temperature, pH, salinity, turbidity, and DO to determine the level of pollution in the river.

The network was constructed such that the sensor nodes collected the water parameters and transmitted this data through multihop routing to the base station (local monitoring station). The authors state that the sampling frequency and the accuracy of the samples are determined based on preliminary studies (unspecified in their work). The local monitoring station connects the sensor network to the Internet and transfers all data acquired at the base station to a remote site. At the remote site, the collected data are processed, analyzed, and stored in a database. End users are then able to access the data remotely via the Internet.

The sensor nodes are placed at different distances from the base station and are powered using batteries, and hence have limited lifetime. The nodes nearer to the base station consume more power since they are required to transfer a considerable amount of data from the other sensor nodes to the base station. Therefore, the authors implemented a data fusion algorithm (details not provided) as a way to manage the amount of energy consumed by sensor nodes closer to the base station to decrease the amount of data to be transmitted to prolong the lifetime of the network. Data from the WSN, in the form of graphs and charts, are presented to the Environmental Department of China to identify water pollutants and enable them to take appropriate action. The output in which they were interested was to display a message in case the acquired parameters fell outside a set range and trigger an alarm in such situations to alert management.

6.4. WQM Using a Storm 3 Data Logger and a WSN (Texas, USA)

Finally, a more recent implementation of using a WSN to monitor water quality was presented in Sun et al. [2016] to monitor a pond at Lamar University in Beaumont, Texas. In this work, the authors compare the real-time data collection through a STORM 3 data logger (a specialized water monitoring station produced by WaterLOG [2016]) and a WSN. The WSN is composed of four wireless sensor nodes, two National Instruments

(NI) WSN-3202 and two WSN-3212. The nodes communicate directly with a gateway (NI WSN-9791), which is then connected to the Internet. On the other hand, the data logger is directly connected to the Internet through a cellular communication link (GSM/GPRS), and proprietary software from WaterLOG (Storm Central, a cloud-based data collection platform) allows the user to visualize and analyze the data collected by the logger.

Data was collected from the H-377 temperature sensors every 15 minutes every day for more than 5 months. Each wireless sensor node, instead, was equipped with a DO probe and a pH electrode (both produced by Sensorex). The pH electrode was attached to the WSN-3202 node, and the DO sensor was also attached to a WSN-3212 module. Data was collected for both the DO and pH sensors every hour. The sensors communicated through a gateway node deployed on the field near the pond. The gateway required external power and Internet access for communicating with the nodes and the monitoring center. At the monitoring center, data collection, analysis, and visualization were performed using LabView. In addition, LabView was used to monitor the signal strength of each node and to check the residual energy of the deployed nodes.

The authors conclude that a WSN can efficiently replace a more expensive specialized water monitoring station. However, in both cases, the different sensor probes need to be recalibrated frequently to guarantee a sufficient level of accuracy.

7. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

In the previous sections, we presented a review of WSN-based WQM systems, describing research and implementations as well as the different network architectures, energy considerations, data processing methods, water quality measurements, and other current developments in WQM. Although WSNs have been proposed by several authors as the appropriate infrastructure for WQM systems, there are still areas that require additional investigation.

In particular, although the different system architectures and implementations described in this article have highlighted the potential gains that can be achieved with the use of WSNs for monitoring water quality, they are still affected by the challenges that are limiting the wide diffusion and adoption of WSNs for environmental monitoring. In particular, challenges that arise with power management and energy harvesting, data computation, and data transfer must be considered. Security, privacy, and confidentiality of the data require particular consideration, as WQM systems rely on unsupervised devices deployed in the environment and need to provide online access to the acquired data. Moreover, issues specific to the WQM process arise from the particularly challenging water environment. These include biofouling, sensor drift, and underwater signal propagation.

In this section, we discuss some of the future research directions that require additional attention to improve the performance and reliability of WSN-based WQM systems.

7.1. Data Computation, Analysis, and Reporting

In most WSN-based WQM systems, data computation, analysis, and reporting are performed either at the local monitoring station (base station) or the remote monitoring center. The processes are automated and the outcomes are compared to predefined water quality measurements to draw conclusions. WSNs can be used to perform the computation on different water quality parameters sensed at various sampling locations to determine the water pollution arising at different points of the water source. Although WSNs have the capabilities to sense water parameters from different locations, to the best of our knowledge, specialized algorithms for combining the water quality parameters from the different sampling points have not yet been proposed. New algorithms should therefore be developed to perform the computations at the sample acquisition points in real time. The results from different sensors distributed across the water surface can be merged, and further computations can be performed at the local monitoring station. In addition, the algorithms could be further extended to check for completeness and accuracy before the records are processed for a final decision. This will improve the quality of the acquired data to be compared against the standard threshold values, therefore minimizing redundancies and inconsistencies and finally enabling the generation of higher-quality reports.

Future work should look at performing computation at all points within the WSN architecture—that is, at the source (among the sensor nodes), the local monitoring station, and the remote monitoring station. The sensor nodes' ability to perform computation at the source is essential, but then multiple sensors' data should also be considered for additional computation, performing CTP among the sensor nodes. Moreover, using CTP techniques, individual nodes may offload some of their computation to nearby nodes that have less to compute and/or more energy to process the data. When CTP is explored to its full potential, it could complement existing energy management schemes and augment the overall system performance. It is expected that for the WSN to become more energy efficient, distributed task processing among the sensor nodes in the network will be an effective solution.

In future work, the algorithms and mathematical models can be extended to predict the trends that may result from the changes in water quality. Intelligent systems that incorporate prediction tools can be used to predict the changes in water quality that occur as a result of human activities or other environmental factors to provide early warning signs. This predictive analysis will be essential for economic growth and development, and it will also enable future planning for longer periods of time, letting decision makers know what they can expect in the future [Chapman 1996]. Continuously analyzing and reporting the data collected from the sensor nodes in real time will increase the corrective mechanisms that can be put forth to enhance the quality of the water.

Apart from developing predictive tools, it is also essential to develop detection algorithms of contamination events during the monitoring process. The development of these algorithms will help trigger alarms to the monitoring center in real time to enable prompt intervention and thus limit the spread of the contamination. These real-time sensing platforms are promising for preservation of water resources, as access to high-frequency spatial and temporal information obtained from such platforms can facilitate real-time event detection. When quality and continuous flow of data are obtained from these platforms, novel analytical techniques can be adapted and employed by researchers to analyze the data. Analytic techniques such as time series analysis and anomaly detection, data mining, rule-based decision support techniques for making informed decisions, semisupervised learning for predictive analysis, and the implementation of optimization techniques can all support decision making [Sandha et al. 2016]. Hence, it is expedient to look into these techniques specifically for the data generated from WQM applications.

Currently, WQM application data are stored in local databases. Going forward, these data can be stored over multiple database instances in the cloud using linked-data technology for seamless analysis and limitless scalability by building more responsive geospatial queries to provide a rich interpretation of the condition of the different types of freshwater sources. Cloud computing, geospatial databases, and geographical information systems should be further explored.

7.2. Data Communication and Transmission

The communication architecture serves as the channel between the sensor nodes and the local monitoring station, and then between the local monitoring station and the remote monitoring station. Current works extend the communication design to incorporate a Web interface to enable user participation and reporting.

From our discussions on the communication techniques utilized in existing implementations, it can be noticed that modern wireless technologies such as WiFi Direct and 3G/4G cellular have not been fully explored within the existing implementations of WSN-based WQM systems. It is essential to explore the use of these other communication techniques within a WQM system because of their advantages in terms of bandwidth and coverage. For example, there can be a high gain in using WiFi Direct with respect to bandwidth and coverage as compared to ZigBee; however, in terms of power consumption, ZigBee has a lower power consumption compared to WiFi Direct. Similar considerations can be drawn for the technology used to connect the local monitoring station to the remote monitoring station or to the cloud where, for example, there are clear performance benefits in using LTE (e.g., bandwidth, latency, and coverage) at the expense of a higher energy consumption. These trade-offs should be explored in future WSN-based WQM systems.

In addition to the wireless technology to be used for both the local and remote communication, different network design techniques have yet to be explored. In particular, regarding the local WSN organization, the current body of work on this topic does not define a common network protocol stack to efficiently implement WSN-based WQM systems. As a result, when implementing these systems, researchers need to evaluate different medium access control (MAC) protocols, routing, and clustering techniques to determine the combination that provides the best overall performance. However, as described in Sections 3 and 5.1, most of the systems will share a common network design, such as similar node deployments and water quality parameters. In this perspective, there is the need for a comprehensive evaluation of the limitations on the system design imposed by the traditional network design phase, which can then drive the development of a suitable network protocol stack that can greatly benefit and speed up the deployment of WSN-based WQM systems. Moreover, research is needed to integrate and evaluate different topology control and sensor selection schemes to ensure application-specific QoS and reduce the network energy consumption by allowing, for example, nonselected nodes to sleep (duty cycling).

To interconnect the local WSN with the remote monitoring station, additional studies are necessary to identify the functionalities and number of gateway nodes to be deployed. In this regard, although increasing the number of gateway nodes removes the dependency from a single point of failure, thus improving the reliability/fault tolerance of the system, it will also increase the overall deployment and maintenance costs. Similarly, increasing the functionalities of the gateway requires, among others, an efficient management of the node energy consumption to allow for continuous operation.

Finally, it is important to note that the data communication and transmission protocols need to be integrated with the data computation, analysis, and reporting techniques used by the network. As an example, when gathering correlated data, as is the case for WSN-based WQM systems, a joint data acquisition, compression, and transmission scheme can greatly improve the performance of the network [Pattem et al. 2008].

7.3. Security, Privacy, and Data Confidentiality

Security is very important in preserving and protecting the reliability of a WQM system. One open issue that has not yet been tackled in most WQM systems utilizing WSNs is the security of data, both within the local network and when transmitting this data over the wide area network to the remote monitoring station. Security is critical, as a WQM system must ensure that high-quality water is provided to the consumer, and this is one of the guidelines that has not been given adequate attention in the literature [U.S. EPA 2015b]. Therefore, security mechanisms must be implemented from the water source to the point where the water is utilized by the consumer.

There are several issues that affect the physical security of the local monitoring station, the sensors themselves, and the network in general. To ensure system and data integrity, it is essential to examine the threats that may affect the WQM process and system. Implementing and deploying a WSN architecture requires a high level of physical security [U.S. EPA 2015b], which ensures the integrity of water distribution facilities and deters acts of tampering, theft, and vandalism of the sensor nodes and the local monitoring station.

Current research has not paid much attention to security issues within WQM systems, as traditionally the data was manually obtained from the WQM systems and was then, most of the time, accessed only by a small group of decision makers. However, in recent WQM systems employing WSNs, the data acquisition is automatic and does not require user interaction, and there has been a shift toward an unrestricted Web-based data access. The entire WQM architecture is now tracked online using different Web technologies, distributed databases, servers, and software systems [Storey et al. 2011]. As described in Section 6, most of the existing WQM implementations do not include any security functionality.

In what follows, we briefly present some node and data security mechanisms that need to be considered at the different phases of the WSN framework presented in Section 5. At the network level, we consider the node and data security concerns. The nodes can be tampered with or destroyed by intruders at the water site. Once compromised, these nodes can lure other nodes to send data to them (e.g., a sinkhole or wormhole type of attack). Once received by the compromised node(s), the data can be modified, making the data invalid. The compromised node(s) could also affect sensor activities and traffic analysis. Attackers could also set up other sensor devices nearby the collection point to eavesdrop on transmissions of the WQM data from the WSN. One major concern in WSNs is extending the network lifetime. A security breach and compromised node(s) may exhaust the batteries of the sensor nodes, rendering the network inoperable [Wang et al. 2006; Chen et al. 2009].

At the same time, data integrity and confidentiality is paramount since hackers or intruders can intercept the network and alter the data. This will affect the analysis and the results, and consequently affect decision making. In addition, intruders can attack the route of data transfer and redirect the data for their own gain. When unauthorized users gain access into the database, they may attempt to modify its contents. Therefore, setting up authentication and authorization levels will increase node security. Additionally, injecting malicious code can affect the analyzed data in the system. Malicious code can also be injected into the database, which can result in data loss or data inconsistency [Wang et al. 2006; Chen et al. 2009].

Given the preceding discussion, research is needed to integrate existing security mechanisms within WSN-based WQM systems or, if needed, develop new security measures to protect the entire system against these types of attacks.

7.4. Energy Harvesting

Energy is a precious resource in WSNs, as sensor devices require energy to sense different water quality parameters and to process and transmit the data to the local monitoring station. The need for a continuous source of energy, coupled with the difficulty in replacing the batteries for the sensor nodes at the water source, has led to research into energy harvesting techniques to harness different renewable energy sources.

The main focus of the energy harvesting research to date has been to find suitable methods for opportunistically gathering energy/power from the immediate environment where the sensor network is deployed. The idea is to augment the battery power and store the harvested energy for future use in rechargeable batteries or supercapacitors. In Section 5.3, Table VII shows that in existing WSN-based WQM systems, energy is harvested mainly from the sun using solar panels, and this harvested energy is then used to charge lithium-ion batteries. Solar energy is considered to provide the highest power density among all energy harvesting sources ($15mW/cm^2$ on a bright sunny day) [Morais et al. 2008].

Additionally, as described in Section 5.3, energy management schemes are implemented to regulate the amount of energy used within a sensor node and at the monitoring station. Current approaches for reducing energy drain include the use of ultralow power sensors, duty cycling based on long sleep times, the use of low-power radios, voltage scaling, and the use of algorithmic techniques at different levels of the protocol stack [Mathúna et al. 2008]. When implementing the energy minimization schemes, the sensor nodes are put to sleep or in an idle state as often as possible, and they are only made active for the time the nodes are expected to perform operations such as sampling, data processing, and data transfer. Additional research in this area can ensure that the node power requirements are low enough to be supported by the harvested energy and the rechargeable batteries for long periods of time.

There are several energy harvesting sources that are yet to be considered for use in WSN-based WQM systems. One such energy harvesting source is kinetic energy that can be obtained from flowing water [Morais et al. 2008]. Research done in this area is still in its infancy, but when fully explored and implemented, this could provide significant support for the energy requirements of the sensor nodes used in the WSN-based WQM systems.

Another interesting area to be studied is harvesting energy from radio frequency (RF) sources. This new area also needs to be explored in conjunction with WQM environments. According to Mouser Electronics, Inc. [2015], RF signals can be obtained from natural sources such as sun flares and lightning, and from stars in space that radiate RF waves as they age. Apart from the natural sources, RF signals can also be obtained from the artificially created electromagnetic radio waves created by television broadcasting, radar systems, computer and mobile platform networks, remote control, and remote metering/monitoring. With these vast application domains, it may be possible to generate usable energy from these RF sources. Particularly for WQM, energy can be harvested from water current depending on the water flow rate, either from water flow with greater pressure (turbulent) or flow at a constant velocity. The energy derived from flowing water is mainly kinetic. In harvesting energy from flowing water to power sensor nodes, researchers could explore either the use of small turbines or the use of temperature gradient (i.e., difference in temperature in the water). Energy harvesting from water flow is characterized by low-level power generation that may be useful for low-powered devices such as sensor nodes. Small turbines based on Pelton and propeller designs have been constructed for small-scale energy harvesting systems by Azevedo and Santos [2012]. These hydro turbines are good for generating power directly to charge the batteries of sensor nodes deployed for monitoring freshwater sources. This could serve as a good alternative for harvesting energy to power sensor nodes deployed in shady areas where harvesting energy from solar panels is not feasible. Other devices designed to harvest energy from flowing water include the use of a flag-shaped piezoelectric polymer harvester and microstructured piezo-bimorph generator [Pobering and Schwesinger 2004], an Intellisonde probe (to measure water flow, temperature, and pressure) [Ye and Soga 2011], and an energy harvesting eel [Taylor et al. 2001]. Although these technologies have not yet been fully harnessed and implemented for monitoring water quality in a WSN environment, advances in the manufacturing of wireless sensor nodes are expected to increase to support the implementation of these technologies for WQM.

Additionally, it would be beneficial to consider a hybrid energy harvesting system that derives energy from several different sources simultaneously to ensure continuous operation of the WSN-based WQM system. It is therefore essential to determine how to efficiently incorporate these new renewable energy sources within the WQM environment, where nodes require energy to perform sensing, computation, and data transfer.

Based on the energy consumption in various states in WQM applications (i.e., sensing, processing, and transmission), the development of a complete energy evaluation model is required. This energy evaluation model will take into account the types of parameters that need to be sensed and the sensing frequency, the amount of energy to be harvested from the different harvesting sources, and finally the energy requirement of the protocols and services (e.g., routing protocols or localization). When modeled accurately, these factors will enable a prolonged network lifetime.

7.5. Biofouling

WQM is aimed at collecting data for freshwater analysis. Hence, most sensor devices used for WQM are immersed in the water for a long period of time. In such applications, due to the long-term and continuous monitoring, sensor protection from fouling becomes vital to improve the accuracy of the water quality data obtained over time. Whereas for WSN-based environmental monitoring the power management and battery lifetime are the main issues, for WQM systems the attention is now turning to biofouling as a key factor in determining the length of time that water quality sensors can stay deployed in freshwater sources when these sensors are immersed in the various water bodies [Xylem Inc. 2015a].

The introduction of remote monitoring of water quality parameters with sensor devices makes it difficult to reduce fouling of the devices [Wagner et al. 2006]. To enhance measurement accuracy and prolong the lifetime of the sensors, Delauney et al. [2010] analyzed the biofouling effects on marine sensors' measurements and proposed some promising techniques for the biofouling protection of in situ sensors. The effect of biofouling was also discussed in Regan et al. [2009], in which the authors pointed out that the optical turbidity sensor readings used in their experiments degraded, possibly owing to biofouling, and the data collected was not consistent with the levels that would have been expected over a period of time.

According to Xu et al. [2014], biofouling developing on a sensor device surface is subject to several factors that relate to the different categories of water quality parameters (i.e., chemical, physical, and biological). Biofouling decreases the operating lifetime of sensors deployed in the field and on the whole introduces a degree of error into the data obtained from the sensing operation [Regan et al. 2009]. In MEM, different techniques have been studied to prevent fouling developing on materials used for detecting marine water parameters, such as wiper mechanisms, copper corrosion mechanisms, and chlorine evolution mechanisms [Delauney et al. 2010]. Challenges with these techniques in MEM applications are that the sensor node heads should be designed in such a way as to make it suitable for wiper cleaning and the wipers must be in good condition to perform such functionalities. Additionally, adapting copper corrosion mechanisms for sensor protection does not easily work for existing sensors, and the cost is also relatively high.

With regard to WQM, researchers and manufacturers should look into new ways that WQM sensor devices can be designed with antifouling capabilities to ensure that the sensor devices are operational at all times and to extend the lifetime of the sensor nodes. This is necessary because the existing sensors with antifouling capabilities for freshwater monitoring (YSI EXO sonde and YSI 6-Series sonde have shorter deployment duration, ranging from 60 to 90 days and 30 days, respectively (site dependent) [Xylem Inc. 2015a]. These sensor devices should be able to support local and remote communication technologies. Researchers should also consider the power consumption of sensors in an attempt to introduce new design choices to overcome fouling. In designing these new sensor devices, cost should be considered since the current techniques adapted in MEM are costly to implement. Therefore, low-cost sensor devices that can support longer deployment duration with antifouling capabilities for WQM should be explored and developed for commercial purposes. It will also be beneficial for the research community to analyze the biofouling effects on sensor devices used for measuring water quality parameters in freshwater sources and propose various possible solutions for biofouling protection of sensors.

7.6. Sensor Drift and Calibration

According to Holmberg et al. [1997], *drift* is a temporal shift of sensor response under constant physical and chemical conditions. These conditions are typically induced by water damage to the sensors or water fluxes within the ground, which could affect the interpretation of data to be seen as measurement errors [Luethi and Phillips 2016]. Luethi and Phillips [2016] discussed the challenges and solutions for long-term permafrost borehole temperature monitoring and data interpretation. Utilizing WSN for WQM requires sensors to detect certain parameters in real time, which comes with technology-related limitations known as sensor drift. Sensor drift has to be solved when sensors are going to be deployed for monitoring purposes in which the data obtained might be used for process control and decision making.

Sensor drift affects chemical and biochemical sensors, which are mainly used for sensing and measuring chemical parameters in fresh water due to aging of the sensors, or environmental changes such as temperature and pressure variations [Holmberg et al. 1997; Bourgeois et al. 2003]. Sensor drift affects the accuracy of data collected for analysis over time. This means that using the data for trend analysis or for prediction may result in data inaccuracy and inconsistency. Another limitation with respect to sensor drift is related to calibration. A calibration drift is an electronic drift in the equipment from the last time it was calibrated and is determined by the difference between readings on check standards (solutions that contain a range of routine and challenging analytes, useful for setting up instrumentation or troubleshooting) of a cleaned sensor and a calibrated sensor [Wagner et al. 2006]. Existing techniques use adaptive estimation algorithms to model drifting of sensors in odor recognition applications and adaptive drift compensation models for malodorous sources in environment applications [Holmberg et al. 1997; Romain et al. 2002].

Sensors deployed to monitor freshwater sources over a long period of time are liable to drift, and this drift must be taken into account in data processing/aggregation. It would be beneficial for researchers to study and develop new algorithms and models that consider sensor drift in WSN-based WQM systems. Moreover, research efforts should be put on making the existing sensor devices more stable and less affected by drift when deployed for a long time. In addition, researchers should incorporate sensor drift in protocol analysis when designing various protocols for WSNs for WQM.

7.7. Underwater Propagation

Communication among nodes in underwater WSNs is a challenging task due to limited availability of bandwidth, signal fading, node failure, and propagation delay [Tan et al. 2011; Suciu et al. 2015]. Underwater communication in marine water sources is challenging because GPS signals and other communication technologies, such as ZigBee, do not propagate well through water; hence, an alternative communication such as acoustic communication is needed for such environments [Suciu et al. 2015]. In WQM, most of the deployed systems use terrestrial communication technologies (e.g., GSM, GPRS, ZigBee, WiFi, and WiMax) since the sensor nodes normally are incorporated with a radio module for wireless communication. In monitoring underground water, two or more communication technologies could be adapted for real-time monitoring. Combining underwater acoustic communication and any of the terrestrial communication standards (i.e., GPRS or GSM) will be a better choice when monitoring freshwater sources that require the sensors to be placed underwater. In considering the combination of both underwater and terrestrial communication standards in WQM applications (especially for underground WQM), researchers should look into issues related to the channel and the protocol (e.g., MAC), as well as issues that have to do with the node mobility.

8. CONCLUSIONS

In this article, we provide a survey of the current state of the art in the design and implementation of WSN-based WQM systems, describing a framework for WSN-based WQM systems and discussing the technologies used at each stage in the monitoring process. Furthermore, we describe existing implementations that use WSNs to monitor water quality. The communication techniques, energy management schemes, and data processing approaches employed in these systems are also discussed.

There have been many advances in WQM over the years; however, as highlighted in this article, there are several open issues that need additional research to further the use of WSN-based WQM systems. To the best of our knowledge, there are no security mechanisms discussed in this area. The safety of the data and the entire network in the WQM process is paramount. Issues with malicious attackers or physical breakdown of the infrastructure, eavesdropping, and traffic analysis should be thoroughly considered in future systems. Moreover, energy harvesting techniques that can support the sensor network to make it operational for longer periods of time should also be researched. Finally, data processing and aggregation algorithms should be developed to ensure proper data management, and biofouling, sensor drift, and underwater communication are all issues that should be considered in the development of WSNs for WQM. Addressing these issues will enhance the overall performance and utility of WSN-based WQM systems.

REFERENCES

F. Adamo, F. Attivissimo, C. G. C. Carducci, and A. M. L. Lanzolla. 2015. A smart sensor network for sea water quality monitoring. *IEEE Sensors Journal* 15, 5, 2514–2522.

I. F. Akyildiz and E. P. Stuntebeck. 2006. Wireless underground sensor networks: Research challenges. *Ad Hoc Networks* 4, 6, 669–686. DOI:http://dx.doi.org/10.1016/j.adhoc.2006.04.003

I. F. Akyildiz, P. Wang, and S.-C. Lin. 2016. SoftWater: Software-defined networking for next-generation underwater communication systems. *Ad Hoc Networks* 46, 1–11.

C. Albaladejo, P. Sánchez, A. Iborra, F. Soto, J. A. López, and R. Torres. 2010. Wireless sensor networks for oceanographic monitoring: A systematic review. *Sensors* 10, 7, 6948–6968.

E. Aleisa. 2013. Wireless sensor networks framework for water resource management that supports QoS in the kingdom of Saudi Arabia. In *Proceedings of the Conference on Ambient Systems, Networks, and Technologies (ANT'13)*. 232–239. DOI:http://dx.doi.org/10.1016/j.procs.2013.06.034

A. Alkandari, M. Alnasheet, Y. Alabduljader, and S. M. Moein. 2011. Wireless sensor network (WSN) for water monitoring system: Case study of Kuwait beaches. *International Journal of Digital Information and Wireless Communications* 1, 4, 709–717.

M. K. Amruta and M. T. Satish. 2013. Solar powered water quality monitoring system using wireless sensor network. In *Proceedings of the International Multi-Conference on Automation, Computing, Communication, Control, and Compressed Sensing (iMac4s'13)*. IEEE, Los Alamitos, CA, 281–285. DOI:http://dx.doi.org/10.1109/iMac4s.2013.6526423

I. Amundson and X. D. Koutsoukos. 2009. A survey on localization for mobile wireless sensor networks. In *Mobile Entity Localization and Tracking in GPS-Less Environments*. Lecture Notes in Computer Science, Vol. 5801. Springer, 235–254. DOI:http://dx.doi.org/10.1007/978-3-642-04385-7_16

Analytical Technology, Inc. 2015. Fast, Reliable Fluoride Monitoring! Retrieved November 12, 2016, from http://www.analyticaltechnology.com/analyticaltechnology/gas-water-monitors/product.aspx?ProductID=1076&ImageID=1360.

ATI Analytic Technologies. 2016. Measuring the Air We Breathe and the Water We Drink. Available at http://www.analyticaltechnology.com.

J. A. R. Azevedo and F. E. S. Santos. 2012. Energy harvesting from wind and water for autonomous wireless sensor nodes. *IET Circuits, Devices and Systems* 6, 6, 413–420. DOI:http://dx.doi.org/10.1049/iet-cds.2011.0287

J. Bartram and R. Ballance. 1996. *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes.* E&FN Spon, London, UK.

M. S. BenSaleh, S. M. Qasim, A. M. Obeid, and A. Garcia-Ortiz. 2013. A review on wireless sensor network for water pipeline monitoring applications. In *Proceedings of the 2013 International Conference on Collaboration Technologies and Systems (CTS'13)*. IEEE, Los Alamitos, CA, 128–131.

J. Bhardwaj, K. K. Gupta, and R. Gupta. 2015. A review of emerging trends on water quality measurement sensors. In *Proceedings of the International Conference on Technologies for Sustainable Development (ICTSD'15)*. IEEE, Los Alamitos, CA, 1–6. DOI:http://dx.doi.org/10.1109/ICTSD.2015.7095919

S. Bhattacharya, S. Sridevi, and R. Pitchiah. 2012. Indoor air quality monitoring using wireless sensor network. In *Proceedings of the 6th International Conference on Sensing Technology (ICST'12)*. IEEE, Los Alamitos, CA, 422–427. DOI:http://dx.doi.org/10.1109/ICSensT.2012.6461713

W. Bourgeois, J. E. Burgess, and R. M. Stuetz. 2001. On-line monitoring of wastewater quality: A review. *Journal of Chemical Technology and Biotechnology* 76, 4, 337–348.

W. Bourgeois, A.-C. Romain, J. Nicolas, and R. M. Stuetz. 2003. The use of sensor arrays for environmental monitoring: Interests and limitations. *Journal of Environmental Monitoring* 5, 6, 852–860.

D. G. Burke and J. Allenby. 2014. Low Cost Water Quality Monitoring Needs Assessment. Retrieved November 12, 2016, from http://burkeassociates.biz/low-cost-water-quality-monitoring-needs-assessment/.

J. V. Capella, A. Bonastre, R. Ors, and M. Peris. 2013. In line river monitoring of nitrate concentration by means of a wireless sensor network with energy harvesting. *Sensors and Actuators B: Chemical* 177, 419–427.

D. Carboni, A. Gluhak, J. A. McCann, and T. H. Beach. 2016. Contextualising water use in residential settings: A survey of non-intrusive techniques and approaches. *Sensors* 16, 5, 738.

M. L. Carroll, S. Cochrane, R. Fieler, R. Velvin, and P. White. 2003. Organic enrichment of sediments from salmon farming in Norway: Environmental factors, management practices, and monitoring techniques. *Aquaculture* 226, 14, 165–180. DOI:http://dx.doi.org/10.1016/S0044-8486(03)00475-7

CENSAR Technologies. 2016. Drinking Water Quality—Distribution System Monitoring—Water Plants. Retrieved November 12, 2016, from http://www.censar.com.

N. Chaamwe. 2010. Wireless sensor networks for water quality monitoring: A case of Zambia. In *Proceedings of the 4th International Conference on Bioinformatics and Biomedical Engineering (iCBBE'10)*. IEEE, Los Alamitos, CA, 1–6. DOI:http://dx.doi.org/10.1109/ICBBE.2010.5515792

D. Chapman. 1996. *Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring* (2nd. ed.). University Press, Cambridge, UK.

C. Chen, X. Jun-Ming, and G. Hui-Fang. 2011. Polluted water monitoring based on wireless sensor. In *Proceedings of the International Conference on Electronics, Communications, and Control (ICECC'11)*. IEEE, Los Alamitos, CA, 961–963. DOI:http://dx.doi.org/10.1109/ICECC.2011.6066393

X. Chen, K. Makki, K. Yen, and N. Pissinou. 2009. Sensor network security: A survey. *IEEE Communications Surveys Tutorials* 11, 2, 52–73. DOI:http://dx.doi.org/10.1109/SURV.2009.090205

W.-Y. Chung and J.-H. Yoo. 2015. Remote water quality monitoring in wide area. *Sensors and Actuators B: Chemical* 215, 51–57.

Connecticut Department of Public Health. 2015. Manganese in Drinking Water. Retrieved November 12, 2016, from http://www.ct.gov/dph/lib/dph/drinking_water/pdf/manganese.pdf.

L. E. Cordova-Lopez, A. Mason, J. D. Cullen, A. Shaw, and A. I. Al-Shamma'a. 2007. Online vehicle and atmospheric pollution monitoring using GIS and wireless sensor networks. In *Journal of Physics: Conference Series*, Vol. 76. IOP Publishing Ltd, Bristol, UK, 12–19. DOI:http://dx.doi.org/10.1088/1742-6596/76/1/012019

J. Cotruvo. 2011. Hardness in Drinking-Water: Background Document for Development of WHO *Guidelines for Drinking-Water Quality*. Retrieved November 12, 2016, from http://www.who.int/water_sanitation_health/dwq/chemicals/hardness.pdf.

C. E. H. Curiel, V. H. B. Baltazar, and J. H. P. Ramírez. 2016. Wireless sensor networks for water quality monitoring: Prototype design. *International Journal of Environmental, Chemical, Ecological, Geological, and Geophysical Engineering* 10, 2, 158–163.

L. Delauney, C. Compere, and M. Lehaitre. 2010. Biofouling protection for marine environmental sensors. *Ocean Science* 6, 2, 503–511.

Y. Derbew and M. Libsie. 2014. A wireless sensor network framework for large-scale industrial water pollution monitoring. In *Proceedings of the IST-Africa Conference*. IEEE, Los Alamitos, CA, 1–8. DOI:http://dx.doi.org/10.1109/ISTAFRICA.2014.6880619

S. Dhawan. 2007. Analogy of promising wireless technologies on different frequencies: Bluetooth, WiFi, and WiMAX. In *Proceedings of the 2nd International Conference on Wireless Broadband and Ultra Wideband Communications*. IEEE, Los Alamitos, CA, 14. DOI:http://dx.doi.org/10.1109/AUSWIRELESS.2007.27

J. Dong, G. Wang, H. Yan, J. Xu, and X. Zhang. 2015. A survey of smart water quality monitoring system. *Environmental Science and Pollution Research* 22, 7, 4893–4906.

M. Eckenfelder. 2001. Government of British Columbia, Environmental Protection Division: Water Quality Guidelines for Temperature. Retrieved November 12, 2016, from http://www.env.gov.bc.ca/wat/wq/BCguidelines/temptech/temperature.html.

D. Estrin, L. Girod, G. Pottie, and M. Srivastava. 2001. Instrumenting the world with wireless sensor networks. In *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, Vol. 4. IEEE, Los Alamitos, CA, 2033–2036. DOI:http://dx.doi.org/10.1109/ICASSP.2001.940390

D. Estrin, A. Sayeed, and M. Srivastava. 2002. Wireless sensor networks. In *Proceedings of the 8th ACM International Conference on Mobile Computing and Networking (MobiCom'02)*, Vol. 255. ACM, Atlanta, GA.

K. Farrell-Poe. 2005. Water Quality and Monitoring. Available at https://cals.arizona.edu/watershedsteward/resources/docs/guide/(10)Water%20Quality.pdf.

A. Faustine, A. Mvuma, H. Mongi, M. Gabriel, A. Tenge, and S. Kucel. 2014. Wireless sensor networks for water quality monitoring and control within Lake Victoria basin: Prototype development. *Wireless Sensor Network* 6, 12, 281–290. DOI:http://dx.doi.org/10.4236/wsn.2014.612027

D. Feng, L. Lu, Y. Yuan-Wu, G. Li, S. Li, and G. Feng. 2014. Device-to-device communications in cellular networks. *IEEE Communications Magazine* 52, 4, 49–55.

M. S. Garcia, D. Carvalho, O. Zlydareva, C. Muldoon, B. F. Masterson, M. J. O'Grady, W. G. Meijer, J. J. O'Sullivan, and Gregory M. P. O'Hare. 2012. *An Agent-Based Wireless Sensor Network for Water Quality Data Collection*. Springer, Berlin, Germany, 454–461. DOI:http://dx.doi.org/10.1007/978-3-642-35377-2_63

F. Ge and Y. Wang. 2016. Energy efficient networks for monitoring water quality in subterranean rivers. *Sustainability* 8, 6, 526.

H. B. Glasgow, J. M. Burkholder, R. E. Reed, A. J. Lewitus, and J. E. Kleinman. 2004. Real-time remote monitoring of water quality: A review of current applications, and advancements in sensor, telemetry, and computing technologies. *Journal of Experimental Marine Biology and Ecology* 300, 1, 409–448.

L. M. Goddijn and M. White. 2006. Using a digital camera for water quality measurements in Galway Bay. *Estuarine, Coastal and Shelf Science* 66, 3, 429–436.

Hach. 2016. Leading the Way in Water Analytics. Available at http://www.hach.com.

D. G. Hadjimitsis, M. G. Hadjimitsis, K. Themistocleous, and A. Agapiou. 2009. Integration of micro-sensor technology and remote sensing for monitoring coastal water quality in a municipal beach and other areas in Cyprus. In *Proceedings of SPIE 7472: Remote Sensing for Agriculture, Ecosystems, and Hydrology XI*. 1–8. DOI:http://dx.doi.org/10.1117/12.830582

J. Hall, A. D. Zaffiro, R. B. Marx, P. C. Kefauver, E. R. Krishnan, R. C. Haught, and J. G. Herrmann. 2007. On-line water quality parameters as indicators of distribution system contamination. *Journal of the American Water Works Association* 99, 1, 66–77.

Q.-D. Ho, Y. Gao, and T. Le-Ngoc. 2013. Challenges and research opportunities in wireless communication networks for smart grid. *IEEE Wireless Communications* 20, 3, 89–95.

M. Holmberg, F. A. M. Davide, C. Di Natale, A. D'Amico, F. Winquist, and I. Lundström. 1997. Drift counteraction in odour recognition applications: Lifelong calibration method. *Sensors and Actuators B: Chemical* 42, 3, 185–194.

In-Situ. 2016. Water Monitoring Equipment, Water Monitoring Testing, and More. Available at https://in-situ.com.

Trupti Jadhav, Ulka Patil, Sonali Masrankar, Shweta Mestry, Manjiri Pathak, Vijaya Jadhav, and Savita Chavan. 2016. Analysing quality of water and soil using WSN. *Imperial Journal of Interdisciplinary Research* 2, 5, 1033–1035.

P. Jiang, H. Xia, Z. He, and Z. Wang. 2009. Design of a water environment monitoring system based on wireless sensor networks. *Sensors* 9, 8, 6411–6434.

N. Jin, R. Ma, Y. Lv, X. Lou, and Q. Wei. 2010. A novel design of water environment monitoring system based on WSN. In *Proceedings of the 2010 International Conference on Computer Design and Applications (ICCDA'10)*, Vol. 2. IEEE, Los Alamitos, CA, V2-593–V2-597. DOI:http://dx.doi.org/10.1109/ICCDA.2010.5541305

Y. Kaizu, M. Iio, H. Yamada, and N. Noguchi. 2011. Development of unmanned airboat for water-quality mapping. *Biosystems Engineering* 109, 4, 338–347.

E. Karami, F. M. Bui, and H. H. Nguyen. 2012. Multisensor data fusion for water quality monitoring using wireless sensor networks. In *Proceedings of the 4th International Conference on Communications and Electronics (ICCE'12)*. IEEE, Los Alamitos, CA, 80–85. DOI:http://dx.doi.org/10.1109/CCE.2012.6315875

F. A. Katsriku, M. Wilson, G. G. Yamoah, J. D. Abdulai, B. M. A. Rahman, and K. T. V. Grattan. 2015. Framework for time relevant water monitoring system. In *Computing in Research and Development in Africa*. Springer, Basel, Switzerland, 3–19. DOI:http://dx.doi.org/10.1007/978-3-319-08239-4_1

K. K. Khedo, R. Perseedoss, and A. Mungur. 2010. A wireless sensor network air pollution monitoring system. arXiv:1005.1737. http://arxiv.org/abs/1005.1737.

O. Korostynska, A. Mason, and A. I. Al-Shamma'a. 2013. Monitoring pollutants in wastewater: Traditional lab based versus modern real-time approaches. In *Smart Sensors for Real-Time Water Quality Monitoring*. Vol. 4. Springer, Berlin, Germany, 1–24. DOI:http://dx.doi.org/10.1007/978-3-642-37006-9_1

Laird Technologies. 2012. Understanding Range for RF Devices. Retrieved November, 2016, from http://www.lairdtech.com/solutions/white-papers/understanding-range-rf-devices.

C.-T. Lee and K.-L. Wong. 2010. Planar monopole with a coupling feed and an inductive shorting strip for LTE/GSM/UMTS operation in the mobile phone. *IEEE Transactions on Antennas and Propagation* 58, 7, 2479–2483.

Libelium. 2014. Smart Water Sensors to Monitor Water Quality in Rivers, Lakes and the Sea. Retrieved November 12, 2016, from http://www.libelium.com/smart-water-sensors-monitor-water-quality-leakages-wastes-in-rivers-lakes-sea.

Libelium. 2016. Connecting Sensors to the Cloud. Available at http://www.libelium.com.

K. Loizou and E. Koutroulis. 2016. Water level sensing: State of the art review and performance evaluation of a low-cost measurement system. *Measurement* 89, 204–214.

R. Luethi and M. Phillips. 2016. Challenges and solutions for long-term permafrost borehole temperature monitoring and data interpretation. *Geographica Helvetica* 71, 121–131.

C. Ó. Mathúna, T. O'Donnell, R. V. Martinez-Catala, J. Rohan, and B. O'Flynn. 2008. Energy scavenging for long-term deployable wireless sensor networks. *Talanta* 75, 3, 613–623.

M. L. McFarland and T. L. Provin. 1999. Hydrogen Sulfide in Drinking Water: Causes and Treatment Alternatives. Retrieved November 12, 2016, from http://soiltesting.tamu.edu/publications/L-5312.pdf.

D. Mo, Y. Zhao, and S. Chen. 2012. Automatic measurement and reporting system of water quality based on GSM. In *Proceedings of the 2012 2nd International Conference on Intelligent System Design and Engineering Application (ISDEA'12)*. IEEE, Los Alamitos, CA, 1007–1010. DOI:http://dx.doi.org/10.1109/ISdea.2012.595

A. H. Moon, U. Iqbal, and G. M. Bhat. 2015. Secured data acquisition system for smart water applications using WSN. *Indian Journal of Science and Technology* 9, 10, 1–11.

R. Morais, S. G. Matos, M. A. Fernandes, A. L. G. Valente, S. F. S. P. Soares, P. J. S. G. Ferreira, and M. J. C. S. Reis. 2008. Sun, wind and water flow as energy supply for small stationary data acquisition platforms. *Computers and Electronics in Agriculture* 64, 2, 120–132.

Mouser Electronics, Inc. 2015. RF Wireless Technology. Retrieved November 12, 2016, from http://www.mouser.com/applications/rf-wireless-technology/.

K. Murphy, B. Heery, T. Sullivan, D. Zhang, L. Paludetti, K. T. Lau, D. Diamond, E. Costa, and F. Regan. 2015. A low-cost autonomous optical sensor for water quality monitoring. *Talanta* 132, 520–527.

M. A. Nasirudin, U. N. Za'bah, and O. Sidek. 2011. Fresh water real-time monitoring system based on wireless sensor network and GSM. In *Proceedings of the IEEE Conference on Open Systems (ICOS'11)*. IEEE, Los Alamitos, CA, 354–357. DOI:http://dx.doi.org/10.1109/ICOS.2011.6079290

N. Nasser, A. Ali, L. Karim, and S. Belhaouari. 2013. An efficient wireless sensor network-based water quality monitoring system. In *Proceedings of the 2013 ACS International Conference on Computer Systems and Applications (AICCSA'13)*. IEEE, Los Alamitos, CA, 1–4.

T.-D. Nguyen, T. T. Thanh, L.-L. Nguyen, and H.-T. Huynh. 2015. On the design of energy efficient environment monitoring station and data collection network based on ubiquitous wireless sensor networks. In *Proceedings of the 2015 IEEE RIVF International Conference on Computing and Communication*

Technologies-Research, Innovation, and Vision for the Future (RIVF'15). IEEE, Los Alamitos, CA, 163–168.

R. Noble and R. Weisberg. 2005. A review of technologies for rapid detection of bacteria in recreational waters. *Journal of Water and Health* 3, 381–392.

E. O'Connor, D. Zhang, A. F. Smeaton, N. E. O'Connor, and F. Regan. 2012. Multi-modal sensor networks for more effective sensing in Irish coastal and freshwater environments. In *Proceedings of the 2012 Oceans Conference*. IEEE, Los Alamitos, CA, 1–9. DOI:http://dx.doi.org/10.1109/OCEANS.2012.6404894

B. O'Flyrm, R. Martinez, J. Cleary, C. Slater, F. Regan, D. Diamond, and H. Murphy. 2007. SmartCoast: A wireless sensor network for water quality monitoring. In *Proceedings of the 32nd IEEE Conference on Local Computer Networks (LCN'07)*. IEEE, Los Alamitos, CA, 815–816. DOI:http://dx.doi.org/10.1109/LCN.2007.34

C. G. Panayiotou, D. Fatta, and M. P. Michaelides. 2005. *Environmental Monitoring Using Wireless Sensor Networks*. Technical Report. Department of Electrical Engineering, University of Cyprus, Nicosia.

L. Parra, E. Karampelas, S. Sendra, J. Lloret, and J. J. P. C. Rodrigues. 2015. Design and deployment of a smart system for data gathering in estuaries using wireless sensor networks. In *Proceedings of the 2015 International Conference on Computer, Information, and Telecommunication Systems (CITS'15)*. IEEE, Los Alamitos, CA, 1–5.

S. Pattem, B. Krishnamachari, and R. Govindan. 2008. The impact of spatial correlation on routing with compression in wireless sensor networks. *ACM Transactions on Sensor Networks* 4, 4, Article No. 24. DOI:http://dx.doi.org/10.1145/1387663.1387670

J. Peng. 2009. The design of wetland water environmental monitoring system using digital video based on wireless sensor networks. In *Proceedings of the WRI International Conference on Communications and Mobile Computing (CMC'09)*, Vol. 2. IEEE, Los Alamitos, CA, 391–395. DOI:http://dx.doi.org/10.1109/CMC.2009.220

D. P. Pereira, W. R. A. Dias, M. Braga, R. D. S. Barreto, C. M. S. Figueiredo, and V. Brilhante. 2008. Model to integration of RFID into wireless sensor network for tracking and monitoring animals. In *Proceedings of the 11th IEEE International Conference on Computational Science and Engineering (CSE'08)*. IEEE, Los Alamitos, CA, 125–131. DOI:http://dx.doi.org/10.1109/CSE.2008.25

S. Pobering and N. Schwesinger. 2004. A novel hydropower harvesting device. In *Proceedings of the 2004 International Conference on MEMS, NANO, and Smart Systems (ICMENS'04)*. IEEE, Los Alamitos, CA, 480–485.

O. Postolache, J. D. Pereira, and P. S. Girão. 2014. Wireless sensor network-based solution for environmental monitoring: Water quality assessment case study. *IET Science, Measurement, and Technology* 8, 6, 610–616.

M. Rahnema. 1993. Overview of the GSM system and protocol architecture. *IEEE Communications Magazine* 31, 4, 92–100. DOI:http://dx.doi.org/10.1109/35.210402

A. S. Rao, S. Marshall, J. Gubbi, M. Palaniswami, R. Sinnott, and V. Pettigrovet. 2013. Design of low-cost autonomous water quality monitoring system. In *Proceedings of the Conference on Advances in Computing, Communications, and Informatics (ICACCI'13)*. IEEE, Los Alamitos, CA, 14–19. DOI:http://dx.doi.org/10.1109/ICACCI.2013.6637139

N. Rapousis, M. Katsarakis, and M. Papadopouli. 2015. QoWater: A crowd-sourcing approach for assessing the water quality. In *Proceedings of the ACM Conference on Cyber-Physical Systems for Smart Water Networks (CySWater'15)*. ACM, New York, NY, Article No. 11. DOI:http://dx.doi.org/10.1145/2738935.2738946

Z. Rasin and M. R. Abdullah. 2009. Water quality monitoring system using ZigBee based wireless sensor network. *International Journal of Engineering and Technology* 9, 10, 24–28.

F. Regan, A. Lawlor, B. O. Flynn, J. Torres, R. Martinez-Catala, C. O'Mathuna, and J. Wallace. 2009. A demonstration of wireless sensing for long term monitoring of water quality. In *Proceedings of the Conference on Local Computer Networks*. IEEE, Los Alamitos, CA, 819–825. DOI:http://dx.doi.org/10.1109/LCN.2009.5355047

C. Ritter, M. Cottingham, J. Leventhal, and A. Mickelson. 2014. Remote delay tolerant water quality montoring. In *Proceedings of the 2014 IEEE Global Humanitarian Technology Conference (GHTC'14)*. IEEE, Los Alamitos, CA, 462–468. DOI:http://dx.doi.org/10.1109/GHTC.2014.6970323

A.-C. Romain, P. André, and J. Nicolas. 2002. Three years experiment with the same tin oxide sensor arrays for the identification of malodorous sources in the environment. *Sensors and Actuators B: Chemical* 84, 2, 271–277.

T. G. Sanders. 1983. *Design of Networks for Monitoring Water Quality*. Water Resources Publication, Littleton, CO.

S. S. Sandha, S. Randhawa, and B. Srivastava. 2016. *Blue Water: A Common Platform to Put Water Quality Data in India to Productive Use by Integrating Historical and Real-Time Sensing Data*. IBM Research Report. IBM.

K. E. Sawaya, L. G. Olmanson, N. J. Heinert, P. L. Brezonik, and M. E. Bauer. 2003. Extending satellite remote sensing to local scales: Land and water resource monitoring using high-resolution imagery. *Remote Sensing of Environment* 88, 1, 144–156.

S::can. 2016. S::can Home Page. Retrieved November 12, 2016 from http://www.s-can.at.

L. A. Seders, C. A. Shea, M. D. Lemmon, P. A. Maurice, and J. W. Talley. 2007. LakeNet: An integrated sensor network for environmental sensing in lakes. *Environmental Engineering Science* 24, 2, 183–191.

D. Shin, S. Y. Na, J. Y. Kim, and S.-J. Baek. 2007. Sonar localization using ubiquitous sensor network for water pollution monitoring fish robots. In *Proceedings of the IEEE International Symposium on Signal Processing and Information Technology*. IEEE, Los Alamitos, CA, 80–85. DOI:http://dx.doi.org/10.1109/ISSPIT.2007.4458027

Tongxin Shu. 2016. *Power Management in a Sensor Network for Automated Water Quality Monitoring*. Ph.D. Dissertation. University of British Columbia.

B. Sidhu, H. Singh, and A. Chhabra. 2007. Emerging wireless standards: WiFi, ZigBee and WiMAX. *World Academy of Science, Engineering and Technology* 25, 2007, 308–313.

S. Silva, H. N. Nguyen, V. Tiporlini, and K. Alameh. 2011. Web based water quality monitoring with sensor network: Employing ZigBee and WiMax technologies. In *Proceedings of the Conference on High Capacity Optical Networks and Enabling Technologies (HONET'11)*. IEEE, Los Alamitos, CA, 138–142. DOI:http://dx.doi.org/10.1109/HONET.2011.6149804

M. V. Storey, B. van der Gaag, and B. P. Burns. 2011. Advances in on-line drinking water quality monitoring and early warning systems. *Water Research* 45, 2, 741–747.

R. O. Strobl and P. D. Robillard. 2008. Network design for water quality monitoring of surface freshwaters: A review. *Journal of Environmental Management* 87, 4, 639–648.

G. Suciu, V. Suciu, C. Dobre, and C. Chilipirea. 2015. Tele-monitoring system for water and underwater environments using cloud and big data systems. In *Proceedings of the 2015 20th International Conference on Control Systems and Computer Science*. 809–813. DOI:http://dx.doi.org/10.1109/CSCS.2015.31

B. Sun, F. Ahmed, F. Sun, Q. Qian, and Y. Xiao. 2016. Water quality monitoring using STORM 3 data loggers and a wireless sensor network. *International Journal of Sensor Networks* 20, 1, 26–36.

Sun Microsystems. 2007. Sun Small Programmable Object Technology (SPOT). Retrieved November 12, 2016, from http://academic.fuseyism.com/ambassador/slides/sunspot.pdf.

T. V. Suslow. 2004. *Oxidation-Reduction Potential (ORP) for Water Disinfection Monitoring, Control, and Documentation*. Technical Report. ANR Publication 8149. Division of Agriculture and Natural Resources, University of California.

R. Szewczyk, J. Polastre, A. Mainwaring, and D. Culler. 2004. Lessons from a sensor network expedition. In *Wireless Sensor Networks*. Lecture Notes in Computer Science, Vol. 2920. Springer, 307–322.

H.-P. Tan, R. Diamant, W. K. G. Seah, and M. Waldmeyer. 2011. A survey of techniques and challenges in underwater localization. *Ocean Engineering* 38, 14 (2011), 1663–1676.

G. W. Taylor, J. R. Burns, S. M. Kammann, W. B. Powers, and T. R. Wel. 2001. The energy harvesting eel: A small subsurface ocean/river power generator. *IEEE Journal of Oceanic Engineering* 26, 4, 539–547.

Technical Associates. 2016. Technical Associates Home Page. Retrieved November 12, 2016, from http://www.tech-associates.com.

TPS Pty Ltd. 2008. 90-FLT Sensor. Retrieved November, 2016, from http://tps.com.au/products/products/combination-and-multiparameter-meters/portable-conductivity-salinity-tds-meters/90-fl-series.html.

G. Tuna, O. Arkoc, and K. Gulez. 2013. Continuous monitoring of water quality using portable and low-cost approaches. *International Journal of Distributed Sensor Networks* 2013, Article No. 249598. DOI:http://dx.doi.org/10.1155/2013/249598

G. Tuna, B. Nefzi, O. Arkoc, and S. M. Potirakis. 2014. Wireless sensor network-based water quality monitoring system. *Key Engineering Materials* 605, 47–50. DOI:http://dx.doi.org/10.4028/www.scientific.net/KEM.605.47

United Nations. 2005. United Nations Environment Programme: Operational Guide for Data Submission. Retrieved November 12, 2016, from http://www.unep.org/gemswater/Portals/24154/pdfs/op_guide_for_data_2005.pdf.

Universe Today. 2015. What Percent of Earth Is Water? Retrieved November 12, 2016, from http://www.universetoday.com/65588/what-percent-of-earth-is-water/.

U.S. EPA. 2015a. Online Water Quality Monitoring Primer for Water Quality Surveillance and Response Systems. Retrieved November 12, 2016, from http://www.epa.gov/sites/production/files/2015-06/documents/online_water_quality_monitoring_primer.pdf.

U.S. EPA. 2015b. Water Quality Surveillance and Response System Fact Sheet and Primer. Retrieved November 12, 2016, from http://water.epa.gov/infrastructure/watersecurity/lawsregs/upload/epa817b15002.pdf.

USGS. 2015. The World's Water. Retrieved November 12, 2016, from http://water.usgs.gov/edu/earthwherewater.html.

H. van Niekerk. 2004. U. N. E. P. Global Environmental Monitoring System/Water Programme: South African Monitoring Programme Design. Retrieved November 12, 2016, from https://www.dwaf.gov.za/iwqs/water_quality/GEMS/South_African_UNEP_GEMSWater_Monitoring_Programme.pdf.

S. Verma and Prachi. 2012. Wireless sensor network application for water quality monitoring in India. In *Proceedings of the National Conference on Computing and Communication Systems (NCCCS'12)*. IEEE, Los Alamitos, CA, 1–7. DOI:http://dx.doi.org/10.1109/NCCCS.2012.6412990

WA Health. 2012. Sodium in Drinking Water. (2012). Retrieved November, 2016 from http://ww2.health.wa.gov.au/Articles/S_T/Sodium-in-drinking-water.

T. R. Wagh and A. P. Rao. 2014. River monitoring an application for wireless sensor network platform. *International Journal of Emerging Technology and Advanced Engineering* 4, 11, 511–515.

R. J. Wagner, R. W. Boulger Jr., C. J. Oblinger, and B. A. Smith. 2006. *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting*. Technical Report. U.S. Department of the Interior, Washington, DC.

D. Wang, R. Xu, X. Hu, and W. Su. 2016. Energy-efficient distributed compressed sensing data aggregation for cluster-based underwater acoustic sensor networks. *International Journal of Distributed Sensor Networks* 12, 3, Article No. 8197606.

J. Wang, X.-l. Ren, Y.-l. Shen, and S.-y. Liu. 2010. A remote wireless sensor networks for water quality monitoring. In *Proceedings of the Asia-Pacific Conference on Innovative Computing and Communication and the International Conference on Information Technology and Ocean Engineering (CICC-ITOE'10)*. IEEE, Los Alamitos, CA, 7–12.

X. Wang, L. Ma, and H. Yang. 2011. Online water monitoring system based on ZigBee and GPRS. *Procedia Engineering*, 2680–2684. DOI:http://dx.doi.org/10.1016/j.proeng.2011.08.504

Y. Wang, G. Attebury, and B. Ramamurthy. 2006. A survey of security issues in wireless sensor networks. *IEEE Communications Surveys and Tutorials* 8, 2, 2–23. DOI:http://dx.doi.org/10.1109/COMST.2006.315852

Z. Wang, Q. Wang, and X. Hao. 2009. The design of the remote water quality monitoring system based on WSN. In *Proceedings of the 5th International Conference on Wireless Communications, Networking, and Mobile Computing (WiCom'09)*. IEEE, Los Alamitos, CA, 1–4. DOI:http://dx.doi.org/10.1109/WICOM.2009.5303974

WaterLOG. 2016. WaterLOG Home Page. Retrieved November 12, 2016, from http://www.waterlog.com.

WHO. 2003. Total Dissolved Solids in Drinking-Water: Background Document for Development of WHO *Guidelines for Drinking-Water Quality*. Retrieved November 12, 2016, from http://www.who.int/water_sanitation_health/dwq/chemicals/tds.pdf.

WHO (Ed.). 2011. *Guidelines for Drinking-Water Quality* (4th ed.). WHO Press, Geneva, Switzerland.

WiFi Direct. 2015. NFC vs Bluetooth vs Wifi Direct: Comparison, Advantages and Disadvantages. Retrieved November 12, 2016, from http://www.itechwhiz.com/2014/01/nfc-bluetooth-Wifidirect-comparison-differences.html.

G. Wiranto, G. A. Mambu, Hiskia, I. D. P. Hermida, and S. Widodo. 2015. Design of online data measurement and automatic sampling system for continuous water quality monitoring. In *Proceedings of the IEEE International Conference on Mechatronics and Automation (ICMA'15)*. IEEE, Los Alamitos, CA, 2331–2335. DOI:http://dx.doi.org/10.1109/ICMA.2015.7237850

G. Xu, W. Shen, and X. Wang. 2014. Applications of wireless sensor networks in marine environment monitoring: A survey. *Sensors* 14, 9, 16932–16954.

Xylem Inc. 2015a. 10 Tips to Prevent Biofouling on Water Quality Instruments. Retrieved November 12, 2016, from https://www.ysi.com/File%20Library/Documents/Tips/E108-Antifouling-Tips-Book.pdf.

Xylem Inc. 2015b. Water Quality Instrumentation. Retrieved November 12, 2016, from http://www.globalw.com/catalog_wq.html.

S. G. S. Yadav, A. Chitra, and C. L. Deepika. 2015. Reviewing the process of data fusion in wireless sensor network: A brief survey. *International Journal of Wireless and Mobile Computing* 8, 2, 130–140.

S.-C. Yang and Y. Pan. 2010. The application of the wireless sensor network (WSN) in the monitoring of Fushun Reach River in China. In *Proceedings of the 2nd International Conference on Computer and Network Technology (ICCNT'10)*. IEEE, Los Alamitos, CA, 331–333. DOI:http://dx.doi.org/10.1109/ICCNT.2010.70

X. Yang, K. G. Ong, W. R. Dreschel, K. Zeng, C. S. Mungle, and C. A. Grimes. 2002. Design of a wireless sensor network for long-term, in-situ monitoring of an aqueous environment. *Sensors* 2, 11, 455–472.

G. Ye and K. Soga. 2011. Energy harvesting from water distribution systems. *Journal of Energy Engineering* 7–17.

YSI. 2016. Water Quality Sampling and Monitoring. Available at https://www.ysi.com.

R. Yue and T. Ying. 2011. A water quality monitoring system based on wireless sensor network and solar power supply. In *Proceedings of the IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER'11)*. IEEE, Los Alamitos, CA, 126–129. DOI:http://dx.doi.org/10.1109/CYBER.2011.6011777

Zap Technologies. 2016. Detect. Respond. Available at http://www.zapstechnologies.com.

M. Zennaro, A. Floros, G. Dogan, T. Sun, Z. Cao, C. Huang, M. Bahader, H. Ntareme, and A. Bagula. 2009. On the design of a water quality wireless sensor network (WQWSN): An application to water quality monitoring in Malawi. In *Proceedings of the International Conference on Parallel Processing Workshops (ICPPW'09)*. IEEE, Los Alamitos, CA, 330–336. DOI:http://dx.doi.org/10.1109/ICPPW.2009.57

A. Zhan, G. Chen, and W. Wang. 2009. Utilizing automatic underwater vehicles to prolong the lifetime of underwater sensor networks. In *Proceedings of the 18th International Conference on Computer Communications and Networks (ICCCN'09)*. IEEE, Los Alamitos, CA, 1–6. DOI:http://dx.doi.org/10.1109/ICCCN.2009.5235299

S. Zhang and L. Zhang. 2011. Water pollution monitoring system based on ZigBee wireless sensor network. In *Proceedings of the International Conference on Electronics, Communications, and Control (ICECC'11)*. IEEE, Los Alamitos, CA, 1775–1779. DOI:http://dx.doi.org/10.1109/ICECC.2011.6067965

B. Zhou, W. Dehua, L. Pan, L. Bo, and G. Zeng. 2012a. Water quality automatic monitoring system based on GPRS data communications. In *Proceedings of the Conference on Modern Hydraulic Engineering*. 840–843. DOI:http://dx.doi.org/10.1016/j.proeng.2012.01.820

Y. Zhou, D. Wen, F. Yuan, J. Li, and M. Li. 2012b. Research of online water quality monitoring system based on ZigBee network. *Advances in Information Sciences and Service Sciences* 4, 5, 255.

X. Zhu, D. Li, D. He, J. Wang, D. Ma, and F. Li. 2010. A remote wireless system for water quality online monitoring in intensive fish culture. *Computers and Electronics in Agriculture* 71, S3–S9.

Received February 2016; revised August 2016; accepted October 2016