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Physical and chemical water quality parameters sensing IoT systems for improving water productivity

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Abstract

The paper presents a study of Internet of Things (IoT) systems used on physical and chemical water quality and resources sensing. The United Nations (UN) Sustainable Development Goals (SDGs) for 2030, declaring a commitment to "Ensure availability and sustainable management of water and sanitation for all", is taken as a reference for the ensuing analysis of the literature. The IoT is changing the landscape of environmental resources monitoring and the case of water quality and quantity is no exception. A comparison among IoT based sensing systems is presented. It is focused on: the sensors; data communication hardware and the software protocols and processing devices. The most measured parameters are selected according to a scientific literature sample encompassing the last few years and including over 30 papers. The sample consists of the most relevant papers on the subject. . A general architecture for the collection and processing of water quality data is discussed. This data assists to water productivity investigations. The architecture integrates the sensing of physical and chemical parameters, data communication and processing.

Keywords: Internet of Things; Sensing; System Architectures; Water Productivity; Water Quality

INTRODUCTION

Water is an essential asset for life, for human and animal consumption, used in food production, either in agriculture or aquaculture, and even in leisure activities. With an increasing population and industrialization, rapid urbanization and environment deterioration, having a serious impact on the quality and quantity of available water, its assessment is a crucial task. The understanding of the water quality concept and its assessment has evolved along the time (Boyd, 2015; Chapman, 1996; Li and Liu, 2019). Both concepts, water quantity and water quality, have a parallel importance being in an inevitably way mutually correlated. Along most of the human history their evaluation was based on sensory perception and on the observation of the effects that the water had on living organisms. With the expansion of the water use requirements and the capability to measure and interpret water properties, the observation and evaluation methods changed. Water quality describes the chemical, physical and biological characteristics of water, in relation to natural quality, human effects and intended usage.

The recent technological evolution in sensor technology, microcontrollers and microcomputers, communication devices and renewable energy sources, has made possible the development of low-cost scalable and replicable systems using an Internet of Things (IoT) approach that can be used for in-*situ* continuous monitoring of the most important parameters related to water quality, allowing to improve the efficiency in the use of the water resources (Li and Liu

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2019; Park *et al*., 2020; Tiyasha *et al*., 2020; Topp *et al*., 2020).

A comprehensive set of papers published about water quality monitoring using an IoT approach is here discussed in a summarized way. A general IoT based system architecture for surface water quality monitoring is presented. It is designed using as reference a set of papers published on the subject during the last few years. The most common parameters measured by water quality monitoring systems using an IoT approach and with common commercial of the shelf components (COTS) are presented. Also, the most common data communication hardware and software protocols, and the processing devices used in this kind of systems, are typified and used as a base for the design of a general architecture.

A scalable and replicable general architecture concept with the goal of cost reduction and some sort of standardization is one of the results the authors aimed for.

Although it is important to consider the ease of access and reliability of power sources in surface water quality analysis systems, the large set of different in-*situ* locations with varying types of power access prevented the authors of including this in the general architecture design.

The subject of sensing in water resources is developed in Section 2. It starts by contextualizing the theme under the UN Sustainable Development Goals. The specific theme of in-*situ* observations is presented in Section 3, within the context of IoT systems. Section 4 presents a review of a set of papers published about water quality monitoring following an IoT approach during the last few years. Section 5 presents a general architecture for water quality IoT based sensing system derived from the analysis of published papers on the subjects. The paper finishes with Section 6 where a synthesis of the main aspects of this work are presented and some perspectives of future research are enumerated.

ATER QUALITY SENSING

For 2030 the United Nations (UN) established 17 sustainable development goals (SDGs), which replaced the previous Millennium Development Goals (MDGs) targeted to reduce extreme poverty in the world by 2015. Even if the new SDGs cover an ambitious range of global topics they still include water and sanitation at its core in the new agenda, a dedicated SDG 6 declaring a commitment to “Ensure availability and sustainable management of water and sanitation for all”. Given the increasing evidence that water sector’s plays a decisive role in human rights, poverty reduction, inequality elimination, peace, justice and the environment, it should be considered that SDG6 constitutes a great opportunity to accelerate progress on the UN 2030 Agenda (UN-Water, 2018).

In order to achieve the SDG6 global targets the monitoring of water resources plays an important and crucial aspect, independently of how they are incorporated into national planning processes and policy making of each country. The monitoring will be challenging, not only related with the different levels of countries technological development, but also because current methods of measuring the quality and use of water and sanitation services are either expensive or somehow elusive (Andres *et al*., 2018).

In order to adequately address water resources quality around the globe it should be recognized the existence of a variety of monitoring methods with different levels of technology and cost of implementation. According to a technical report of the World Meteorological Organization (WMO, 2013) within water quality monitoring there is no simple, single method which can be applied across the board, in every situation, stating that the challenge for water managers is in the efficient use of a group of technologies specifically to address each situation.

Up to date reviews about the state of the art in monitoring surface waters such as those of Andres *et al*. (2018) and Huang *et al*. (2018) point towards the increasing benefits of the use of in-*situ* instrumentation technologies integrated with Earth observation through data collected from satellite-based optical sensors, mainly because it may help meeting many of the challenges of information asymmetry and data gaps, with clear benefits especially in the developing countries.

A complete assessment of water quality, the overall process of evaluation of the physical, chemical and biological status of water in relation to natural quality, human effects and intended uses, which may affect human health and aquatic ecosystems balance, needs the assessment of the major components of water bodies in terms of hydrology and physical, chemical and biological parameters. Water quality monitoring, on the other hand, is the actual collection of information at set locations and at regular intervals in order to provide the data which may be used to define current conditions, establish trends, etc. (Chapman *et al*., 1996). Water quality assessment includes the use of monitoring to define the condition of the water, to provide the basis for detecting trends and to provide the information enabling the establishment of cause-effect relationships.

The procedures to assess the water quality have been defined in several standards, directives and regulations, according to: (i) different uses, such as drinking water, bathing water, irrigation water, aquaculture; (ii) pollution caused by certain dangerous substances discharged into the aquatic environment; (iii) ecological and chemical status; (iv) groundwater protection (Chapman *et al*., 1996; EPA, 2001).

An example of in-*situ* water quality assessment enforced by national and European legislation is presented in Palma *et al*. (2010, 2014). The case of study assesses the spatial and temporal variability of the water and sediments quality in the Alqueva reservoir. The study derives from the demands for good ecological potential and chemical status of the European Water Framework Directive (WFD) for heavily modified water bodies (EEC, 2000). The authors tried to stablish the variability of water ecological status of some areas in Alqueva reservoir using a total of 26 physical and chemical parameters. Modern IoT systems provide a low-cost and continue remote monitoring solution for most of the in-*situ* parameters such as temperature, electrical conductivity (EC), potential of hydrogen (pH), dissolved oxygen (DO), oxidation and reduction potential (ORP).

IN-*SITU* OBSERVATIONS

All around the world the necessity to monitor water resources over large areas in short time intervals is still increasing, being more relevant in the most industrialized countries due to pollution and contamination. The amount of drinkable and irrigation water on earth is being reduced day by day, leading to the possibility that in this century, water quality could become one of the major challenges that human beings are likely to face (Jaywant and Arif, 2019). The climate change is one of the main factors of this reduction and reinforces the importance of real time monitoring of water data (Gaaloul *et al*., 2020). During the last decades, the detection of physical and chemical properties, biological conditions or pollutants in water has been improved as new technologies have become available, within this present menace some of the in-*situ* technologies used to monitor water quality assume particular importance, especially the ones that are portable.

The technical report (WMO, 2013) assumes several advantages for the use of portable devices, as follows: i) rapid results that can be sent immediately; ii) continuous and automatic monitoring; iii) short-term management; iv) monitoring of decontamination processes; v) early warning systems and applications; vi) reduction in error associated with sample preparation, transport and storage.

The Internet of Things (IoT) is changing the landscape of environmental resources monitoring and the case of water quality and quantity is no exception. The scope of an IoT system varies from a small system, which contains uniquely identifiable things, to a system that interconnects millions of things with a capacity to deliver complex services (Minerva *et al*., 2015). Many of its concepts were present in the paradigm of Ubiquitous Computing that was developed in the Xerox

Palo Alto Research Center (PARC) in the late 1980s by Weiser. The idea of spreading computers ubiquitously throughout the environment with the focus on the way how computers would be embedded within the complex social framework of daily activity, and how they would interplay with the rest of the physical environment, "the real world", was on the basis of that paradigm. It defined a smart environment as "the physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, embedded seamlessly in the everyday objects of our lives, and connected through a continuous network" (Weiser *et al*., 1999; Gubbi *et al*., 2013) which is the basis of the IoT. The use of the term "Internet of Things" began in late 1990s, with works related to electronic product code (EPC) and related Radio Frequency Identification (RFID) standards. The research programme at the Auto-ID Center at MIT (directed by Ashton), aiming at the creation of an "internet of things", i.e. a tight coupling of physical items and digital information flows based on inexpensive RFID tags, is considered to have coined the term (Ashton, 2009; Gubbi *et al*., 2013; Minerva *et al*., 2015; Thiesse and Michahelles, 2006).

An IoT system, can be defined as a network of uniquely identifiable things which have sensing and/or actuation capabilities, are potentially programmable and/or have processing capabilities. Through the exploitation of unique identification and sensing, information about the thing can be collected and its state can be changed from anywhere, anytime, by anything. In a large environment scenario, the IoT is a self-configuring, adaptive, complex network that interconnects the things to the Internet through the use of standard communication protocols. The interconnected things have physical or virtual representation in the digital world which contains information including the thing's identity, status, location or any other business, social or privately relevant information. The things offer services, with or without human intervention, through the exploitation of unique identification, data capture and communication, and actuation capability. The service is exploited through the use of intelligent interfaces and is made available anywhere, anytime, and for anything taking security into consideration (Minerva *et al*., 2015).

A view of the future of Internet technologies in the context of environmental applications is presented by Granell *et al*. (2016), where societal problems pointed out by the EU for Horizon 2020 are related to the contributions of the Internet, in particular mentioning IoT and Big Data, which is linked to deep learning and to pattern recognition.

A review of the recent advances in ICT and field applicable sensor technology for monitoring water quality, mainly focusing on water resources, such as rivers and lakes is presented in Park *et al*. (2020) and it is compared with traditional water quality monitoring.

WATER QUALITY MONITORING WITHIN IOT

One of the first water quality monitoring systems to adopt an IoT like approach was presented by Simbeye and Yang (2014) and Simbeye *et al*. (2014). The system consists of a wireless sensor network (WSN) for water quality monitoring and control in aquaculture, with sensor nodes built around a microcontroller unit (MCU), each with a pressure type level sensor, a temperature sensor, a pH sensor, and a DO sensor. The nodes communicate with each other and with a gateway connected to a host computer by the ZigBee protocol. The host computer is used for data analysis, processing and presentation sending the data to users and to a remote server with a GSM module. This approach is closely followed by Das and Jain (2017), where the authors propose a low-cost real-time water quality monitoring system to track the level of pollution in rivers and to send alerts accordingly. The use of microcontrollers using Zigbee and GSM for data communication is also chosen by the authors. Temperature, pH and EC sensors have their signals acquired and processed by a MCU, which transmits the data using Zigbee between nodes and uses WiFi and GSM to send data to a server. A similar approach is followed by Menon *et al*. (2017). It discusses a low-cost proposal for water quality monitoring in natural water bodies, also built with a ZigBee network of Libelium WaspMote units. These units are MCU based but admit a heterogeneous range of data transmission systems: LoraWan, 4G, WiFi and Zigbee. The sensor nodes present temperature, pH, turbidity, DO, sulphate ions, ammonia and nitrate sensors. A smart water quality monitoring system for seawater, described in Prasad *et al*. (2015), is also built around a Waspmote module. The selected sensors measure temperature, pH, ORP and EC, and are controlled by the Waspmote which acquires and processes the sensors signals and sends the data to the Internet. This is done either by a GSM module, using the FTP protocol to send the data to a remote server, or by a serial communication link to a server in the cloud.

A low cost IoT system for real time monitoring of water quality based on Arduino boards is presented in Daigavane and Gaikwad (2017). Several sensors that measure physical and chemical parameters of the water, including temperature, pH, turbidity and flow, are controlled by the MCU (ATmega328) connected to a web server by WiFi. The data is processed by the system and sent through the Internet. Saravanan *et al*. (2018) presents a system to be used in water distribution and monitoring using the same kind of low-cost microcontroller boards. The system uses flow, temperature and color sensors controlled by an Arduino board with a GSM module and stores the sensor data in a web server. Data analysis can be done and reported anywhere and anytime through a web browser. Systems made out of these low cost MCU boards and variations are also presented in several studies (Chowdury *et al*., 2019; Encinas *et al*., 2017; Hanifah and Supangkat, 2019; Kamaludin and Ismail 2017; Parameswari and Moses, 2018; Pranata *et al*., 2017; Shafi *et al*., 2018; Zainuddin *et al*., 2019).

In Pranata *et al*. (2017) an IoT system is proposed for water quality monitoring using a publisher/subscriber architecture. The system is composed of a network of Relay Nodes (Publishers), with temperature, pH, and DO sensors, controlled by an Arduino, and communicate with the Gateway Nodes (Subscribers) with Zigbee. The data is also communicated to a computer (Server) with Zigbee. An IoT system implementation embedding a RFID system, a WSN platform and Internet Protocol (IP) based communication into a single platform for water quality monitoring is presented in Kamaludin and Ismail (2017). The network sensor nodes comprise temperature and pH sensors, controlled by an Arduino and communicate through the DigiMesh network protocol.

Another IoT system based on Arduino modules is presented in Encinas *et al*. (2017). The system has three sensors, for temperature, pH and DO. The sensor data is transmitted via the Zigbee protocol with the Arduino module used as the communication coordinator. The sensing node sends the information through a Xbee transmitter module to a computer where it is received by the receiver Xbee module, through serial communication. This data is read by an application developed in C#. The data in the application is deployed and stored in a MySQL database management system (DBMS) and sent through a web service available on the cloud. This web service adopts a SOAP (Simple Object Access Protocol) service, a lightweight protocol intended for exchanging structured information in a decentralized, distributed environment.

Security considerations concerning the critical aspects of the data in a water quality monitoring IoT system are addressed in Parameswari and Moses (2018). Some Water Quality information IoT systems are designed without security consideration, originating a confidentiality vulnerability. In this research, the major contribution is the proposal of a secure process of a modern monitoring system of water quality based on a WSN. Nodes are made with an Arduino board with temperature, pH, turbidity and EC sensors and a WiFi transceiver module.

A real time embedded prototype to record the water quality parameters from water samples collected from various sources across a specific study area uses the same kind of board in Shafi *et al*. (2018). An Arduino controller acquires pH, turbidity and temperature signals, controls a solenoid valve for flow control and sends the data to the cloud with a WiFi shield. Processed data can be remotely monitored, and the water flow can be controlled, using the proposed solution. Predictive analysis of the collected data is performed using Machine Learning (ML) algorithms applied to the water quality classification problem.

Machine Learning techniques are also proposed in Chowdury *et al*. (2019). The system consists of a WSN with nodes made around a variation of the Arduino board, based on an ATmega2560 MCU. Each node includes a microcontroller, communication system for inter and intra node communication and several sensors: DO, turbidity, pH, temperature, EC, total dissolved solids (TDS), salinity. Data collected are sent to a server PC and can be displayed in a visual format. The system proposes the integration of Big Data Analytics (Apache Spark) and Deep Learning (DL). Deep learning techniques usually use convolutional neural network (CNN) models.

A system made around an ARM MCU, the low energy consumption platform LPC1768, is presented by Kafli and Isa (2017). Several sensors, including temperature, humidity, carbon monoxide, air temperature and humidity, carbon monoxide, pH and water level, and the Global Positioning System (GPS), monitor the environment in rivers or lakes and send the collected data to a wired Internet router. Data is analyzed by a cloud server with Artificial Intelligence (AI) software (IBM Watson IoT platform).

A more feature rich ARM MCU from the SMT32 family is used in systems presented by Zhang *et al*. (2020a) and Zhang *et al*. (2020b). The first is an IoT water quality monitoring system which collects and stores aquaculture water quality parameters, such as DO, pH value, temperature, ammonia nitrogen content and nitrite content and provides alerts when the real-time detection data is beyond the safety scope. It takes advantage of the processing power of the STM32F767 chip to simultaneously process multiple pieces of collected data. The pre-processed data is stored in a local server which can be accessed by remote clients. The second is a proposal for a general use water quality monitoring system made around a STM32F103 chip. The data from temperature, pH and turbidity sensors is acquired and pre-processed by the ARM MCU and transmitted by WiFi (ESP8266 chip) to a cloud server to be displayed and analyzed, providing remote real-time monitoring of water quality, statistics of water quality data, abnormal alarms, and online query by mobile terminals.

Among the reasons for the rapid increase of IoT systems is the availability of low-cost, energy efficient and powerful hardware. The Espressif Systems ESP family of low-cost and low-power 32-bit MCUs provide an interesting choice for the development of this kind of systems for water quality and quantity monitoring. An IoT based water quality monitoring system built around a ESP8266 MCU is proposed in Spandana and Rao (2018). This system uses temperature, pH, water level and CO2 sensors, controlled by the MCU, that sends the pre-processed signals with its WiFi built-in core to a server. Another IoT system built around an ESP MCU for a water channel monitoring is proposed in Lameira (2020). This system is based on the low-cost ESP32 MCU, that already contains Bluetooth and Wi-Fi communications. To extend communications there are boards available that include LoRa and/or GSM communications and GPS positioning. This system possesses temperature, pH and turbidity sensors, and measures the water level in the channel using an ultrasonic sensor. The data is communicated between nodes with LoRa and is sent by the gateway node to the Internet using GSM.

Ubiquitous equipment in this area are the low-cost Single Board Computers (SBC). These devices are capable of running a full operating system and are accessible to non-technical users Johnston *et al*. (2016), providing other interesting alternatives to the development of water quality monitoring systems within IoT.

A general use water quality monitoring system developed around a SBC is presented in Vijayakumar and Ramya (2015). It consists of several sensors that measure temperature, pH, turbidity, EC and DO which are controlled by a Raspberry Pi (RPiB+). The SBC acquires and processes the sensors signals and sends the processed data to the Internet and to mobile devices nearby. In Raju and Varma (2017) a Raspberry Pi (RPi3) is also used to acquired and process the signals of temperature, pH, DO, EC, ammonia, nitrate and carbonate sensors. Processed data is sent by WiFi to a local server connected to the cloud. A similar approach is followed by Budiarti *et al.* (2019) in an environmental and water management monitoring program using standard water quality monitoring sensors (YSI - Model 600R - Multiparameter Water Quality Sonde, with temperature, DO, EC, Salinity, Specific Conductance, pH and TDS). The probe is connected to a Raspberry Pi via RS232 and the SBC is connected by WiFi to a router/modem that connects the system to the Internet. In Ratnam *et al.* (2019) a prototype of a water quality monitoring system and control, to be used in aquaculture, is developed around a Raspberry Pi. Temperature and pH sensors are controlled and have their signals acquired by the SBC. A system of pumps, also controlled by the SBC, naturally evacuates the wastewater and refills with fresh water in case of need. Data is sent to Internet with WiFi. Another proposal that uses a SBC is described in Salunke and Kate (2017). The suggested platform is Intel Galileo Gen 2 (which was discontinued) with temperature, pH, turbidity and water level sensors.

The combination of low-cost and low-power feature rich MCU boards with SBCs makes another interesting architecture for water quality monitoring systems: a WSN with sensing nodes based on MCUs/SBCs, which control sensors, acquires their signals, pre-processes data and communicates with SBC based aggregator systems. These further analyze and process data and afterwards send the results to a remote server in the cloud for more processing.

An IoT platform with multiple Mobile Sensor Nodes (MSN) for the spatial and temporal quality evaluation of surface water is presented in Li *et al*. (2017). Each MSN is composed of five sensors (temperature, pH, DO, EC and ORP) controlled by a MCU (ATmega1281+RPi3) and mounted on a remotely operated vehicle (ROV). The nodes transmit the collected data by WiFi or Zigbee to a base station (PC) which is connected by GSM, 3G or 4G to the Internet.

The design and implementation of a water quality monitoring system for crab farming using IoT, aiming to assist the farmers for maintaining acceptable levels of water quality, is described in Niswar *et al.* (2018). The system mainly consists of sensor nodes as publishers, a SBC (Raspberry Pi 3) based broker using MQTT (Mosquito-based MQTT) and mobile client devices (farmer or researcher) as subscribers. The sensor nodes are built with MCU (ATmega2560), LoRa wireless interface, and water quality sensors including temperature sensor, pH sensor and salinity sensor. A web-based monitoring system using UI nodes (Node-Red Dashboard) allows the access to water quality levels remotely.

The system proposed by Martínez *et al*. (2020) consists of a WSN of sensor nodes made with a combination of ARM MCUs (Kinetis K66) with an SBC (RPiZero), which control a portable ion chromatography system that enables cost-effective direct in-*situ* detection of nitrite and nitrate in natural waters. The paper presents the integration of this WSN in a complete IoT system providing preventive and data analytics mechanisms to support decision making.

Another class of systems is based on Field Programmable Gate Arrays (FPGA) for processing and communications. The main advantage of these type of systems is the possibility of their reconfiguration, however, for off the shelf sensors, and standard protocols, the usually higher cost of such type of systems and the need of special programming tools and skills do not justify their use in water quality monitoring systems development. The system presented in Wong and Kerkez (2016) is programmed in C and the FPGA features an ultra-low power ARM-Cortex M3 and an IP cellular module for Internet connectivity, besides several ADC and amplifiers. The system has an ultrasonic depth probe and a pressure sensor to measure water level, and trigger a water quality industrial sampler also based on the reading of a conductivity sensor. The system described in Myint *et al.* (2017) has a temperature, pH, turbidity, carbon dioxide and an ultrasonic sensor that measures the water level. For communication, it uses the Zigbee protocol implemented on the FPGA core. The system in Zin *et al.* (2019) is similar to the previous one in terms of sensors and communications.

A synthesis of the analysis provided in this section results in Table 1, relative to sensed parameters, Table 2, about MCUs and SBCs and Table 3, about data communications

A GENERAL ARCHITECTURE FOR AN IOT SYSTEM FOR PHYSICAL AND CHEMICAL WATER QUALITY PARAMETERS AND RESOURCES MONITORING

Systems architectures may be represented with several types of diagrams (Serpanos and Wolf, 2017). A layer-based diagram for general IoT systems is represented in Figure 1. The top layer represents the applications part of the system. It is deeply connected to the concrete type of application. It may have varying degrees of data processing. Sometimes a simple graphical view available through a web server is enough, but in other instances it may have some type of pattern recognition and machine learning back-end providing automatic actions.

The network layer may comprise the physical communications and the corresponding data exchange protocols. Examples of the first are the Ethernet and wireless hardware. This diagram shows a very general view on IoT systems architectures. To derive an architecture diagram more connected to water quality IoT systems an analysis and review of the published literature is deemed necessary. The following paragraphs are devoted to this purpose.

Table 1 presents a list of parameters commonly measured in recently proposed IoT water quality systems. Table 3 lists the hardware and software communication protocols and Table 2 enumerates the MCU chips and SBCs used in these systems. The most commonly measured water quality parameters, the signal flow and processing are hence presented in the general architecture shown in Figure 2.

The water temperature is represented by T and it is sometimes measured at different depths. The water acidity is measured using pH probes and is represented in Figure 2 by pH. The amount of water available is indirectly measured using a measure of the water level, L. The turbidity is also a common parameter and is represented by TU. The dissolved oxygen, DO, sensor is also usually found in the literature. One of the most ubiquitous sensors, a type of current sensor, is used for the EC parameter.

The SBCs and MCUs subsystem comprises data acquisition, control and communications. It receives as input the values that are sent from the sensors. These values may be digital or analog. When analog signals are present, they are converted to digital form by analog to digital converters (ADCs) that are commonly found in modern microcontrollers. From Table 2 we conclude that the most used MCU in these systems is the chip present in Arduino Uno boards. The Arduino platform provides a cost-effective way to rapidly design this type of systems. It provides analog to digital conversion and data communication hardware (Monk, 2017). The Raspberry Pi SBC is also very common. It has support for a full-blown operating system (OS) and has very good documentation. The OS range from Linux Debian, Ubuntu, etc., to Windows and even

Table 1. The table presents a list of parameters and sensors for a sample of relevant IoT based water quality and resources systems (temperature (T), potential of hydrogen (pH), turbidity (Tu), , electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), oxidation and reduction potential (ORP), water level (WL), water pressure (p), water flow (Fl))

Reference	T	pH	Tu	EC	TDS	DO	ORP	WL	p	Fl	CO	CO_2	NH_3	NO_2^-	NO_3^-	SO_4^{2-}
Simbeye et al., 2014	X	X				X		X								
Vijayakumar and Ramya 2015	X	X	X	X		X										
Prasad et al., 2015	X	X	X	X			X									
Wong and Kerkez 2016				X				X	X							
Daigavane and Gaikwad 2017	X	X	X							X						
Kafli and Isa 2017	X	X						X			X					
Menon et al., 2017	X	X	X			X										X
Myint et al., 2017	X	X	X					X				X				
Salunke and Kate 2017		X	X					X								
Das and Jain 2017	X	X		X												
Pranata et al., 2017	X	X				X										
Kamaludin and Ismail 2017	X	X														
Li et al., 2017	X	X		X		X	X									
Encinas et al., 2017	X	X				X										
Raju and Varma 2017	X	X		X		X							X		X	
Saravanan et al., 2018	X		X							X						
Niswar et al., 2018	X	X		X												
Parameswari and Moses 2018	X	X	X	X												
Shafi et al., 2018	X	X	X							X						
Spandana and Rao 2018	X	X						X				X				
Budiarti et al., 2019	X	X		X		X										
Chowdury et al., 2019	X	X	X	X		X	X									
Gao et al., 2019	X	X	X	X		X		X								
Ratnam et al., 2019	X	X														
Lameira 2019	X	X			X											
Hanifah and Supangkat 2019	X	X	X	X	X					X						
Zainuddin et al., 2017	X	X	X							X						
Zin et al., 2019	X	X	X					X				X				
Zhang and Mao et al., 2020	X	X				X							X	X		
Zhang et al., 2020	X	X	X													
Martínez et al., 2020														X	X	

Table 2. The table presents a list of data acquisition and control hardware for a sample of relevant IoT based water quality and resources systems. Most of the systems have micro-controller (MCU), microcomputer (usually single board computer (SBC)) based data acquisition and control hardware

Reference	Microcontroller	Microcomputer	Other
Simbeye et al., 2014	ATmega8A		
Simbeye et al., 2014	ATmega16L		
Vijayakumar and Ramya 2015		RPi B+	
Prasad et al., 2015	ATmega1281		
Wong and Kerkez 2016	ARM CortexM3		FPGA-Cypress PSoC5LP
Daigavane and Gaikwad 2017	ATmega328		
Kafli and Isa 2017	LPC1768		
Meno et al., 2017	ATmega1281		
Myint et al., 2017			FPGA- CycloneV DE1-SoC
Salunke and Kate 2017		Galileo Gen2	
Das and Jain 2017	LPC2148		
Pranata et al., 2017	ATmega328		
Kamaludin and Ismail 2017	ATmega328		
Li et al., 2017	ATmega1281	RPi 3	
Encinas et al., 2017	ATmega328		
Raju and Varma 2017		RPi 3	
Saravanan et al., 2018	ATmega328		
Niswar et al., 2018	ATmega2560	RPi 3	
Parameswari and Moses 2018	ATmega328		
Shafi et al., 2018	ATmega2560		
Spandana and Rao 2018	ESP8266		
Budiarti et al., 2019		RPi 3	
Chowdury et al., 2019	ATmega2560		
Gao et al., 2019			
Ratnam et al., 2019		Rpi	
Lameira 2019	ESP32		
Hanifah and Supangkat 2019	ATmega328		
Zainuddin et al., 2019	ATmega2560/ ATmega328		
Zin et al., 2019			FPGS-Altera (NIOS II)
Zhang and Mao et al., 2020	SMT32F767		
Zhang et al., 2020	SMT32		
Martínez et al., 2020	ARM CortexM4	RPi Zero	

Table 3. The table presents a list of communication protocols for a sample of relevant IoT based water quality and resources systems

Reference	Hardware						Software		
	ZigBee	**LoRa**	**WiFi**	**Ethernet**	**GSM**	**Other**	**HTTP**	**MQTT**	**Other**
Simbeye et al., 2014	X				X				
Simbeye et al., 2014	X				X				
Vijayakumar and Ramya 2015			X				X		
Prasad et al., 2015				X	X	RS232	X		FTP
Wong and Kerkez 2016					X	SDI12	X	X	CoAP
Daigavane and Gaikwad 2017			X				X		
Kafli and Isa 2017				X			X		
Menon et al., 2017	X	X	X	X	X		X		
Myint et al., 2017	X		X	X			X		
Salunke and Kate 2017			X	X			X		SSH
Das and Jain 2017	X		X	X	X		X		
Pranata et al., 2017	X		X	X			X		Pub/Sub
Kamaludin and Ismail 2017				X		DigiMesh	X		
Li et al. 2017	X		X		X		X		
Encinas et al., 2017	X		X	X			X		SOAP
Raju and Varma 2017			X	X			X		
Saravanan et al., 2018				X	X		X		
Niswar et al. 2018		X	X		X			X	
Parameswari and Moses 2018			X	X			X		
Shafi et al., 2018			X				X		
Spandana and Rao 2018			X				X		
Budiarti et al., 2019					X		X	X	
Chowdury et al., 2019			X						
Gao et al., 2019		X			X		X		
Ratnam et al., 2019									
Lameira 2019		X			X				
Hanifah and Supangkat 2019					X				
Zainuddin et al. 2019	X		X						
Zin et al. 2019	X								
Zhang and Mao et al., 2020						RS485			
Zhang et al., 2020			X						
Martínez et al., 2020					X				

a real-time operating system (RTOS). Many dedicated libraries for a large set of programming languages are available (Upton and Halfacree, 2016). It lacks support for analog to digital conversion and is therefore usually connected to MCU boards when analog sensors are present.

Sometimes, dedicated electronics is present in these IoT solutions for signal conditioning and processing. Some of these subsystems perform some control tasks, namely whenever some sort of mechanical actions must be taken. One of the most important actions performed by these subsystems is data communication.

This is generally bidirectional. IoT systems use the Internet for data transmission. The adoption of the Internet protocol is one of the main characteristics that sets these systems aside from other types of proposals. In previous systems non Internet data communication was used, whether using periodical human based in-*situ* data collection or some sort of radio or line communication.

It is typical with IoT systems that the data transferred over the Internet to central servers is to be stored in electronic databases. The data is processed with several types of applications. One type of application is an alert system where an alarm is triggered when some sort of water quality or resource scarcity problem is detected. Another type of application processes the data and presents graphics showing the evolution of parameters within some time frame. Some of the most recent and most promising systems use the large set of collected data for machine learning applications. The data is analyzed with a finer look at the details thus allowing for some predictions and better water resources management. It is common nowadays to include a Geographical Information System (GIS) in this type of IoT systems. An easy superposition of sensing data to cartographic data is a result of using these systems. The output maps permit an easier identification of present and future problems in water quality and resources.

CONCLUSIONS

During the last years, the IoT approach introduced a cost-effective way to gather data from the physical world in large quantities. The IoT paradigm results from the junction of several technologies: the Internet; cheap sensors; cheap MCUs and SBCs.

Water quality is not only important in terms of drinking water supply but also in terms of smart/precision agriculture. The water quality and resources data integration, within the smart/precision agriculture IoT systems context, is a hot topic. The physical and chemical characterization of the water supply can be used for the improvement of farming productivity. The list of the most common water quality parameters produced in this paper can be deemed to make a useful contribution to the design of cost effective smart/precision agriculture IoT systems.

The climate change challenge makes the immediate access to water quality data crucial. Although remote sensing is a very important tool in this context, it does not fully replace in-*situ* data collection. IoT based in-*situ* water quality and resources sensing systems using COTS provide a fast and cheap way to deploy real-time monitoring and data collection products. The increased amount of data allows the design of modern machine learning and artificial intelligence software, providing a faster and better analysis of the evolution of water quality and resources in many parts of the planet. The authors scrutinized a large set of recently published papers on

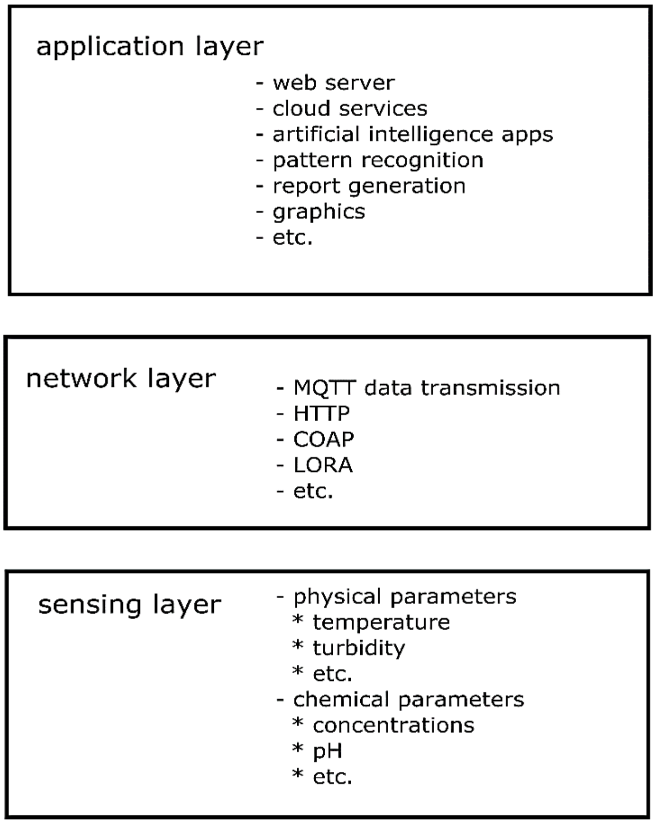

Fig. 1. A layer-based view of a general IoT data collection system

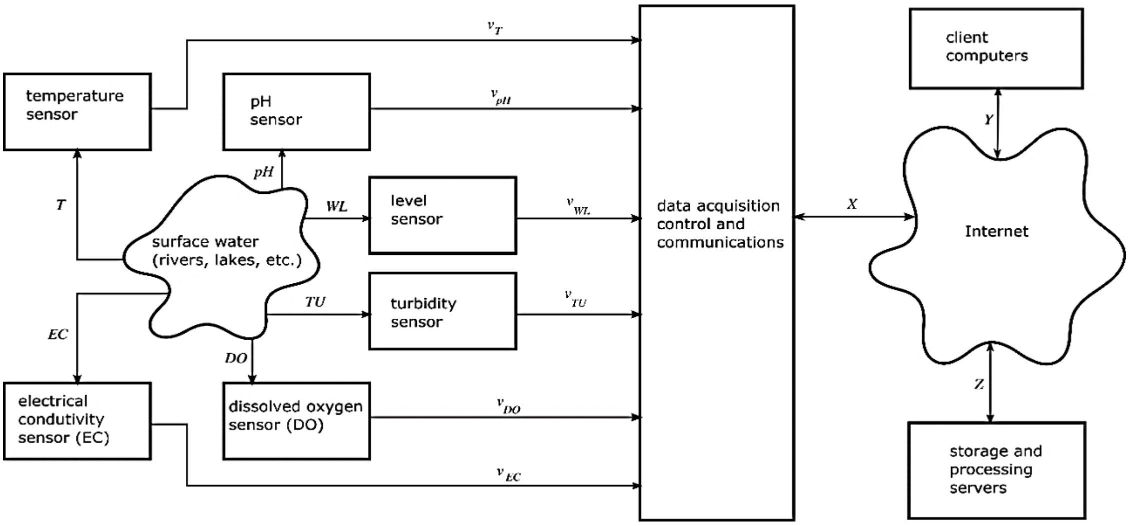

Fig. 2. A general architecture for the most common elements of an IoT based water quality monitoring system

the subject of IoT systems for water quality and resources sensing and derived a general architecture built around the most common proposals. It represents the most usual sensors for gathering data, the most common single board computers and microcontrollers and data communication protocols.

Future work will be the concrete design of cost-effective devices under the framework of this general architecture proposal and the integration with a set of data analysis servers. These servers should integrate remote sensing data, originating from several sources, such as satellite and aerial data, and the in-*situ* data, whether it is collected by these IoT based systems or by humans. Modern artificial intelligence based servers integrated with current Geographical Information Systems (GIS) would provide a dynamic, easy to follow, and high quality perspective on the evolution of water quality and resources and the consequences of climate change or other human related activities, namely pollution sources.

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