A sustainable wireless sensor system for water quality monitoring

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Abstract: Smart cities utilize Internet of Things (IoT) technologies to advance sustainable urban environments and to manage natural resources, including water sources for human use. Smart city applications for water quality (WQ) monitoring deploy wireless sensor systems for on-site WQ monitoring and real-time data processing to detect detrimental changes in water parameters. However, direct environmental impacts of wireless sensor systems are usually overlooked when considering the benefits of deploying IoT-based solutions for WQ monitoring. Sensor nodes in wireless sensor systems are often exposed to unfavorable environments that damage the sensor nodes, requiring frequent replacements and generating electronic waste (e-waste). In this paper, a sustainable wireless sensor system (WSS) for WQ monitoring is developed to mitigate the direct environmental impacts of wireless sensor systems deployed in WQ monitoring for smart cities. The sustainable WSS includes a cloud server and wireless sensor nodes comprised of reusable microcontrollers and e-waste sensors. WQ indexes based on German standards are calculated on site owed to embedded computing capabilities present in the sensor nodes. The sustainable WSS is compared against a benchmark system for validation, using drinking water probes from different locations of a metropolitan city.

Keywords: Smart city; Circular economy; Wireless sensor system (WSS); Electronic waste (e-waste); Water quality monitoring; Sustainability.

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1 Introduction

Due to industrialization, urbanization, intensive agricultural activities, and population growth, the demand for water supply and water quality (WQ) has amplified. Water sources are exposed to the consequences of global warming and pollution caused by human activities. Therefore, the quality of water sources for water supply is a current environmental challenge and the monitoring of WQ is a matter of research [1].

Traditional WQ monitoring systems build upon water samples collected for analysis in laboratories, rendering monitoring systems expensive and labor-intensive. In recent years, WQ monitoring based on Internet of Things (IoT) technologies has been introduced and developed [2]. Using wireless sensor systems, WQ parameters such as temperature, pH, turbidity, and electrical conductivity (EC) may be monitored in real time to detect detrimental changes in WQ [3]. However, direct environmental impacts of wireless sensor systems are usually overlooked when considering the benefits of deploying IoT-based solutions for WQ monitoring. Introducing new technologies, such as IoT devices, entails a growth in producing electronic waste (e-waste) [4]. Sensor nodes in wireless sensor systems often have short life spans and are exposed to environmental factors that may damage the sensor nodes, requiring frequent replacement. Current research has laid emphasis on increasing life spans by optimizing the energy consumption of wireless sensor systems rather than on circular economy approaches, which focus on the reusability of wireless sensor system (WSS) components. Energy efficiency is indeed one of the critical parameters to determine the sustainability of wireless sensor systems [4]. Studies have proposed renewable power supply sources, for example, for an underwater WSS that has been powered by solar panels [5]. Circular economy approaches have been briefly explored by citizen projects to develop an environmental sensor node using e-waste sensors [6], and, more recently, by researchers to develop a structural health monitoring system using e-waste and recycled materials [7].

For WQ monitoring, the implementation of wireless sensor systems using e-waste and circular economy concepts have not been sufficiently addressed. Adopting e-waste in wireless sensor systems may be a valid approach to convey sustainable WQ monitoring systems if the performance of e-waste components can be ensured. Hence, the performance of a sustainable WSS is investigated in this work. First, the WSS is developed, consisting of e-waste components (i.e., a temperature sensor, a pH sensor, a turbidity sensor, an EC sensor, two microcontrollers) and a cloud server. The system is based on a four-layer IoT architecture and the e-waste sensors are harvested from home appliances such as refrigerators, dish washers, washing machines, and aquarium tanks. Using the embedded computing capabilities of the reused microcontroller, a WQ index (WQI) is estimated by the WSS. Then, the WQI is used to validate the sustainable WSS by comparing the results with those from a benchmark WQ monitoring system comprised of commercial sensors. The paper concludes with a summary of the work, conclusions, and an outlook for future work.

2 Development of a sustainable water quality monitoring system

The sustainable WSS presented in this section is based on a four-layer IoT architecture [8], and takes advantage of modern concepts of monitoring [9], embedded systems, and intelligent sensor technologies [10]. The hardware components and the software implementation of the sustainable WSS are presented in this section, as well.

2.1 System architecture

The system architecture of the sustainable WSS is based on IoT technologies and consists of four layers, (i) an application layer, (ii) a middleware layer, (iii) a physical layer, and (iv) a security layer, which are outlined in Figure 1. Users interact with the *application layer* through a dashboard accessible via a web-based interface, which provides real-time visualizations of WQ data. The *middleware layer* is hosted in a cloud server. The cloud server manages the backend services of the system using the Node-RED development environment, which is a framework that provides visual, flow-based programming for developing the backend logic of the sustainable WSS. The *physical layer* of the sustainable WSS consists of a wireless sensor node that collects WQ data, i.e. temperature, pH, turbidity, and EC. In addition, the wireless sensor node has the computing power to process the raw data using embedded algorithms and to calculate WQ indices. The data processed on board is sent to the middleware layer for data storage and visualization using the message queuing telemetry transport (MQTT) communication protocol. The data is stored in a MySQL database developed for WQ monitoring data. Last, but not least, the *security layer* provides authentication services, such as log for privacy and security of all layers.

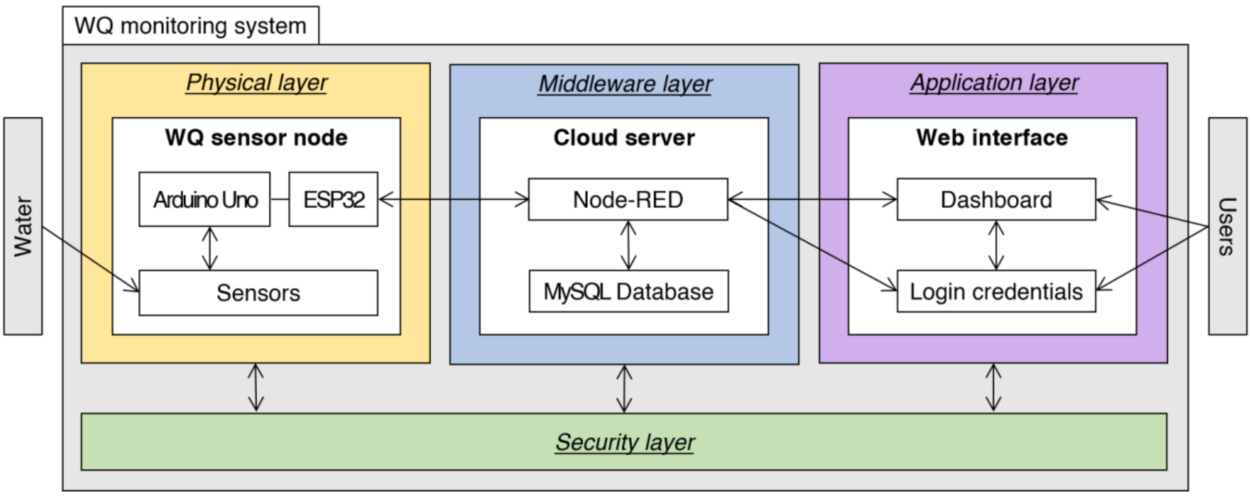

Figure 1: System architecture of the sustainable WSS.

2.2 Hardware components

The sustainable WSS is comprised of two microcontrollers, an Arduino Uno and an ESP32. The Arduino Uno is connected to an NTC thermistor, an EGA135 pH sensor, a TSD-10 turbidity sensor, and an SEN016 EC sensor. Figure 2 shows the sustainable WSS assembly. The four sensors obtained from e-waste generate analog signals, which the Arduino Uno microcontroller converts to digital outputs through an analog-to-digital-converter. The ESP32 microcontroller acts as a Wi-Fi module for the Arduino Uno. The microcontrollers are connected to a 5 V power supply. It should be noted that the Arduino Uno microcontroller and the e-waste sensors must be compatible regarding communication interfaces and voltage. The temperature sensor is harvested from a refrigerator, the turbidity sensor from a dishwasher, and the pH sensor as well as the EC sensor are harvested from aquarium tanks. The e-waste sensors are calibrated against commercial sensors to adjust the output data of the sensors, correlating output voltages to known values.

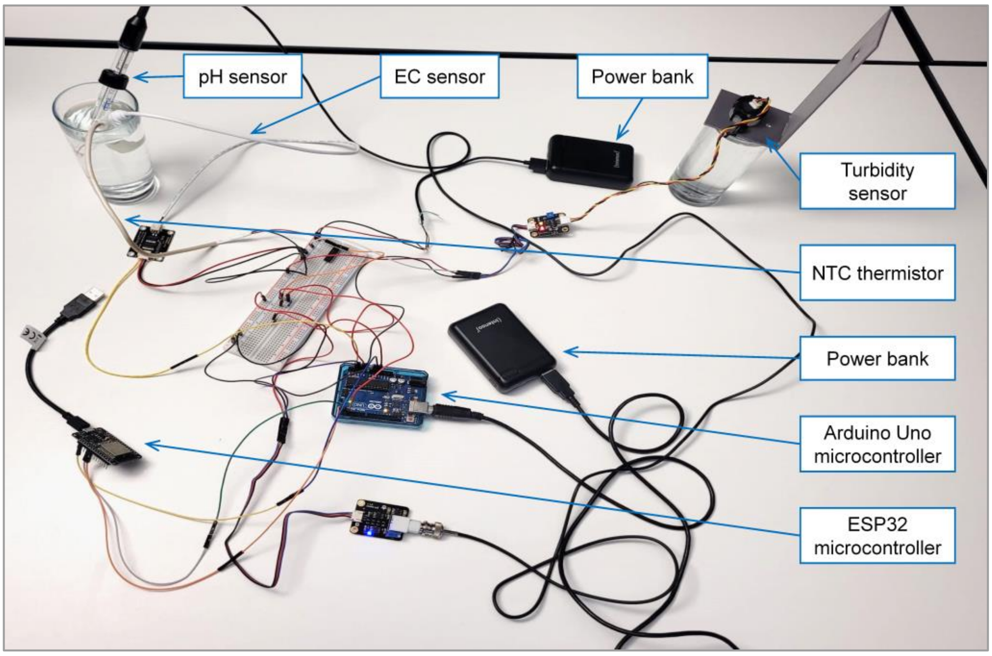

Figure 2: Sustainable WSS assembly.

2.3 Software implementation

Arduino Uno is an open-source microcontroller that runs embedded software to send the data collected by the sensors to the cloud server. Arduino programs, or *sketches,* are written using the Arduino Software IDE and uploaded to the non-volatile memory of the Arduino Uno microcontroller via serial bus. A flowchart of the *sketch* written for the wireless sensor node developed in this work is shown in Figure 3. The program begins by initializing the sensors, including variables corresponding to the WQ parameters and the WQI. Then, the sensor data is collected and assigned to the WQ parameter variables, i.e. raw WQ data. The raw data is then normalized and used to compute the WQI using the weighted arithmetic water quality index method [11] and the German WQ standards for drinking water [12]. Finally, the normalized WQ data and the WQI are sent to the server for storage to the MySQL database.

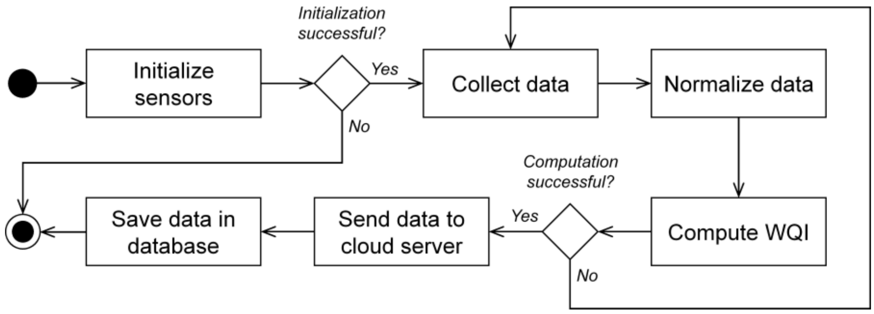

Figure 3: Flowchart of the software program embedded in the Arduino Uno microcontroller.

3 Validation of the sustainable water quality monitoring system

The validation of the WSS is conducted with different drinking water samples where temperature, pH, turbidity, and EC are monitored. The validation aims to determine the performance of implementing e-waste sensors in wireless sensor systems by comparing the results with a conventional WSS consisting of benchmark commercial sensors.

3.1 Experimental setup

Three main areas of a metropolitan city are selected in the validation test to collect water samples. The water samples are transported to a laboratory with water bottles, where the validation test is conducted. The measurements are taken consecutively to assure a consistent acquisition of parameters; the WSS is placed on a static table to conduct accurate experiments. Three different water samples are placed in glass cups to obtain the measurements. The temperature sensor and the electrodes of the pH sensor and the EC sensor are inserted in the water, while the turbidity sensor is placed on the surface of water samples. The measurements are then compared to the measurements of a commercial WSS consisting of a DS18B20 temperature sensor, a SEN0160 pH sensor, a SEN0189 turbidity sensor, and a KS0429 total dissolved solids (TDS) sensor.

3.2 Results and discussion

The WQI is interpreted according to [13] into five categories: Excellent (index value 0 to 25), good (index value 26 to 50), poor (index value 51 to 75), bad (index value 76 to 100), and unsuitable (index value more than 100). The WQ indices obtained with the sustainable WSS and the commercial WSS are in the range of excellent and good WQ. The data collected with the sustainable WSS presents the same trend as the commercial WSS and no faults have been detected during data collection. The average of WQ indices obtained from the sustainable and commercial WSS for each selected location are summarized in Table 1. The WQI calculated for location 1 is defined as good WQ, while location 2 possesses the best drinking WQ of the three locations, followed by location 3.

Table 1: Comparison of the average WQI obtained with the sustainable and commercial WSS.

WQI	Sustainable WSS	Commercial WSS
Location 1	27.26	17.29
Location 2	21.03	11.19
Location 3	24.64	15.42

By analyzing the sensor data for each WQ parameter, it is possible to explain the differences between the estimated WQ indices. The weight of each WQ parameter in the WQI depends on the values specified in the German standard for drinking water, where the temperature has a weight of 0.155, pH has a weight of 0.268, turbidity has a weight of 0.574, and EC has a weight of 0.003. Therefore, turbidity and pH are the WQ parameters with the highest weights when calculating the WQI. A comparison of the averaged WQ parameters obtained for the experiment by the sustainable and commercial WSS is presented in Table 2. The turbidity is of 0 NTU, which is expected for clear water; therefore, no deviation exists in the results of the sustainable and of the commercial WSS. The highest deviation in pH value between the sustainable WSS (S) and the commercial WSS (C) is of 0.47 for location 2, which is significant considering the pH value range according to the German standard is between 6.5 and 9.5. Hence, the accuracy of the pH sensors has a significant impact in estimating WQ indices.

Table 2: Comparison of the averaged WQ parameters obtained with the sustainable (S) and commercial (C) WSS.

WQ Parameters	Temperature (°C)		pH		Turbidity (NTU)		EC (µS/cm)	
WSS	**S**	**C**	**S**	**C**	**S**	**C**	**S**	**C**
Location 1	10.50	12.25	8.06	7.64	0	0	280.00	315.11
Location 2	11.80	12.06	7.88	7.41	0	0	446.87	440.39
Location 3	11.64	12.00	8.04	7.72	0	0	363.42	419.34

The performance and accessibility of e-waste sensors should be considered when developing sustainable wireless sensor systems. In the one hand, performance issues have been observed in this study for the NTC thermistor and the turbidity sensor. The sensor data from the NTC thermistor, harvested from a refrigerator, has required longer time to stabilize, as compared to the DS18B20 temperature sensor because the plastic cover of the thermistor has a lower thermal conductivity than the steel cover of the DS18B20 temperature sensor. Therefore, the DS18B20 temperature sensor performs faster than the NTC thermistor. The turbidity sensor, harvested from a dishwasher, has required to be calibrated before each use due to a damaged potentiometer in the sensor circuit deregulating the output voltage. On the other hand, the accessibility of the e-waste sensors depends on how widely used the sensors are in electronic devices and home appliances. In this study, the EC sensor was harder to acquire than the pH sensor, the turbidity sensor, and the thermistor, which are more frequently used and more accessible than the EC sensor.

4 Summary and conclusions

A sustainable WSS, assembled from e-waste sensors, has been proposed to reduce the environmental impact of wireless sensor systems in smart city applications. The sustainable WSS builds upon a four-layer IoT architecture, on cost-efficient hardware components, and on embedded software applications. The sustainable WSS measures essential drinking WQ parameters, such as temperature, pH, turbidity, and EC. The embedded software computes the water quality index of drinking water as an assessment method. The WSS has been assembled using an Arduino Uno and an ESP32 that serves as a Wi-Fi module for communication via MQTT with a cloud server. The validation of the sustainable WSS has been conducted through a comparison with a commercial WSS, showing results comparable to the commercial WSS. In summary, this work proves that wireless sensor systems deploying e-waste are promising alternatives to common approaches, to achieve WQ monitoring goals. In future research, other e-waste sensors may extend the sustainable WSS, such as near infrared spectroscopy sensors to monitor the quality of rainwater. Digital e-waste sensors instead of analog sensors may also be explored. Finally, reducing energy consumption of the WSS and using green energy as a power supply, e.g. using solar panels, may be investigated in future research as well.

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