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RESEARCH ARTICLE

# A Real-Time Remote Monitoring of Water Quality by Means of a Wireless Sensor Network

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Water is the key component of life on planet Earth. Although most of the Earth's surface is covered by water only a very small percentage of it is drinkable "fresh water." Drinkable water quality is influenced by several factors, like the construction of dams and embankments, the irrigation practices, and the anthropogenic activities. In order to control water quality, it is essential to understand the sources of pollutants by frequent water quality monitoring. Conventional monitoring of water quality calls for the collection of large numbers of samples and long delays until the results are available. Therefore, rapid monitoring of water quality is very important, proven by the large number of systems proposed for this kind of automatic monitoring. In this work, we propose a wireless sensor network (WSN)-based monitoring system controlled by a web-based online interface which allows the remote water quality monitoring via Internet. This brings advantages over traditional monitoring systems in terms of cost effectiveness, portability and applicability. Simulation-based studies concerning the wireless network aspects, as well as the practical output of the proposed system are presented for the evaluation of its effectiveness.

**Keywords:** Water Quality, WSN-Based Water Quality Monitoring, Web-Based Online Interface.

## 1. INTRODUCTION

Water is the most important of the available natural resources; it is the key component of life on planet Earth. Although most of the Earth's surface is covered by water only a very small percentage of it is drinkable "fresh water"; while the demand for good quality drinkable water is rapidly increasing the last decades.[1] The use of water depends on its suitability for the different intended purposes. Therefore, the quality of groundwater is very important as well as its quantity.[2] It is well known that in many countries the water quality of lakes and reservoirs suffers from degradation due to contaminated inflows. Therefore, the continuous monitoring of water quality is essential to ascertain the sources of pollutants in order to take measures to prevent pollution. The European Water Framework Directive (WFD) is the main reference guide for preserving aquatic environment in Europe. Dissolved oxygen (DO), pH, electrical conductivity (EC), temperature, turbidity and nitrate are the main parameters for determining the water quality as stated by WFD[3] and US EPA.[4] Generally, chemical analyses of the samples taken to assess water quality are performed at laboratories. This procedure is time consuming and causes considerable delays in water quality monitoring. In this respect, the real-time monitoring is strongly desirable because of its ability to provide the basis for an on-time warning of authorities and people.

In this paper, a novel wireless sensor network (WSN)-based monitoring system is proposed for the remote water quality assessment in real-time. The proposed system consists of several portable water quality monitoring nodes with wireless interfaces and periodically measures major water quality parameters such as Electrical Conductivity (EC), Dissolved Oxygen (DO), pH, temperature, turbidity and nitrate. In the proposed system, the nodes form a WSN and send their measurements to a web server through a gateway to provide information on the quality of the supplied water. The system has many

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advantages over traditional laboratory-based water quality analyses including cost-effectiveness, accuracy, portability and rapid assessment. Simulation-based studies concerning the wireless network aspects, as well as the practical output of the proposed system are presented for the evaluation of its effectiveness. First, an investigation of the wireless network performance of the employed WSN is presented by means of five appropriately designed simulation scenarios, revealing the competing design parameters as well as their relation. Then, the effectiveness of the practical output of the proposed system, that is the digital color-coded maps of the monitored water parameters, is examined. The corresponding investigation was performed by means of a set of Geographic Information System (GIS)-based simulation studies using an artificially constructed sensor readings dataset.

The remainder of this paper is organized as follows. Section 2 presents in short the related work on WSN-based water quality monitoring systems. Section 3 introduces the details of the proposed WSN-based real-time monitoring system. Section 4 gives the details of the web-based online interface which allows remote monitoring via Internet. The proposed system is evaluated in Section 5. Finally, conclusions are summarized Section 6.

## 2. RELATED WORK

Due to the offered advantages, portable water quality analysis systems have drawn the attention of research communities during the last years. Multi-probe Sondes with sensors for measuring water quality parameters were used to analyze water quality in different case studies, e.g., Refs. [5–7]. Considering the impact of several pollutants on water quality, timely water measurements at appropriate locations play a key role for human beings, animals, even for plants.[8] An automatic water quality monitoring system consisting of three monitoring stations has been proposed in Ref. [9]. The objective of this system was to analyze the relation between weather conditions and water quality in reservoirs.

Recently, there has been much advancement in water quality sensor technologies,[10] communication systems and computing technologies. A review of these advancements can be found in Ref. [11]. Further to water supply networks, the periodical analysis of water quality is also important for fish farms. The implementation of a wireless water quality monitoring system for fish farms is explained in Ref. [12]. Due to the increasing interest in wireless sensor networks (WSNs), the use of WSNs in water quality monitoring systems has been proposed in several studies. A WSN-based water quality monitoring system implemented in River Turia in Spain has been proposed in Ref. [13]. In this case study, nitrate levels were periodically monitored. A similar study which was implemented at 14 different locations is given in Ref. [14]. This study proposes a WSN-based measurement system for chemical analyses of water including nitrate, ammonium and chloride. Due to the success and benefits of the prototype implementations, real-world case studies like the ones in Refs. [15–17] have been implemented.

Since WSN nodes are battery-operated devices, their lifetimes are limited. Therefore, energy harvesting methods[18,19] can be used to extend the lifetimes of battery-operated sensor nodes. A prototype water quality monitoring system based on WSN nodes powered by solar cells was designed and implemented in Ref. [20]. WSNs are also used in several agricultural processes.[21] An example of these processes, a WSN-based water quality management system for irrigation, is given in Ref. [22]. A similar study which describes the implementation of a WSN for the temperature monitoring of shellfish catches is presented in Ref. [23]. Though there are other emerging techniques for water quality monitoring such as remote sensing,[24] their implementations are restricted to monitoring rough sensing of a few parameters including turbidity, chlorophyll and temperature.

In contrast to the approaches found in the literature, which focus on the overall system design, the sensor technologies, the communication infrastructures and the benefits of water quality monitoring systems, this study investigates the details of an online water quality monitoring system with a web-based interface which provides timely data to utility providers and subscribers. The proposed system is portable and consists of wireless monitoring nodes mounted on small buoys fixed at designed sampling points by using anchors. In this study, specific attention is given to the WSN-related design difficulties of the proposed system.

## 3. THE PROPOSED WSN-BASED WATER QUALITY MONITORING SYSTEM

A wireless sensor node principally consists of a microcontroller, a storage unit, A/D converters, a radio transceiver module, a battery, and sensors for measuring different environmental parameters. It converts data frames carrying measurements to radio messages and sends these frames to a gateway, generally referred to as the "sink." A wireless sensor network (WSN) is composed of several wireless sensor nodes distributed over a geographic area in order to observe specific phenomena. In WSNs, nodes automatically establish and maintain connectivity by using mesh-networking protocols.[25] The sensor gateway and its associated middleware enable the WSN to communicate with the outside world.

In this study, water quality parameters including EC, DO, pH, temperature, turbidity and nitrate are monitored by a WSN. Figure 1 illustrates the proposed implementation of the WSN-based water quality monitoring system. In this system, portable water quality monitoring nodes

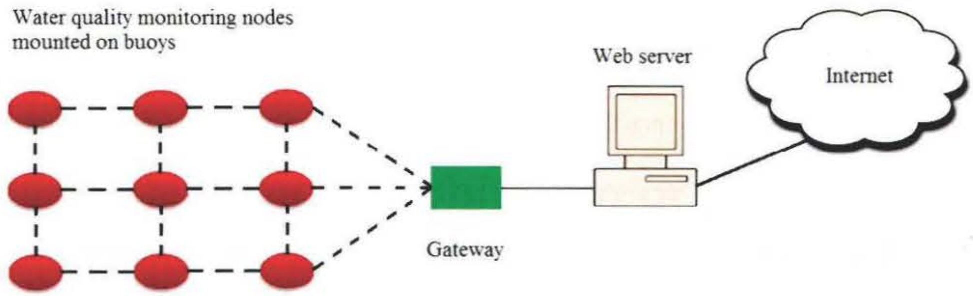


**Fig. 1.** WSN-based online water quality monitoring system.

with probes for water analyses mounted on buoys monitor water quality at specified time intervals. The actual positions of the buoys are determined after a specific site-survey at the site (lake, reservoir/dam) of interest, in order for the representative locations for the effective water quality monitoring to be determined. The monitoring sensors nodes form a WSN and send their measurements to the web server through the gateway. The gateway provides connection between the WSN and a web server which is located at the control center of a utility provider. The web server provides a data repository to store the measurements and render the measurements available to Internet users.

## 4. THE WEB-BASED ONLINE INTERFACE OF THE PROPOSED SYSTEM

A web-based interface has been developed for the WSN-based water quality monitoring system, characteristic snap-shots of which are presented in Figures 2 and 3. The interface is hosted by an Apache web-server running on an Ubuntu server. The web-server periodically polls the data from the gateway and updates the reference pages enabling various reports, statistics and graphics. The data polled by the web-server are stored in a MySQL database. Since the web-server is directly connected to the Internet, the reference pages can be accessed using different devices such as smart phones, tablets, notebooks, etc. The interface can be managed and supervised by authorized users. On the physical side, whenever its timer shows, as defined by the polling interval of the web-server, each water quality monitoring node gets the data from its sensors' transducers, and builds a data frame that consists of its identifier, a time stamp and the obtained measurements. This frame is transmitted to the gateway over the ad-hoc network architecture.

Through the web-based interface, utility providers and subscribers can easily check the quality of their water. Depending on the configuration of the water quality monitoring nodes, the measurements shown on the interface are refreshed at specified time intervals such as 15 min, 30 min, 1 hour, 6 hours, 12 hours, and 1 day. Since the web server stores all the data, the utility providers and customers can also look at past measurements referring to a specific time (cf. Fig. 3). Through the administration screen, the interface also allows for adding new nodes and new water quality parameters.

## 5. PERFORMANCE EVALUATIONS

The performance evaluation of the proposed solution is attempted in two different levels using corresponding simulation studies. First, an investigation of the wireless

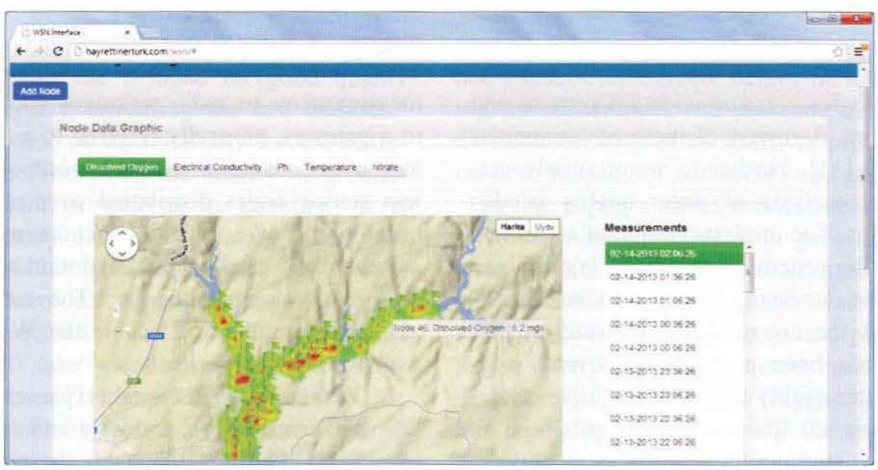


**Fig. 2.** Online interface of the real-time water quality monitoring system. Note that the details of a specific node can also be shown by clicking the corresponding mark on the map.


Fig. 3. Measurement history of a specific node.

network performance of the employed WSN is presented, which was conducted by means of five appropriately designed simulation scenarios, revealing the competing design parameters as well as their relation. Then, the effectiveness of the practical output of the proposed system, that is the digital color-coded maps of the monitored water parameters, is examined. The corresponding investigation was performed by means of a set of Geographic Information System (GIS)-based simulation studies using an artificially constructed sensor readings dataset.

## 5.1. Investigation of the Wireless Network Aspects of the Proposed System

In the this set of performance evaluations, five different scenarios were considered in order to show the efficiency of the proposed WSN-based water quality monitoring system in terms of network performance. In order to do this, real code running under the emulated hardware for sky motes was emulated. In these emulation-based studies, "PRR" is the packet reception rate, "Time Active (%)" is the average percentage of time during which the nodes are active, "Time Tx (%)" is the average percentage of time during which the nodes transmit, "Time Rx (%)" is the average percentage of time during which the nodes receive, "MRM" is the multi-ray Model and "UDGM" is the unit disk graph model with distance loss.

*Scenario* 1: This scenario involves two water quality monitoring nodes and its objective was to evaluate the performance of the WSN when the distance between the nodes varies.

Main parameters of this scenario:

- Packet generation interval = 5 s
- Application packet length = 23 octets
- MAC: CSMA/CA and contikiMAC with an 8 Hz check rate
- Radio Model: MRM
- Tx: not directional
- Rx Sensitivity = −85 dB.

Considering the results of this simulation study, Figure 4, it can be concluded that when the distance between WSN nodes is increased, the PRR drops and the average percentage of time during which the WSN nodes transmit increases, since the receiver needs to acknowledge the packet. This way the power consumption increases.

*Scenario* 2: This scenario involves two water quality monitoring nodes and its objective was to evaluate the performance of the WSN when the packet generation interval varies.

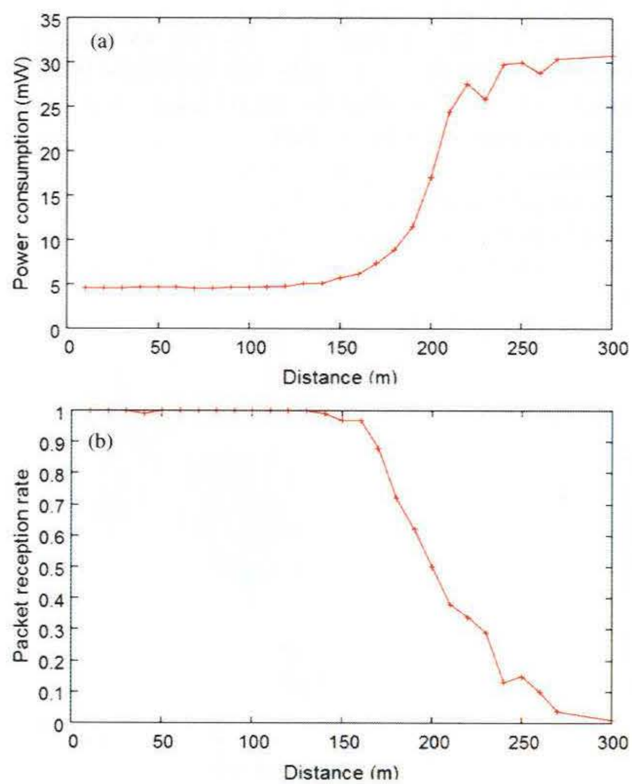


Fig. 4. Results of the first scenario. (a) Power consumption versus distance. (b) Packet reception rate versus distance.

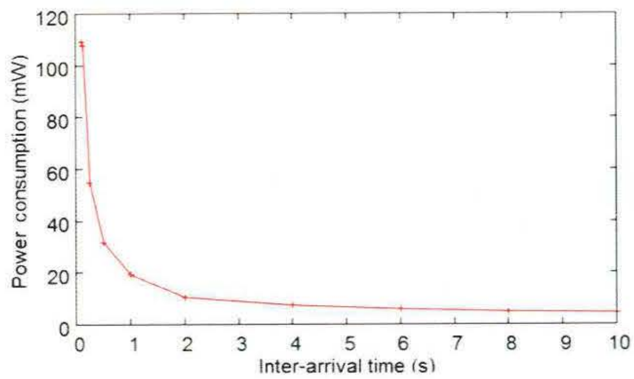


**Fig. 5.** Results of the second scenario: Power consumption versus inter-arrival time.

Main parameters of this scenario:
- Distance between the nodes = 30 m
- Application packet length = 23 octets
- MAC: CSMA/CA and contikiMAC with an 8 Hz check rate
- Radio Model: MRM
- Tx: not directional
- Rx Sensitivity = −85 dB.

Considering the results of the simulation study according to the second scenario, see Figure 5, it can be concluded that when packet generation interval is reduced in WSNs, the average percentage of time during which the WSN nodes transmit/receive increases, which justifies the increase in power consumption.

*Scenario* 3: This scenario involves two water quality monitoring nodes and its objective was to evaluate the performance of the WSN when the packet length varies.

Main parameters of this scenario:
- Distance between the nodes = 3 m
- Packet generation interval = 5 s
- Application packet length = 23 octets
- MAC: CSMA/CA and contikiMAC with an 8 Hz check rate
- Radio Model: MRM

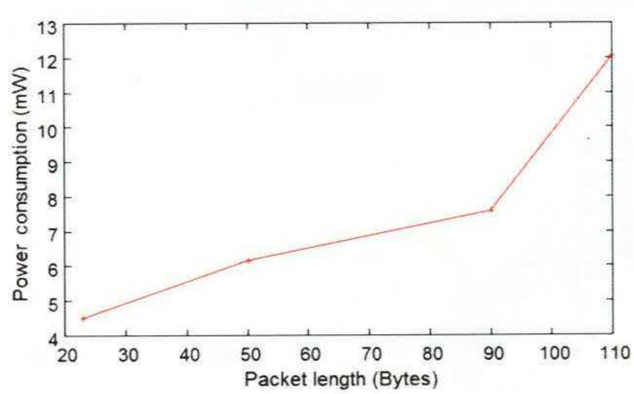


**Fig. 6.** Results of the third scenario: Power consumption versus packet length.

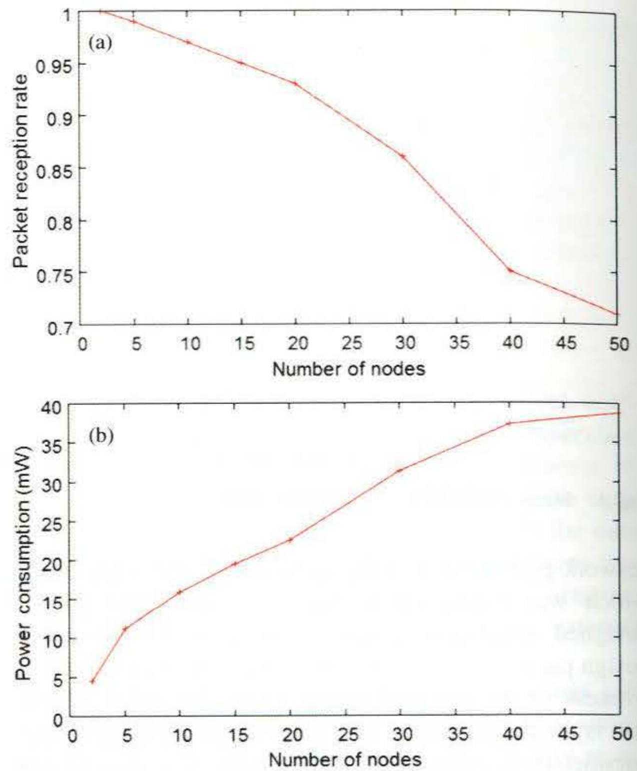


**Fig. 7.** Results of the fourth scenario. (a) Packet reception rate versus the number of nodes (b) power consumption versus the number of nodes.

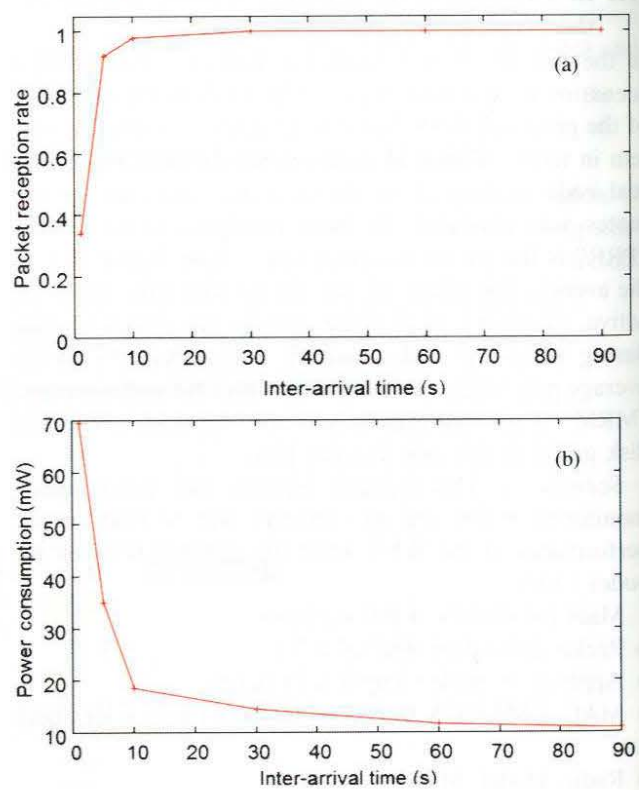


**Fig. 8.** Results of the fifth scenario. (a) Packet reception rate versus inter-arrival time. (b) Power consumption versus inter-arrival time.

- Tx: not directional
- Rx Sensitivity = −85 dB.

Examining Figure 6 which presents the results of this simulation study, it can be concluded that when the packet length is increased, the average percentage of time during which the WSN nodes transmit/receive, as expressed by the corresponding consumed power, increases.

*Scenario* 4: This scenario involves a group of water quality monitoring nodes and its objective was to evaluate the performance of the WSN when the number of nodes varies. All the nodes in this scenario were within 1 hop.

Main parameters of this scenario:

- Packet generation interval = 5 s (periodic with a different random offset for each node)
- Application packet length = 23 octets

**Table I.** Dataset used in the simulation study.

| *X* | *Y* | Temp (°C) | EC (mS/cm) | $NH_4$(Nitrate) (mg/L) |
|---|---|---|---|---|
| 523710 | 4620530 | 17.7 | 7 | 4 |
| 523640 | 4620530 | 17.6 | 7 | 3.8 |
| 523640 | 4620570 | 17.8 | 7 | 4 |
| 523680 | 4620570 | 17.9 | 7.8 | 3.7 |
| 523610 | 4620650 | 17.9 | 7 | 3.6 |
| 523550 | 4620660 | 18 | 7.6 | 3.7 |
| 523560 | 4620720 | 17.8 | 8 | 3.8 |
| 523500 | 4620800 | 17.8 | 8.2 | 3.9 |
| 523430 | 4620890 | 17.9 | 8.1 | 3.5 |
| 523520 | 4620900 | 17.9 | 8.4 | 4 |
| 523620 | 4620900 | 18 | 8.3 | 4 |
| 523670 | 4620950 | 18 | 8.7 | 3 |
| 523550 | 4620950 | 18 | 8.3 | 3.7 |
| 523380 | 4620950 | 17.9 | 8.4 | 3.6 |
| 523340 | 4621000 | 17.8 | 8.5 | 3.7 |
| 523450 | 4621000 | 18 | 8.7 | 4 |
| 523550 | 4621000 | 18.3 | 8.8 | 3.1 |
| 523100 | 4621000 | 18.4 | 9 | 3 |
| 523200 | 4621000 | 18.5 | 8.7 | 3.2 |
| 523300 | 4621000 | 18.6 | 9 | 3.7 |
| 523400 | 4621000 | 18.4 | 8.7 | 3.8 |
| 523500 | 4621000 | 18.7 | 8.8 | 3.9 |
| 523600 | 4621000 | 18.8 | 8.9 | 3.8 |
| 523100 | 4621200 | 19 | 9 | 3.7 |
| 523300 | 4621200 | 19 | 9.1 | 3.7 |
| 523500 | 4621200 | 18.7 | 9.1 | 3.7 |
| 523100 | 4621400 | 20 | 9.3 | 3.8 |
| 523200 | 4621400 | 22 | 9.4 | 4 |
| 523500 | 4621400 | 24 | 9.5 | 3.7 |
| 523700 | 4621400 | 25 | 9.5 | 3.5 |
| 523500 | 4621500 | 25 | 9.5 | 3.6 |
| 523600 | 4620420 | 17 | 7 | 4 |
| 523760 | 4620420 | 17 | 7 | 3.8 |
| 524000 | 4621600 | 18.4 | 9 | 3 |
| 524000 | 4621400 | 19 | 9 | 3.7 |
| 524000 | 4620400 | 20 | 9.1 | 3.8 |
| 523810 | 4620500 | 24 | 9.4 | 3.7 |
| 523810 | 4620400 | 18.4 | 9.1 | 3.7 |
| 523810 | 4620300 | 18.8 | 9 | 4 |
| 523000 | 4621450 | 18.4 | 9 | 3 |
| 523000 | 4621190 | 19 | 9 | 3.7 |
| 523000 | 4621000 | 20 | 9.1 | 3.8 |

- MAC: CSMA/CA and contikiMAC with an 8 Hz check rate
- Radio Model: MRM
- Tx: not directional
- Rx Sensitivity = −85 dB.

Considering the results of the simulation study for the fourth scenario, Figure 7, it can be concluded that when number of nodes in the proposed WSN is increased, the PRR drops and the average percentage of time during which the WSN nodes transmit/receive, or equivalently the consumed power, increases.

*Scenario* 5: This scenario involves a group of water quality monitoring nodes and its objective was to evaluate the performance of the WSN when the packet generation rate varies and the RPL routing protocol is used. It consists of a multi-hop network with 32 nodes (1 receiver = node 1), while node 1 was always active in this scenario.

Main parameters of this scenario:

- Distance between the nodes = 3 m
- Packet generation interval = 5 s (periodic with a different random offset for each node)
- Application packet length = 23 octets
- MAC: CSMA/CA and contikiMAC with an 8 Hz check rate
- Radio Model: United Disk Graph Model with distance loss
- Transmission range = 50 m
- Interference range = 50 m (no interference above transmission range)
- Tx: not directional
- Rx Sensitivity = −85 dB.

Taking the results of this simulation study into consideration, Figure 8, it can be concluded that when the event inter-arrival frequency increases, the PRR drops and the average percentage of time during which the WSN nodes transmit/receive, i.e., power consumption, increases.

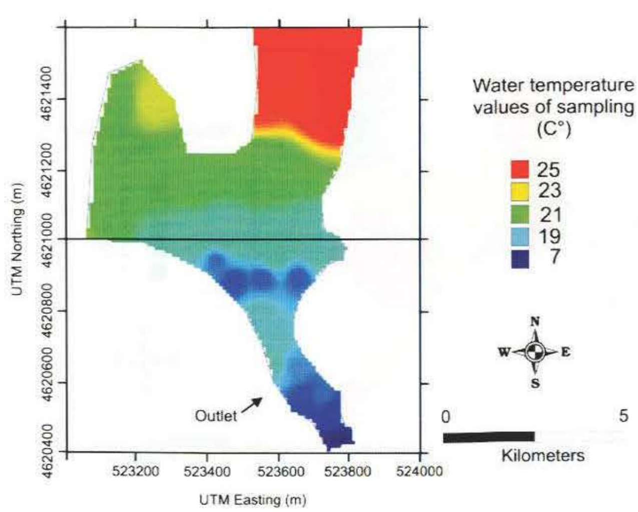


**Fig. 9.** Temperature analysis of the case study.

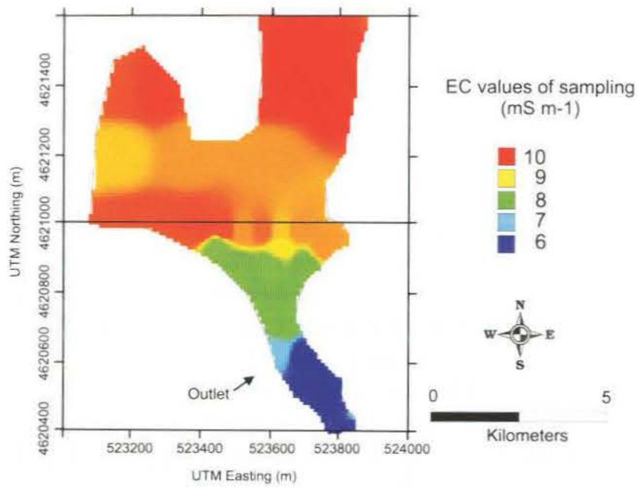


**Fig. 10.** EC analysis of the case study.

From the above presented five simulated scenarios, it can be concluded that there is a trade-off between the design parameters of the WSNs. Therefore, for each specific application it is necessary to evaluate the parameters and balance the trade-offs between them before the corresponding real-world deployment are attempted. Each application case is expected to have a different optimum balance of these trade-offs.

### 5.2. Evaluation of the Produced GIS Outputs of the Proposed System

In the second level of performance evaluation, a sample dataset of sensor readings from a water reservoir, listed in Table I, was created in order to show the effectiveness of the mapping output of the proposed system. Using this dataset, a set of Geographic Information System (GIS)-based simulation studies was conducted. The results of these simulation studies, which concern the construction of digital color-coded maps of the considered water reservoir, are given in Figures 9–11, depicting the spatial distribution of the different monitored water quality indicators. From these figures, it is evident that the proposed system provides eloquent water quality color-maps to utility providers and customers and in this way helps to visualize different water quality parameters. With the aid of these maps the source and the spreading direction of the contaminant can easily be determined. This brings advantages over conventional observation methods as fast and accurate precautions to stop the contamination with the GIS outputs could easily be taken.

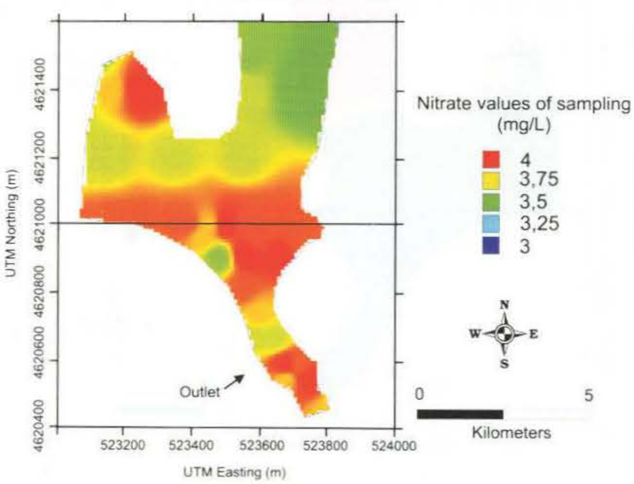


**Fig. 11.** Nitrate analysis of the case study.

## 6. CONCLUSION AND FUTURE WORK

This paper presents the details of a novel WSN-based real-time water quality monitoring system and presents simulation studies conducted in order to show the associated design challenges which affect the overall effectiveness of the proposed system, as well as the efficiency of the final resulting color-maps showing special distribution of different monitored parameters related to water quality. The proposed system eliminates the need for periodical time-consuming water quality analyses and helps the improvement of the quality of the supplied water through continuous monitoring. At the same time, it brings cost advantages to utility providers by eliminating periodical laboratory expenses.

The proposed system utilizes a group of portable Sondes with solar panels for energy harvesting and IEEE 802.15.4-based wireless interfaces mounted on buoys. The Sondes form a WSN to communicate over and send their measurements at regular time intervals to a central PC over the WSN. As proven by the presented simulation results, the applicability of the proposed system depends on several parameters such as transmission frequency, transmission power, packet size and node-related parameters. Moreover, the finally produced color-maps provide an eloquent presentation of the quality status of water that is readily perceived by the utility providers and customers. Our future work concerns the conduction of field tests of the proposed system at the water reservoir of Kirklareli (Kirklareli dam), Turkey.

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