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Water Quality Monitoring in Smart City: A Pilot Project

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Abstract: A smart city is an urban development vision to integrate multiple information and communication technology (ICT), "Big Data" and Internet of Things (IoT) solutions in a secure fashion to manage a city's assets for sustainability, resilience and liveability. Meanwhile, water quality monitoring has been evolving to the latest wireless sensor network (WSN) based solutions in recent decades. This paper presents a multi-parameter water quality monitoring system of Bristol Floating Harbour which has successfully demonstrated the feasibility of collecting real-time high-frequency water quality data and displayed the real-time data online. The smart city infrastructure – Bristol Is Open was utilised to provide a plug & play platform for the monitoring system. This new system demonstrates how a future smart city can build the environment monitoring system benefited by the wireless network covering the urban area. The system can be further integrated in the urban water management system to achieve improved efficiency.

Key Words: Water Quality Monitoring, High-frequency, Real-Time, Internet of Things, Smart City

1 Introduction

Water covers 71% of the Earth's surface. It is one of the vital resources for all known forms of life on the Earth to survive. However, only 2.5% of this water is freshwater, and even less than 0.3% of all freshwater is in rivers, lakes, and the atmosphere. Water system is an essential component in a smart city for its sustainability and resilience. As we are entering a data-rich era, the amount of data being collected by human beings is accelerating with the popularity of Internet. In terms of data related to water, many data sources (smart meters, smart sensors and smart services, remote sensing, earth observation systems, model outputs, etc.) have been continuously accumulating significant amount of data [1]. For example, the Next Generation Weather Radar (NEXRAD), the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement Mission (GPM) have collected tens of terabyte of data [2–4]. The significant amount of the rainfall observation data is due to the high spatial and temporal coverage and resolution and its dimensions, e.g., 2-D in space and 1-D in time. The large amount of remote sensing precipitation data, though with considerable uncertainty, could counter the uncertainty in the hydrological model resulting better performance than gauge-based data [5]. However, the measurement of water quality is usually based on single spot with no spatial coverage. Also, the manual lab-based monitoring approach has its inherited disadvantage of low sampling frequency. The manual in-situ monitoring approach and the modern WSN-based solutions make use of the electronic sensors to measure water quality, which can provide data in high frequency to overcome the shortage of the traditional approach. Areal estimates of water quality of lakes or rivers from remote sensing images is another approach to monitor water quality because every substance gives off a unique spectral signature. The relationship between the percentage of reflectance and the wave-length when a substance is exposed to electromagnetic spectrum is known as spectral signature which is unique for every substance [6]. Thus, the amount of substance in water can be estimated by the intensity of the reflectance at different wavelengths through building empirical statistical regression between them [7–11]. It is foreseeable that the water quality data will grow in a fast speed with the advancement in the monitoring techniques.

However, the remote sensing estimation of water quality suffers from the relative low spatial resolution which makes it difficult to monitor water quality for freshwater such as rivers, channels, ponds in urban area. Owing to the advance in smart city and Internet of Things, the network infrastructure in the urban area, both wired and wireless, is developing rapidly, and new network protocols have been developed such as ZigBee, Z-WAVE, INSTEON, WAVENIS, LoWPAN, NB-IoT, LoRaWAN, etc. Environment monitoring is without doubt one of the key applications of Internet of Things [12]. Bristol Is Open (BIO) is a joint venture between the University of Bristol and Bristol City Council, with collaborators from industry, local institutions, communities, and local authorities. BIO provides an open programmable Information and Communications Technology (ICT) infrastructure, offering ‘City Experimentation as a Service (CEaaS)', for researchers to conduct user-defined experiments in the heart of Bristol city. The harbourside is a focal area of Bristol with new buildings and features redeveloped in the last ten years, attracting numerous visitors by the diversity of attractions and beautiful views.

The urban surface water quality has a significant impact on the property values regardless of whether they are waterfront properties or not. Keeping the water quality in good condition would please people as well as benefit the aquatic ecosystems [13,14]. So, there is a timely opportunity to explore the new water quality monitoring approach with the help of the cutting-edge ICT technology.

This paper provides a timely review of a state-of-the-art wireless protocols developed for IoT to point out the new opportunities for the WSN-based solution for water quality monitoring for the future. It then describes the BIO pilot project multi-sensor and camera monitoring of Bristol Floating Harbour to prove the concept of Wi-Fi based wireless sensor network solution for water quality monitoring in smart city. The water quality monitoring system developed in this project utilised the Bristol Is Open (BIO) infrastructure for wireless communication and data processing, storage and redistribution. This is the first attempt to collect water quality data in real time and high frequency in the Bristol urban area with the Wi-Fi network provided by BIO. The system consists of the entire procedures from data acquisition, data transmission, data storage and data visualisation with the help of cloud computing, software defined network and open source platforms developed in IoT era. A few selections of results are presented afterwards together with the discussion of the potential value of the system.

2 Background

2.1 Internet of Things

The term Internet of Things has gradually become popular in recent years after the flourishing of cloud computing, big data, and artificial intelligence. Evidence of the popularity of IoT has been found on the increasing trend of the Google search volume of the term "Internet of Things" [15]. In the foreseeable future of Internet of Things, it aims to integrate heterogeneous communication technologies, both wired and wireless, to connect trillions of devices to contribute the vision of a global infrastructure of networked physical objects [16,17]. Although there are many ways to describe an IoT, we can define it as a worldwide network of uniquely addressable interconnected objects, based on standard communication protocols [12]. The vision of a future smart environment is described by Mark Weiser 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" [18]. The idea of IoT is useful in many application scenarios such as healthcare and wellness, home and building automation, improved energy efficiency, industrial automation, smart metering and smart grid infrastructures, environmental monitoring and forecasting, asset management and logistics, vehicular automation and smart transport, precision agriculture, smart shopping, etc [15,17,19]. The number of application is usually limited by human's creation rather than technical challenges.

The connectivity of the physical objects is the fundamental requirement of IoT. There are a variety of network protocols developed in the IoT era. They are usually different combinations of power consumption, data rates and range. Radio-frequency identification (RFID) uses electromagnetic fields to automatically identify and track tags which contain electronically stored information attached to objects [20]. RFID is now popularly used to tracking objects, people, and animals, which, to some extent, inspired the boom of IoT[21]. ZigBee is a wireless short-range (10 ~ 20 m), low-rate (20 Kbps ~ 250Kbps), low-cost and low-power communication protocol based on IEEE 802.15.4. ZigBee devices can easily form a mesh network to transmit data over long distances by passing data through of intermediate devices to reach more distant ones [22]. Application areas of ZigBee include Smart Home, building automation, embedded sensing, industrial control, wireless sensor networks, etc. Z-Wave is a low bandwidth wireless half duplex protocol in a low-cost control network, used to communicate short control messages in a reliable manner from a control unit to one or more nodes in the network. Z-Wave defines two types of devices: controllers and slaves. Controllers poll or send commands to the slaves, which reply to the controllers or execute the commands [23]. INSTEON is a peer-based solution for home automation developed by SmartLabs and promoted by the INSTEON Alliance. It provides a simple and cost-effective solution for devices to be networked in powerline or radio frequency, or both. No master controller or complex routing software is required as each device is designed as a peer to transmit, receive or repeat messages [24]. Wavenis is a RF based wireless protocol stack developed by Coronis Systems for control and monitoring applications in several environments, including home and building automation. It extends the industry standard Bluetooth protocol to provide secure and reliable wireless connections with long range and low power consumption [25]. People are usually more familiar with the IP-based protocols such as Bluetooth, Wi-Fi, since they are widely used in smart phones and laptops nowadays. Wi-Fi features high bandwidth, which can reach up to 7 Gbps based on the latest IEEE 802.11ac standard with medium range, around 30m to 100m, but also comes with high power inefficacy [26]. 6LowPAN (IPv6 Low-power wireless Personal Area Network) is an important IP-based solution as it uses IPV6 to extend the IP addresses to approximately 5 x 10^{28} addresses to provide enough addresses for every connected object based on the commonly used IPV4. The standard has the freedom of frequency band and physical layer and can also be used across multiple communications platforms, including Ethernet, Wi-Fi, 802.15.4 and sub-1GHz ISM [27]. The latest and the protocols which are gaining more and more momentum are LoRaWAN and NB-IoT. LoRaWAN is a Low Power Wide Area Network (LPWAN) that defines the communication protocol and system architecture for a Low Power Wide Area Network (LPWAN) based on the physical layer of LoRa patented by Semtech. LoRaWAN features a combination of long range, low power consumption and secure data transmission. The range of LoRa can reach up to 15 km in rural area and the data rates range from 0.3 Kbps to 50 Kbps [28,29]. NarrowBand IoT (NB-IoT) is a Low Power Wide Area Network (LPWAN) radio technology standard developed by the 3rd Generation Partnership Project (3GPP) to enable future IoT devices to use cellular telecommunications bands. NB-IoT features wide coverage, extreme low power consumption (10-year battery life) and massive connections. The current cellular network is not the best solution for IoT for the cost of the devices, short battery life and unsuitable for occasional small data transmission. NB-IoT was designed and frozen at Release 13 to overcome these issues of current cellular network [30,31]. As new protocols are still being developed for future IoT applications, this paper cannot cover all the relevant technologies, but only a summary of some popular ones in Table 1. However, giving such many options for connectivity, it might be difficult to decide the suitable solution to use for a desired scenario. In Bristol, the Bristol Is Open platform provides common network connectivity such as RFID, Wi-Fi and mobile network for researchers to conduct experiments in the Bristol city centre in a plug & play manner.

Table 1: Summary of some relevant IoT communication protocols

Protocol	Coverage Range	Data Rates	Power Consumption
ZigBee	Short (10-20 m)	Low (20 Kbps ~ 250Kbps)	Low
Z-Wave	Short (30 m)	Low (40 Kbps ~ 100Kbps)	Ultra - low
INSTEON	Short (50 m)	Very Low (38.4 Kbps)	Low
Wavenis	Long (1 Km)	Low (4.8 Kbps ~ 100 Kbps)	Low
Wi-Fi	Medium (30 – 100 m)	High (typical 100 ~ 300 Mbps, up to 7 Gbps)	High
6LowPAN	N/A	N/A	Low
LoRaWAN	Very Long (15 Km)	Very Low (0.3 Kbps ~ 50 Kbps)	Low
NB-IoT	Very Long (10 ~ 15 Km)	Medium (2 Mbps)	Ultra - Low

2.2 Water Quality Monitoring

In the past few decades, water quality monitoring systems have evolved from the manual lab-based monitoring approach to the manual in-situ monitoring approach, and finally to the modern WSN-based solutions [32]. The operational water quality monitoring has been followed a simple work flow for many years that water samples are manually collected and transported to a laboratory for analysis to detect chemicals and microbial contaminants [33]. The manual lab-based monitoring approach could provide sufficient water quality parameters and has been used for many years, but its limitations cannot be ignored [32]. First, the specialised apparatus and trained personnel are necessary to assess the quality of the water samples. Second, it is time consuming for humans to collect the water sample from the site, to transport the water sample to the laboratory and analyse the water sample in the laboratory, which makes it difficult to monitor water quality in real time by this approach. Third, the cost of this approach is very high in terms time, effort, and resource investment in the design and implementation of these systems as well as the cost of building the platforms (either fixed or movable) for data collection, the cost of the lab-based sensor hardware, and the cost of the subsequent system maintenance. Fourth, the temporal sampling frequency of this approach is usually low, not enough for extensive data analysis. Thus, it could result in high uncertainty when data analysis was carried out with low frequency data [34]. Fifth, real-time water condition change cannot be detected as it is time consuming to carry out the manual lab-based monitoring approach.

New in-situ sensors have been developed to measure water quality parameters in the field and in real time, known as the manual in-situ monitoring approach, to overcome some limitations of the manual lab-based monitoring approach. In this approach, users use the in-situ water quality sensors to measure water quality parameters on site and take the real time reading from the hand hold device connected to the sensor. The continuous monitoring of water quality can be achieved by leaving the sensor on site to collect and store the data inside the sensor unit, however, data cannot be automatically sent to users for processing and visualisation. Wireless Sensor Network (WSN) has becoming a better solution for water quality monitoring with the development of wireless communication technology for a few reasons. First, the in-situ sensor can be fixed on the site to collect data continuously and consistently. Second, the water quality sampling frequency can be adjusted to a desired rate without considering additional cost of money or time which is an important factor for manual monitoring approach. Third, the water quality data can be processed and visualised to the end users in real time. Forth, remote control and configuration of the sensor unit are possible [32]. Although, the WSN based solution is quite flexible in the system architecture, it generally consists of five steps: data acquisition, data transmission, data processing, data storage and data redistribution. Water quality parameters can be either collected through in-situ water quality sensor or seldom water samples analysed at local laboratory, and then transmitted to a data centre for processing and storage. The data transmission system of the remote water quality monitoring systems is commonly built on cellular network (GSM/GPRS) [35–38] or satellite data link [39]. New networks have also been utilised to set up wireless sensor network, e.g., Zigbee is commonly used [40][41], and sometimes Wi-Fi network [42]. It is believed that the new communication technologies recently developed for IoT will substantially push the development of WSN-based water quality monitoring system to even higher levels. The data centre can be either a local server cluster or make use of the computing cloud. Data redistribution is the procedure that the data reaches the end users, e.g., email, text message, web-page, mobile app, etc.

Apart from these three generations of water quality monitoring approaches mentioned above, robotic devices based on the combination of robotics and WSN technology have been developed and tested for water quality monitoring [43] such as Autonomous Underwater Vehicles (AUVs) [44,45] and Autonomous Surface Vehicles (ASVs) [46,47]. Biomimetic robots such as fish robots [48,49] has also been developed as a derivative of AUVs featuring better mobility under water. The water quality monitoring robots are able to provide a better spatial coverage of water quality data with the help of the built-in GPS or sonar positioning system than the fixed sensors, but the energy harvesting and the wireless data transmission are still problematic especially for long-term deployment of AUVs. The wireless sensor network is likely to evolve into mobile sensor network [50] providing the advancement of robotics and relevant technologies in the future.

The current water quality monitoring scheme in Bristol is operated by Bristol City Council started from January 1995. Multiple sampling sites are being monitored by the manual lab-based monitoring approach. Five sites are sampled monthly and four sites are sampled weekly as shown in Figure 1. Water quality parameters being monitored include total coliforms, E-Coli, Presumptive Enterococci, Faecal streptococci, temperature, pH, conductivity, dissolved oxygen (DO), phosphates and salinity [51]. It is a timely opportunity to use the Bristol Is Open infrastructure started running on late 2016 to build a real-time high-frequency remote water quality monitoring system. It is one of the pioneers to use Wi-Fi in an urban area to monitor water quality.

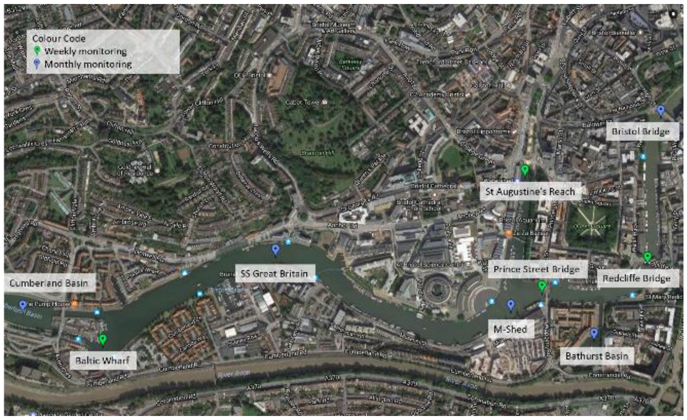

Figure 1:Bristol City Counil water quality monitoring locations

3 Methods

3.1 Bristol Is Open

Bristol Is Open (BIO) as shown in Figure 2 [52] is a joint venture between the University of Bristol and Bristol City Council, with collaborators from industry, local institutions, communities, and local authorities. BIO has developed an open programmable ICT infrastructure offering ‘City Experimentation as a Service (CEaaS)', providing a user-defined experimental environment in the heart of the city. Providing CEaaS enables experimenters to design, develop and test novel technologies within communications, cloud and Internet of Things (IoT) without impacting on city services.

The infrastructure is powered by a 'City Operating System' which combines multiple experimental facilities and capabilities comprising:

- Active Nodes: Four carrier grade network nodes (active nodes) offering access to SDN enabled dynamic optical switching supporting multi-Terabit/sec data streams, SDN enabled multi-rate layer 2 switching (1-100GE) and layer 3 routing. The active nodes are equipped with programmable hardware platforms and high-performance servers to allow open access to the infrastructure and a capability to create and experiment with new hardware and software solutions.

- Wireless nodes: The wireless infrastructure specifically includes overlapping wireless connectivity solutions using a combination of mobile and Wi-Fi technologies, enhanced with direct connections to the optical network.

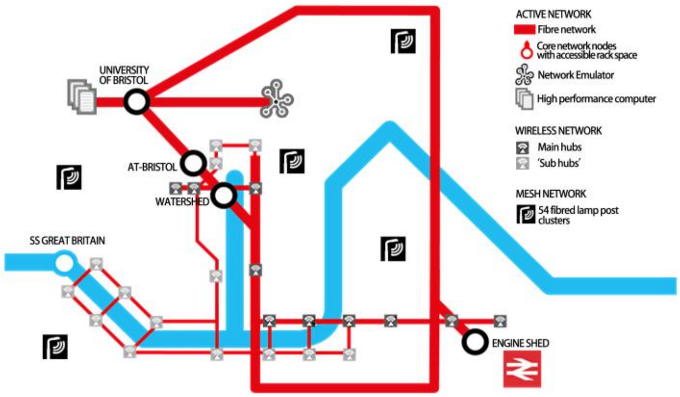

Figure 2: Bristol Is Open infrastructure

3.2 Site Selection

Three locations in Bristol Harbourside have been selected as testing sites for the water quality monitoring system. Based on the BIO Wi-Fi coverage, site accessibility and security consideration, the three testing sites have been selected as shown in Figure 3 and Table 2. Site 1 is at the pontoons secured by the gate, north to the Pero's Bridge. Site 2 is located at the pontoons to the east of Prince Street Bridge. Site 1 and Site 2 are secured by gates, only accessible for the ship owners instead of public to ensure the security of the sensor. Site 3 is located on the pontoon only accessible by a boat, which on the other hand, provides high security. The sites selected are close to the current operational water quality sampling locations by the environment team in Bristol City Council, aiming to compare sensor readings with the data collected by them.

Table 2: Information of the three test water quality monitoring sites

Site	Site 1	Site 2	Site 3
Location	St Augustine's Reach	Prince Street Bridge	Redcliffe Bridge
Latitude	51.451218	51.448802	51.449094
Longitude	-2.597943	-2.595751	-2.592850
Data collection period	2017/4/11 17:30 -2017/5/10 14:15,	2017/5/10 15:00, 2017/6/5 14:30,	2017/6/8 15:00 – 2017/8/1 14:45

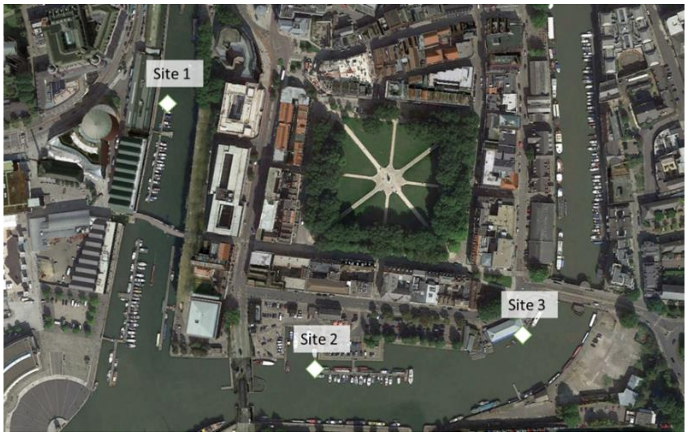

Figure 3: Map of the three test water quality monitoring sites

3.3 System Architecture

3.3.1 General Layout

The multiparameter and video camera water quality monitoring system consists of data acquisition module, data transmission module, power supply module, data storage module and data redistribution module shown in Figure 4, which covers the whole processes of WSN-based water quality monitoring system. The details of the modules are discussed in the following subsections. The system utilised the products available from the vender, the Bristol Is Open network infrastructure and open source software to achieve the fast and cost-effective system development and implementation. The power supply module was built into an on-site system covered in a weather proof case shown in Figure 5 with the data acquisition module connected to it via water proof connectors. The water proof case was locked by a pad lock for safety. An example of the system deployed on site is given in Figure 6. The lead acid battery in the water proof box weights over 10 kg, providing sufficient stability to resist the wind load without extra fixtures.

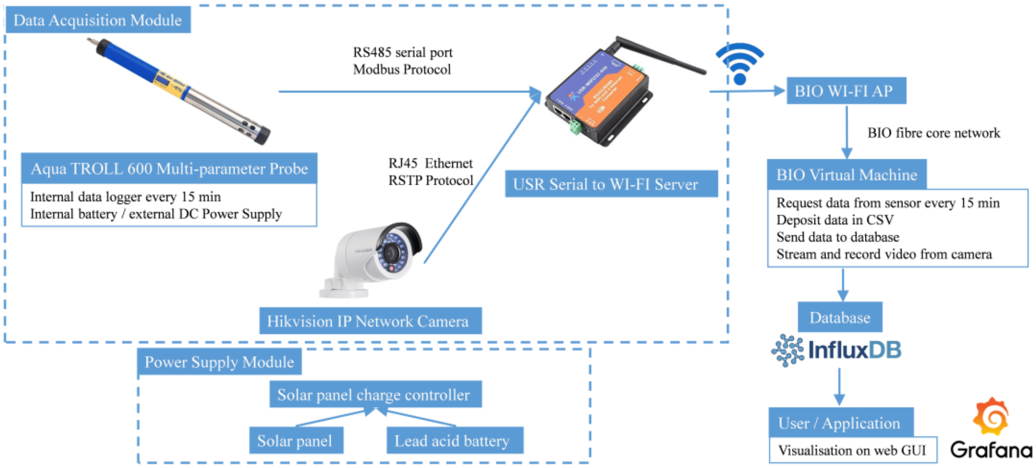

Figure 4: General design of the wireless water quality monitoring system

Figure 5: The water proof IP67 case for the on-site modules

Figure 6: Water quality monitoring system deployed on site

3.3.2 Data Acquisition Module

The data acquisition unit has two components, an In-situ Aqua Troll 600 multi-parameter water quality sonde to measure the water quality and a Hikvision IP Network Camera DS-2CD2042WD-I to capture the video image of the water surface in 720p 6fps respectively. The multiparameter sonde has four sensor ports installed with a dissolved oxygen (DO) sensor, a conductivity sensor, a turbidity sensor and a pH/oxidation reduction potential (ORP) sensor. An additional temperature sensor is built-in within the sonde separated from the four sensors. The DO sensor measures DO concentration in mg/L, saturation and oxygen partial pressure. The pH sensor measures pH in both pH value and mV and ORP in mV. The turbidity sensor measures turbidity in NTU using optical nephelometers which takes the measurement of diffuse radiation. It also converts Total Suspended Solids (TSS) from turbidity. The conductivity sensor measures actual conductivity of the water and calculates specific conductivity with temperature. Salinity also is calculated from actual conductivity and temperature [53]. Data was logged in the internal SD card every 15 min and transmitted to the data storage module through Bristol Is Open network when requested. The water quality sonde was deployed near water surface, approximately 50 cm deep. The video camera was mounted on a tripod to achieve stability. The video was encoded in H.264+ by the video camera in a resolution of 1280*720 at 6 fps. The framerate was set to 6 fps, lower than normal video to save the volume of the video file. Also, high framerate was unnecessary as the video image was supposed to be used to briefly identify the condition of the water body.

3.3.3 Power Supply Module

Like many existing remote water quality monitoring applications [32], the data acquisition module was powered by solar panel rather than the grid to achieve independence and mobility. The solar energy is a “free” power source and can provide the highest power density compared with other energy harvest methods [54]. The video camera and the serial to Wi-Fi server were powered by a lead acid battery charged from the solar panel. A solar panel charge controller was used to control the voltage from the solar panel in the daytime and disconnect the solar panel during the night. Although the multiparameter sonde was powered by 2 internal D-cell alkaline batteries which can last for 9 months [53], it was also connected to the lead acid battery as a backup power supply to provide addition system redundancy and robustness. The deep cycle AGM lead acid battery has a capacity of 36 Ah providing 72-hour power supply without charging from the solar panel based on the estimated average system power consumption of 500 mA. A 50 W solar panel and solar panel charge regulator were used to charge the battery during the day time.

3.3.4 Data Transmission Module

The data transmission unit utilised the BIO Wi-Fi network available around the Bristol floating harbour. However, the wireless data transmission methods of common data loggers current available on the market are usually based on GSM network or satellite network rather than Wi-Fi. One of the innovations of this system is that common on-site data logging device and telemetry system was bypassed by the serial to Wi-Fi server (USR-WIFI232-630), so the virtual machine provided by Bristol Is Open (BIO VM) can direct request and receive data from the water quality sonde through the wireless network. The physical connection was set up between the sensor and the BIO VM by the serial-to-WIFI server which was physically connected to the water quality sonde on site through RS485 and BIO network through Wi-Fi. The BIO VM can communicate with the serial to WIFI server through TCP/IP within a software defined subnet work provided by Bristol Is Open. The video camera is also connected to the serial to Wi-Fi server via RJ45.

As the multi-parameter water quality sonde supports Modbus protocol [55], all the data communication program with the water quality sonde used the Modbus protocol. MODBUS is an application layer messaging protocol, positioned at level 7 of the OSI model, which provides client/server communication between devices connected on different types of buses or networks [56]. There are different versions of Modbus, e.g., for serial lines (Modbus RTU and Modbus ASCII) and for Ethernet (Modbus TCP). Standard Modbus RTU is meant for transmission over serial lines (RS232 or RS485 are the most common). The message starts with a one-byte Slave ID and ends with a two-byte CRC. It is possible to make the RTU message to run through a gateway onto Ethernet without changing any of the bytes in the message. This is commonly called "RTU over TCP". There is a different specification for Modbus TCP where the message bytes are modified to add the 6-byte MBAP header and remove the two-byte CRC to compile a TCP/IP data unit. There is no significant advantage to using one or the other. The water quality sonde only supports Modbus RTU, so Modbus RTU was used between the sonde and the serial port on the serial to Wi-Fi server.

The serial to Wi-Fi server supports both raw mode, which transfers raw TCP/IP data to serial data to achieve transparent transmission, and mutual conversion mode between Modbus TCP and Modbus RTU. Therefore, there are two possible configurations to set up Modbus communication with the BIO VM and the water quality sonde, namely Modbus RTU Transparent Mode (Mode A) and Modbus RTU to TCP Conversion Mode (Mode B), as shown in Table 3.

Table 3: Water quality sonde connection configuration

	Water Quality Sensor	**Serial to WIFI convertor**	**BIO Wi-Fi**	**BIO VM**
Mode A Modbus RTU Transparent Mode	Modbus RTU	Transparent transmit mode	Modbus RTU over TCP/IP data unit	**Socat**, connect virtual serial port and TCP/IP **Libmodbus**, request data from the virtual serial port in RTU mode
Mode B Modbus TCP to RTU conversion Mode	Modbus RTU	Modbus TCP to Modbus RTU conversion mode	Modbus TCP data unit	**Libmodbus**, request data in Modbus TCP

In Mode A, the serial to WIFI server is set to the raw data mode to achieve transparent data transmission. The serial to Wi-Fi server was connected to the network with TCP/IP, so a virtual serial port was created on the BIO VM to communicate with the sensor with Socat. Socat is a Linux command line based utility that establishes two bidirectional byte streams and transfers data between them. It is used to create a data pipe between the virtual serial port and the serial to WIFI server on TCP/IP. Thus, the water quality sonde was remotely connected to the BIO VM, appearing as a local serial device, achieved by the transparent transmission by the serial to Wi-Fi server and virtual serial port created by Socat. In Mode B, the serial to Wi-Fi server was set to Modbus RTU - Modbus TCP/IP conversion mode. The server converts the Modbus TCP package transmitted through BIO Wi-Fi to Modbus RTU units to communicate with the water quality sonde, so the water quality sonde can be treated as a TCP/IP device in BIO Wi-Fi network. This mode is simpler than the Mode A as it does not require a virtual serial port to be setup on the BIO VM. There is no significant advantage or disadvantage between those two modes. Mode B may be more useful today when everything is connected through TCP/IP. Both Mode A and Mode B were proved and tested to be viable. Mode B was used in the monitoring system. The Modbus connection was implemented by Libmodbus5, an open source C Modbus library providing multi-platform compatibility.

The IP Network Camera supports Real Time Streaming Protocol (RTSP) which is used to capture the video stream from the camera. The Network Camera has its own unique IP in the BIO software defined subnetwork to make it accessible. Owing to the high data rates provided by BIO Wi-Fi, the system can wirelessly transfer the video image to the server.

3.3.5 Data Storage Module

The data storage module utilised the cloud computing facilities provided by Bristol Is Open. There were two virtual machine instances created within Bristol Is Open software defined subnetwork using OpenStack. The virtual machines run Linux system and were accessible through SSH connection. One of the VMs was used to run VLC to stream video data from the video camera and store the video data in one file for each hour. The other VM was used to retrieve the data from the water quality sonde and to log the data in CSV file every 15 mins. A C program was developed to achieve the data request and data logging. The C program also has a HTTP interface to stream the water quality data to the database running on the same VM. The system used InfluxDB to store the time series data. InfluxDB is an open-source time series database developed by InfluxData. It is written in Go and optimised for fast, high-availability storage and retrieval of time series data in fields such as operations monitoring, application metrics, Internet of Things sensor data, and real-time analytics [57]. It is a database designed for time-series data with tags to identify the location of the sensors. It is ideal for this type of WSN based real-time data streaming application. It allows for high throughput ingest, compression and real-time querying of that same data. InfluxDB can handle millions of data points per second. Working with that much data over a long period of time can create storage concerns. A natural solution is to down sample the data; keeping the high precision raw data for only a limited time, and storing the lower precision, summarised data for much longer or forever. InfluxDB offers two features—Continuous Queries (CQ) and Retention Policies (RP) that automate the process of down sampling data and expiring old data.

The water quality data from the multiparameter sonde has redundancy with three duplications, internally logged in the sensor, stored in the CSV file in the virtual machine and streamed to InfluxDB. The multiparameter water quality sonde was configured to record the data in the SD-card within the sensor to prevent data loss when the Wi-Fi network failed, or the virtual machine failed in the worst scenario. The data in the SD-card can be pulled out wirelessly once the Wi-Fi network recovers. The data was recorded in human-readable CSV file to prevent data loss due to the failure of the database. Thus, the redundancy of the data logging could prevent possible data loss due to the failure of the network, failure of the virtual machines and failure of the database.

The security of the data was achieved by both physical method and cybersecurity. The senor system deployed on site was in secured place with no public access, e.g., locked by gates on the pontoon only accessible by the ship owners and Harbour Master. The ship owners and Harbour Master were well informed of the water quality monitoring system and helped to protect the system from unauthorised physical access. The Wi-Fi network was secured by WPA2 that only the system administrators could access the network. Also, the sensor, camera and virtual machines running the data management system were in a software defined subnetwork created for the water quality monitoring system only. The subnetwork was protected by the firewall of BIO shared with the University of Bristol. One public IP has been assigned to one virtual machine running Grafana for data visualisation with only HTTP port open to protect the system from network attack.

3.3.6 Data Redistribution Module

The data redistribution is the process to make the data collected from the water quality sonde available for external application such as live view in webpage, mobile app, email, etc. This system used open source web-based GUI platform called Grafana. Grafana is an open source metric analytics & visualisation suite. It is most commonly used for visualising time series data for infrastructure and application analytics, but many use it in other domains including industrial sensors, home automation, weather, and process control. Grafana provides a plenty of data visualisation tools such as heatmaps, histograms, geomaps, pie chart, etc. to help the users to understand the data. Thresholds can be visually defined by user to get notified from emails or Slack, PagerDuty, VictorOps, OpsGenie, webhook. Grafana natively supports dozens of databases, which makes it easy for users to create dashboards linked to their data source in minutes. Thanks to the open source community, Grafana can be either host on cloud or easily installed on any platform, with hundreds of dashboards and plugins available in the official library [58]. In the water quality monitoring system, the data from multiparameter sonde streamed in InfluxDB was visualised in the Grafana dashboards as shown in Figure 7. The raw data was visualised together with the moving average smoothed data to filter out the noise in the data. The time window of data shown in the dashboard can also be adjusted by the user to see the entire time history or specific period of the sensor readings. The time elapsed from the system to request data from the sensor to presenting the data in the dashboards was within 10 seconds, which could be considered as real-time in this application scenario.

Figure 7: The web-based GUI for real time data visualisation

4 Results and Discussion

As this paper mainly aims to present the remote real-time water quality monitoring system, only a few selections of findings from the water quality data are presented here. As the water quality sonde was placed near the water surface, about 50cm deep, the results reveal the features of the epilimnion or surface layer of the water body that water temperature is high and sensitive to the solar radiation, DO concentration and pH are high. The high-frequency water quality data collected by the project shows features of the water quality parameters that were missed by the weekly/monthly monitoring scheme by Bristol City Council, such as large diurnal cycles in temperature and dissolved oxygen concentration as well as pH values shown in Figure 9, Figure 10 and Figure 11. Figure 8 shows the water temperature data collected by Bristol City Council, which can only illustrate the annual trend of water temperature change, high temperature in summer, low temperature in winter. Although the traditional manual water quality monitoring scheme can provide reasonable seasonal water quality variation since 1995, it lacks the sufficient detail about diurnal fluctuation of water quality [36]. Addition to this, when the sample was taken in that day was not recorded, so it is merely possible to determine how the water quality sampled was different from the daily mean value. For example, taking the fact into consideration that the water temperature is high in the middle of day and low in the early morning, if the time of the sample was not recorded, it is difficult to determine the water temperature measured is higher or lower than the daily mean. Thus, the uncertainty of the manual water quality monitoring scheme is considerably high. Despite the uncertainty and low sampling frequency, the manual water quality monitoring scheme provides a general trend of water quality change in a long term, while the modern in-site water quality sensor can provide sufficient detail information on the actual fluctuation of the water quality.

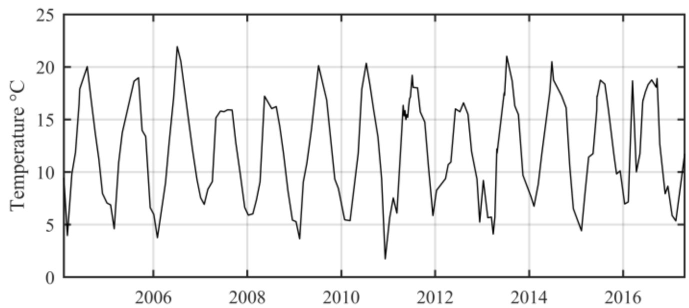

Figure 8: The water temperature data collected by Bristol City Council every two weeks, showing the general seasonal variation of water temperature but lack of details

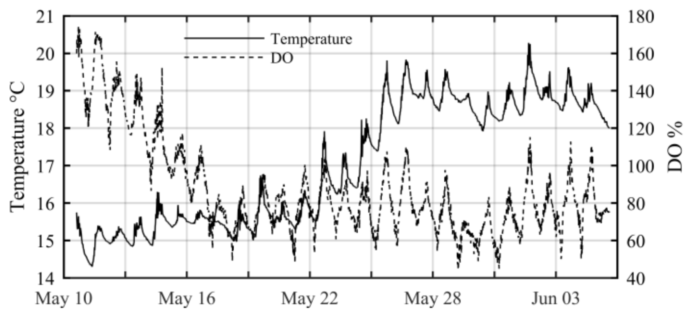

Figure 9: Temperature and DO saturation for site 2 showing diurnal cycles

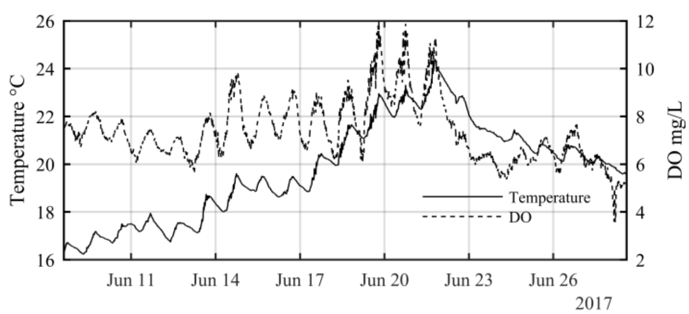

Figure 10: Temperature and DO concentration for site 3 showing diurnal cycles

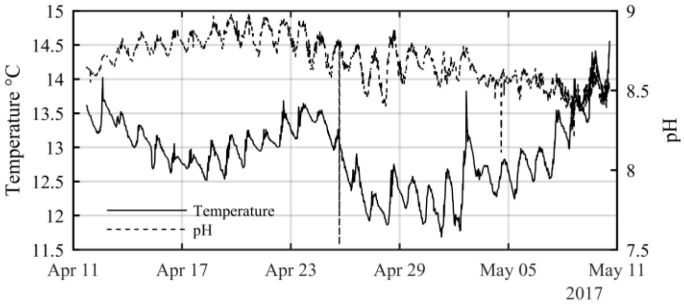

Figure 11 Temperature and pH for site 1 showing diurnal variation and anomalous readings in the raw pH data on 26 April and 5 May

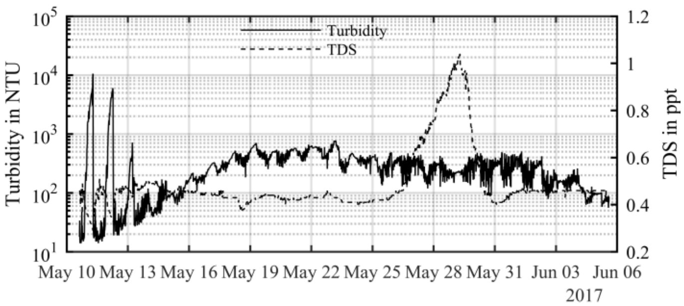

Figure 12: Turbidity and Total Dissolved Solids (TDS) for site 2 showing drifting in the turbidity reading

Considering the diurnal cycle of the water quality, the fundamental factor is supposed to be the solar radiation. Water is heated by the solar radiation in the day time and cooled through radiation during the night. The diurnal cycle for dissolved oxygen centration is supposed to be primarily due to the photosynthesis where Chlorophyll is abundant during the day time and respiration of the aquatic life during the night time. The over-saturation of DO (Figure 10) is possibly due to the intensive photosynthesis due to nutrient (nitrogen and phosphorus) enrichment, sunlight, and low-flow conditions [59]. The water in the Bristol floating harbour is kept at constant level by the weir and lock at the downstream, which can be considered as low-flow. The nutrient level is possible to be high as it is located at the centre of urban area.

However, the data quality of the raw sensor reading is not perfect even though calibration was carried out before the deployment. The sensor could malfunction resulting in anomalous readings in very rare cases, such as sudden drops of pH on 26 April and 5 May shown in Figure 11. The anomalous sensor reading was flagged as anomalous value and replaced by the linear interpolation of the neighbour values. The turbidity reading is highly suspicious as it rose up and dropped down sharply on 11 May and 12 May as indicated in Figure 12. One possible explanation for the suspicious turbidity reading is that aeration caused by the ship wave result in bubbles trapped against the turbidity lenses, thereby resulted in doubtful turbidity readings. Furthermore, bio-fouling is an unavoidable issue for water quality monitoring for long-term deployment. The drift of the turbidity reading from 11th to 19th May in Figure 12 may result from bio-fouling. It may cause notable drift in the sensor readings except the water temperature as the thermistor is merely affected by the bio-fouling.

The results from the video camera was supposed explore the feasibility to identify the visual condition of the water, but the reflection of the sky and cloud contributed to the video image significantly. It is rather hard to identify the colour of the water itself due to the impact of the ambient lighting. The video image could be used to identify the garbage floating on the water surface as shown in Figure 13. However, the reflection from the sunshine (Figure 14) and the reflection from the sky (Figure 15) dominated the video image, thus, it was difficult to identify the colour of the water itself in a constant condition to explore the correlation between the water colour and the water quality. However, the video image can show the condition of the sky and weather which do impact the water quality. So, there might be another possibility in correlating the video data with the water quality. Another thought was that the video image could be useful to identify the algae bloom. However, the event of algae bloom was not observed during the experimental period to test the methodology.

Figure 13: Video image at site 1 taken at 13:37 on 7th May 2017, showing floating garbage on the water surface

Figure 14: Video image on site 2 taken at 16:45 on 23rd May 2017, showing faculae due to the reflection of sunshine

Figure 15: Video image on site 3 taken at 05:02 on 26th June 2017, showing reflection of the sky on the tranquil water surface in early morning

Although the data quality may need further polishing, the presented water quality monitoring system features wireless data transmission, high-frequency and real-time data visualisation. It demonstrated how environment monitoring can be achieved in smart city era. The system can be used to identify and analyse potential pollution source in urban river system once the sensor network is deployed and operating. With the quiet revolution in data analytics and sensing, data transmission, computing power and data management, the abundance of water related data can lead us to the data-driven urban water management which allow us to develop and apply novel data-based methods to optimise the efficiency of the urban water management system [60]. The WSN-based water quality monitoring system is highly valuable for real-time operation of urban water systems. For example, it has been demonstrated that integrated real-time control (RTC) of urban wastewater systems could improve the performance of wastewater treatment plants while saving operational costs and improving river water quality. This could be achieved by optimally balancing the time-based flexible operation of wastewater systems and the dynamic self-purification capacity of the environment through RTC strategies [61]. The water quality monitoring system is applicable for river water in urban environment, wastewater effluent, water treatment plant, etc., to provide real-time operational water quality data for the urban wastewater RTC system. The water quality monitoring system effectively acts as the data source for water quality and can trigger the movement of wastewater treatment plant strategy from the current end-of-pipe permitting to operation-based permitting [62]. Eventually, the water system management can become smart and data-driven for improved efficiency based on the boom of available data.

5 Conclusion

In this paper, a remote real-time high-frequency water quality monitoring system based on the WSN solution is presented. The system consists of data acquisition module, data transmission module, power supply module, data storage module and data redistribution module which covers the whole processes of WSN-based water quality monitoring system. The system utilises Bristol Is Open programmable city infrastructure. The Wi-Fi network for the WSN solution is commonly available in smart cities nowadays, so the experience in this system is useful for environment monitoring in smart cities around the world. The water quality sonde is connected to a TCP/IP subnetwork using serial to Wi-Fi server solution. The software defined network (SDN), cloud virtual machine (VM) and open source software were used for fast and cost-effective system deployment. The system used open source InfluxDB and Grafana as database and data visualisation tools to minimise the cost and effort in developing the software system. The system effectively connected conventional sensors to the Internet, which demonstrated how Internet of Things can be useful in environment monitoring. The system is easily scalable to multiple sites to establish a large sensor network. It also demonstrates the feasibility of using cloud-based virtual machine as servers in the backend in real-time environment monitoring application. The system also features high sampling frequency, low-cost and real-time readings available from a web page. The high-frequency in-situ water quality data shows diurnal cycles in water temperature, DO and pH. Over-saturation of DO was also observed. Such details of water quality variation are of scientific interests and can provide more precise assessment of the water quality compared with the current manual lab-based water quality monitoring scheme in Bristol harbour area conducted by the environment team in Bristol City Council. Although regular maintenance of the sensors including calibration and fouling cleaning is necessary for the in-situ system, the successful combination of water quality sensor, cloud computing, smart city infrastructure and IoT technology shows a bright future for the environment monitoring in IoT era.

Based on the video image collected by the video camera, further work will focus on investigating the feasibility of estimating the water quality parameters from the video image data using numerical models or deep neural network models. Thus, the new method might attract research efforts to build novel methods to assess the areal water quality utilising a large amount of existing surveillance cameras in the urban area. Also, the feasibility of fusing the water quality data with satellite data in such a small scale can be explored to produce a water quality map based on satellite images. The water quality monitoring system will be extended to multiple sites and measure more parameters at the same time. It is worthwhile to explore a water system dynamic model to simulate water movement and quality dynamics in the urban area assimilated with the data collected by the monitoring system. The system is also valuable to be integrated with urban water management system to explore a smart data-driven water management strategy in future smart city.

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