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Real-time water quality monitoring of River Ganga (India) using internet of things

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ABSTRACT

Achieving and maintaining suitable water quality is one of the important parameters to ensure health and well-being of the human as well as ecosystems. Among the various aquatic ecosystems, riverine ecosystems are more prone to pollution and therefore needs to be monitored frequently and on regular time intervals. In this context, real-time water quality monitoring system offers excellent opportunity to keep track of the water quality on a continuous basis; which not only helps to identify the affected location and pollution source, but also creates alert enabling the authorities to take immediate action. One such real-time water quality monitoring system was installed in the River Ganga (India), considering the fragility and significance of the Gangetic ecosystem. In this paper, we have presented the details of the real-time water quality monitoring system installed in River Ganga and results obtained through it for various parameters. The results have also been compared with the standard values. Additionally, based on this preliminary investigation, limitations and recommendations have also been presented to further enhance the utility of the system.

1. Introduction

Regular monitoring of water quality is one of the essential tools to ensure safety of aquatic ecological systems and health of the human and aquatic biota (Badrzadeh et al. 2022; Jain et al. 2018, 2021; Singh et al. 2021; Singh et al. 2022). United Nations sustainable development goals (SDGs) also focus on these issues, such as, good health and well-being (goal no. 3), clean water and sanitation (goal no. 6), life below water (goal no. 14), and life on land (goal no. 15) (SDGs 2015). Therefore, it is important to have regular monitoring to ensure safety and quality of the natural water resources (Abd-Elaty et al. 2022). Traditional methods of monitoring involve timely visits to the study area, sampling, sample transportation, analysis, and data validation. This process is labor-intensive and liable to errors in measurement at various steps. Further, it also results in time-delays many of the times. However, sensitive ecological systems need to be monitored frequently and hence time-delays and errors are not acceptable in these cases. In such a scenario, traditional methods of monitoring do not suffice the purpose and hence there is need of real-time water quality monitoring system based on internet of things.

Real-time water quality monitoring system (RTWQMS) involves placement of sensor based instruments in the river / water bodies which can continuously measure the required parameters. The data is saved in data-loggers and send to the central server through internet, thus making continuous monitoring possible (Pujar et al. 2020; Vasudevan and Baskaran 2021). Many of the countries worldwide are opting for RTWQMS based on internet of things (IoT) for various purposes. In Korea, a real-time prediction model on urban rivers was developed which was able to sense and simulate short-term, real-time changes (Lee et al. 2022). In United Kingdom, a low-cost wireless sensor network,

Abbreviations: CPCB, Central Pollution Control Board, Delhi; CPCB RD-L, CPCB Regional Directorate Lucknow; COVID-19, Corona virus disease 2019; DBU, Designated best use; GPRS, General packet radio service; GSM, Global system for mobile communication; IoT, Internet of things; MLD, Million liters per day; RTWQM, Real-time water quality monitoring; SCADA, Supervisory control and data acquisition; TPD, Tonnes per day; UP, Uttar Pradesh; UPPCB, Uttar Pradesh Pollution Control Board.

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Fig. 1. Flow channel of River Ganga (Jain and Singh 2020)

namely, 'Hydrobean' was designed for catchment water quality monitoring (Benzon et al. 2021; Mlynski et al. 2021). It was able to measure and transmit electrical conductivity, temperature, and pressure continuously to the online portal for observation, thus, addressing the issues of temporal discontinuity and insufficient data quality. A water monitoring network based on open architecture and IoT has been developed in Greece as well, where the automatic monitoring stations were utilized to measure near real-time water level and physicochemical parameters in rivers (Dimitriou et al. 2021). IoT technology has also been used for remote monitoring of algal blooms in the inland waters of Spain as it was able to provide very fine spatio-temporal resolution. The results indicated that the number of plug-and-play nodes must be increased according to the increasing heterogeneity of the system so that a representative view of the water body may be obtained (Pascual-Aguilar et al. 2021). In China, cloud computing and IoT were employed for real-time water quality monitoring in rural tourist areas (Ding and Liang 2021). Similarly, possibility of IoT based technology has also been tested for irrigation management in Nebraska, U.S. (Singh 2021).

River Ganga, the national river of India, is one of the sensitive aquatic system which needs frequent monitoring and supervision owing to the multi-pronged use of its water (viz. drinking, bathing, agricultural, industrial, and recreational) and its proneness to pollution through various causes (Jain and Singh 2020). Notably, River Ganga is one of the most polluted rivers of the world, due to the sewage and industrial discharge received along its 2525 km stretch (Ranjan et al. 2021). Reduced ecological flow in the river due to various abstraction canals, dams / barrages, and climate change further lower down its carrying capacity and aggravate the pollution (Jain and Singh 2020). Therefore, continuous monitoring is essential in order to provide immediate solution in case of any emergency situation. Apropos the scenario, the apex pollution controlling authority in India viz. Central Pollution Control Board (CPCB) has got installed real-time water quality monitoring system at selected sites across the River Ganga. Monitoring stations were also installed at identified sites in selected tributaries and drains joining the River Ganga. The purpose was to monitor water quality of not only the River Ganga main stem, but also of the other possible sources (tributaries and drains) which might bring changes in the river water quality upon mixing. Systematic installation of RTWQMS

Fig. 2. (a) Various components of RTWQMS; (b) Fixed type RTWQMS at the bridge on River Ganga at Shuklaganj, Kanpur/ Unnao, U.P. (Station code: UP-26); and (c) Floating type RTWQMS at River Gomti, Rajwari, Varanasi, U.P. (Station code: UP-55).
(Image Source: CPCB)

at such a large scale in any river in India is a noteworthy attempt. Moreover, the installed system was able to monitor up to 17 water quality parameters, which is a considerable advancement in the field of information processing in real-time. In this paper, we are presenting the data obtained through real-time water quality monitoring system based on IoT employed in River Ganga. The data obtained was also used to determine the water quality class of River Ganga as per the Indian standards, since it helps in taking quick decisions to augment precautionary / remedial measures. Moreover, as this was the first attempt to install and functionalize real-time system at a large scale, data validation was also done. This study specially focuses on assessment of water quality in a specific stretch of the river in Uttar Pradesh (UP), which comes under the jurisdiction of CPCB – Regional Directorate, Lucknow (RD-L) (earlier, Zonal Office (ZO) Lucknow).

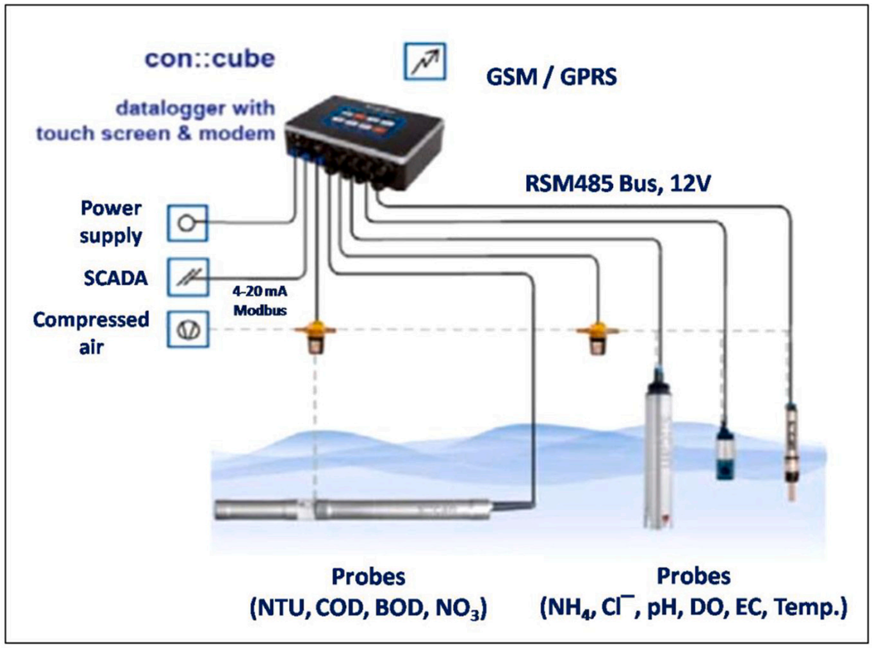
2. Methods

2.1. Study area

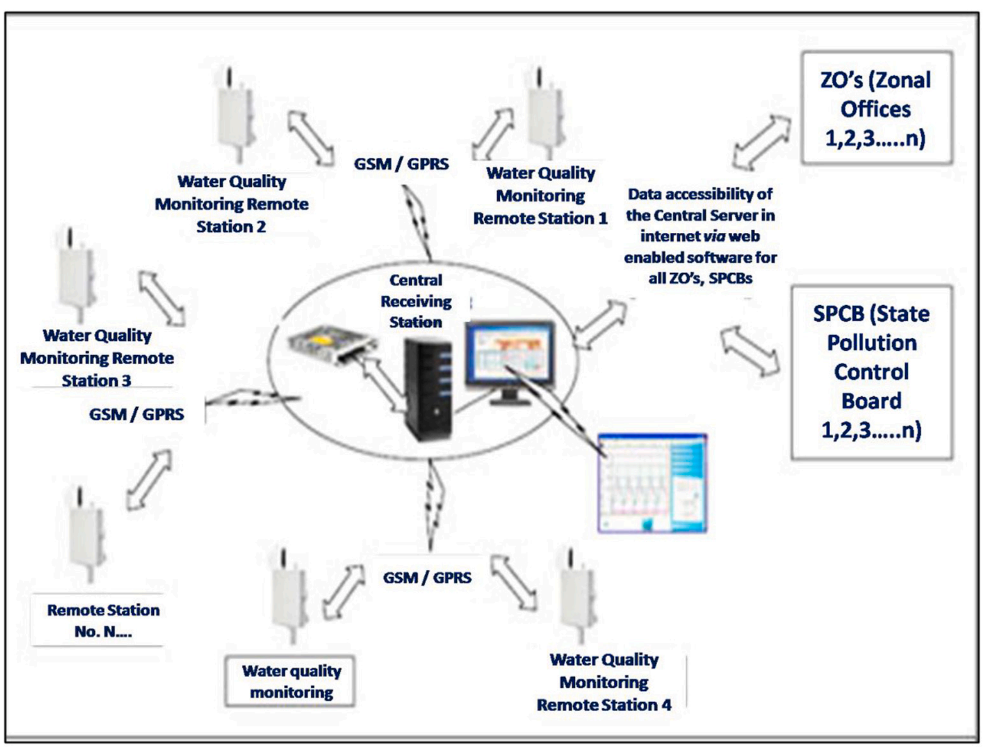
River Ganga originates from Gaumukh in Gangotri glacier in Uttarakhand (India) at about 4100 m above the mean sea level (Jain and Singh 2020). Across its 2525 km stretch, the river flows through Uttarakhand and Uttar Pradesh (1425 km), Bihar and Jharkhand (475 km), and West Bengal (625 km) before eventually emptying into the Bay of Bengal (Fig. 1). Ganga river basin bears the significance of being the largest river basin in India and the fourth largest in the world, supporting the population of approximately 445 million people either directly or indirectly (Jain and Singh 2020; Lokgariwar et al. 2014). The river stretch passing through the Uttar Pradesh receives discharge from 851 grossly polluting industries viz. chemical, distilleries, food and beverages, pulp and papers, sugar, textiles, tanneries, and others (CPCB 2013; UPPCB 2016). Further, 16 drains out of 56 major drains in UP stretch; carrying approximately 2213 MLD sewage having total biochemical oxygen demand load of 107 TPD (CPCB 2020); also discharge in the River Ganga thus resulting in significant pollution. Therefore, RTWQMSs were installed at strategic locations in River Ganga, its major tributaries, and drains confluencing / discharging into it; in order to have continuous monitoring of the river water quality. The present study is based on the real-time data recorded from May 2019 to November 2021.

2.2. Components and working principle of RTWQMS

The RTWQMS encompasses various components, such as, monitoring station, sensor package, wireless network – GSM / GPRS transmitters, data processing and publishing server, compressor, single point grounding system (for fixed stations), floating platform / buoy (for floating stations), solar panel – battery charging system (for remote



(a)



(b)

Fig. 3. Schematic of (a) Data logger connection to sensors; and (b) functioning of RTWQMS.
(Image Source: CPCB)

Table 1
Location and type of RTWQMSs under the jurisdiction of CPCB RD-L in Uttar Pradesh stretch of River Ganga.

S. No.	Station code	Location	District	River/Drain	Station type (fixed/floating)
1	UP-13	Village Tahsipur	Kannauj	Kali*	Floating
2	UP-14	Panchal Ghat	Farrukhabad	Ganga	Fixed
3	UP-16	Mehandi Ghat, Manimau	Kannauj	Ganga	Fixed
4	UP-17	Farrukhabad – Allaganj road	Farrukhabad-Shahjahanpur Border	Ramganga*	Fixed
5	UP-18	Bithoor Bridge, Pariyar Road	Kanpur	Ganga	Floating
6	UP-19	Ganga Barrage	Kanpur	Ganga	Fixed
7	UP-24	Dyodhi Ghat	Kanpur	Ganga	Cross sectional
8	UP-26	Shuklaganj	Unnao/Kanpur	Ganga	Fixed
9	UP-29	Hamirpur Road (NH25)†	Kanpur	Pandu*	Fixed
10	UP-32	Asni Ghat	Fatehpur	Ganga	Floating
11	UP-40	Sirsa	Prayagraj	Ganga	Floating
12	UP-46	Mavaiya	Prayagraj	Mavaiya Drain	Fixed
13	UP-54	Vatsalya Bridge	Varanasi	Varuna*	Fixed
14	UP-55	Village Rajwari	Varanasi	Gomti*	Floating
15	UP-56	Devkali Pump Canal, Saidpur	Ghazipur	Ganga	Fixed

* Tributaries of River Ganga.
† National Highway 25.

stations), web camera, alert system etc. as shown in Fig. 2.

The working principle of RTWQMS is based on Supervisory Control and Data Acquisition (SCADA) system and data logger is comprised of Con::cube for receiving the values of different water quality parameters. Dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total suspended solids (TSS), benzene-toluene-xylene (BTX), turbidity, colour, nitrate, pH, potassium, free ammonia, temperature, fluoride, chloride, and electrical conductivity (EC) were some of the important water quality parameters which were considered for measurement through RTWQMS. Measurement of these parameters was accomplished by sensors/sonde viz., Spectro::lyser (for BOD, COD, TOC, TSS, BTX, turbidity, colour, and nitrate), Ammo::lyser (pH, potassium, and free ammonia), Oxi::lyser (DO and temperature), Floro::lyser (chloride and fluoride), and Condu::lyser (EC). Periodic calibration of the sensor devices was performed using certified reference materials. For calibrations, field meters were used for pH, DO, temperature, EC, NH_4-N, NO_3, TSS, and turbidity while in-house laboratory facility / instruments were used for determining the BOD, COD, TOC, BTX, chloride, fluoride, potassium, and colour. Data generated by these sensors/sonde was displayed on a Con::cube (monitor) (Fig. 3a). The data was further processed in Moni::tool. For receiving the data from Moni::tool, a software system was developed through which the recorded data was transmitted to the central database at CPCB through IoT in real time (Fig. 3b).

3. Results

3.1. Setting up of RTWQMS in Uttar Pradesh stretch of river Ganga

A total of 21 RTWQM stations were planned to be installed in the UP stretch of River Ganga. In phase I of the work, 20 stations were installed, out of which 15 stations are under the jurisdiction of CPCB RD-L (Table 1; Fig. 4). Among these 15 stations, 9 are fixed stations, 5 are floating stations, and 1 is cross-sectional station (Table 1). The fixed and floating stations are equipped to measure up to 17 parameters, viz. BOD, DO, EC, pH, temperature, free ammonia, chloride, COD, TSS, turbidity, colour, fluoride, nitrate, potassium, BTX, TOC, and water level. However, cross sectional station measured BOD, DO, pH, temperature, ammonia, COD, turbidity, and colour. Fixed and floating stations, equipped with sensors, relayed the data to the central data center in CPCB within 5 min of taking the observations, while cross section stations relayed it within 60 min. Further, it was also ensured that speed of the measurement platform, in case of cross-sectional station, was not >5 km/h.

3.2. Water quality data obtained from RTWQMS

The water quality parameters were monitored continuously through RTWQM stations from 2019 to 2021 (though some of the stations were not equipped to measure all the 17 parameters). For each station, data was recorded as per the procedure shown in Fig. 3. Here it is important to mention that calibration of the sensors was a regular task in order to maintain the reliability of the data measured through RTWQMS. Therefore, onsite calibration was performed after every 14 days at the RTWQM stations and values of parameters obtained after calibration were recorded. However, calibrations could not be carried out during Apr. – Jun. 2020 and May 2021 owing to lockdown conditions imposed for COVID-19 pandemic. In this paper, we have presented the data obtained only after performing the calibrations, and therefore, data for the period of Apr. – Jun. 2020 and May 2021 is not presented. Further, as the calibration was performed after every 14 days, two sets (sometimes, three as well) of calibrated data (data obtained after calibration of monitoring sensors) were obtained in each month. For representation purposes, the data obtained after first calibration in any month is shown in this paper. As the dataset is huge, it is not possible to present the entire data, however, a representative set of data for the station number UP-26 (Fig. 2b), which was capable to measure all the 17 parameters, is shown in Fig. 5. Water quality data of each month for rest of the stations is given in supplementary information (Table S1).

The observed data of various parameters obtained from the real-time water quality monitoring system was compared with the standard (permissible) value of that particular parameter for the river (surface) water quality in India (IS 2296:1992, 1992). As per the Indian standards, water quality has been classified into 5 major classes, viz. A, B, C, D, and E (CPCB 2019; IS 2296:1992, 1992) and the water quality criterion for each class has been fixed as per the designated best use (DBU) of the water (Table 2). As the water of River Ganga is used for variety of purposes, such as, drinking, bathing, irrigation, industrial, aquaculture, etc.; the results obtained from RTWQMS were compared with the standard values of various parameters fixed for class A – E (IS 2296:1992, 1992) (Fig. 5). It is noteworthy that standard value for every water quality parameter is not provided for each of the class, rather it is provided as per the corresponding use of the water. For example, the standard values for colour is given for class A, B, and C; but not for class

Fig. 4. Location of RTWQMSs under the jurisdiction of CPCB RD-L in Uttar Pradesh stretch of River Ganga *(Basemap source: Google)*

D and E, as colour is not a significant parameter for determining the water quality for aquaculture, irrigation, and industrial purposes. Similarly, DO value has not been assigned for class E, as dissolved oxygen does not play any role in the water to be used for industries and irrigation activities (IS 2296:1992, 1992) (Fig. 5). Nevertheless, there are some water quality parameters; such as, TSS, turbidity, potassium, BTX, TOC etc.; for which standard values are yet to be developed in DBU classification for class A – E, and therefore, observed values could not be compared in those cases. On the other hand, DBU classification includes the standard value for total coliform organisms (in class A, B, and C) (CPCB 2019; IS 2296:1992, 1992), which is one of the most important parameters as far as drinking water quality is concerned; however, the present RTWQMS was not equipped to monitor this parameter.

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4. Discussion

4.1. Interpretation of water quality data and determination of water quality class of river Ganga based on the data obtained through RTWQMSs

The water quality data obtained from RTWQMS was compared with the standard values, as per IS 2296:1992, 1992. It could be seen that the observed pH values were beyond the range of the standard values i.e. 6.5–8.5 (Class A, B, and D) for 6 times in the study duration (Fig. 5a). pH values beyond the range of Class A, B, and D indicates that the water quality in that particular time of the year was unsuitable for drinking, bathing, and propagation of wildlife and fisheries. pH values were also beyond the range of Class C (6.0–9.0) thrice in the study period, which infers that during those months water quality was not suitable for drinking even after the conventional treatment and disinfection. Further, pH values crossed the standard values as per Class E (6.0–8.5) as well for five times, denoting that water was not suitable to be used even for the purposes of agriculture (irrigation), industrial cooling, and/or controlled waste disposal. Electrical conductivity is an important parameter to look for, if the water is intended to be used for the agricultural purposes, industrial cooling, and/or controlled waste disposal; as higher conductivity may lead to deposition of various salts. Therefore, its standard value has been assigned only for Class E. The graph indicates that EC values were well below the defined standard values making the water suitable for use (Fig. 5 b). Nevertheless, graph also shows some missed data points which are due to the unavailability of data as the instrument was under maintenance during that period.

The observed BOD values through RTWQMS were beyond the standard value of 2 mg/L (class A) for most of the time in the study duration, representing that the river water was not suitable for drinking without any treatment. Further, BOD values were beyond 3 mg/L (class B and C) in four months during the entire study period, which represents pollution in the water body (Fig. 5 c). In such a scenario, bathing in the river water and use of this water for drinking purposes even after the

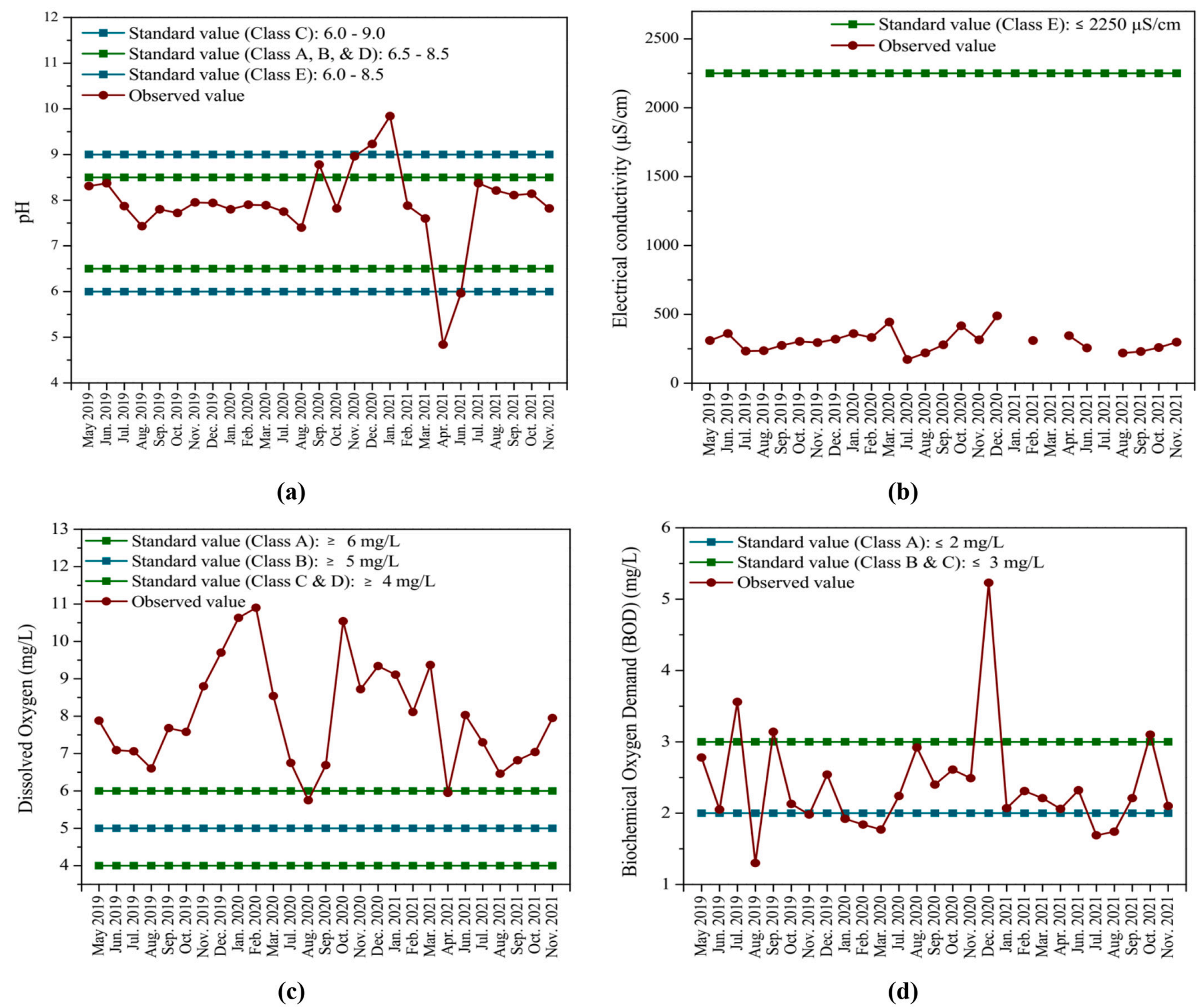


Fig. 5. Water quality data obtained from RTWQMS for the station code UP-26 in Uttar Pradesh stretch of River Ganga (a) pH; (b) Electrical conductivity; (c) DO; (d) BOD; (e) Colour; (f) Chloride; (g) Fluoride; (h) Free ammonia (as N); (i) Nitrate.

conventional treatment and disinfection is not advisable. However, DO values were well above the minimum DO values (≥ 6 mg/L, ≥5 mg/L, and ≥ 4 mg/L for class A, B, C & D, respectively) in almost all the months indicating the suitability of water for the purposes of bathing, drinking (after treatment and disinfection), and propagation of wildlife and fisheries (Fig. 5 d). Colour of the river water was found as per requirement for class B and C, but not for class A; thus restricting the use of water for drinking purposes without any treatment (Fig. 5 e). For chloride, fluoride, nitrate, and free ammonia; the observed values were well within the permissible values, thus posing no risk due to these parameters (Fig. 5 f – i). The observed values for rest of the 8 parameters could not be compared owing to unavailability of standard values for those parameters in Indian context (IS 2296:1992, 1992).

Water quality for a particular parameter may or may not meet the standard value. However, water quality designation of a river / water body in a particular class under DBU classification (Table 2), is based on the integration of all the parameters. Therefore, water quality is determined and classified by integrating all the parameters. In this scenario, the parameter(s) which does/do not meet the standard values become(s) the deciding factor for determination of the water quality class. For example, after the careful analysis of water quality parameters for the station under consideration, viz. UP – 26; it was found that the river water quality met the criteria for all the 5 classes (A, B, C, D, and E) for a total of 5 times during the entire study period (viz. 27 months). Further, water quality met the criteria of at least 4 classes (B, C, D, and E) for 13 times, 2 classes (C and E / D and E) for four times, and only one class (C) for two times (Fig. 6). For a total of 3 times during the entire study period, water quality did not meet the criteria for any of the class, thus restricting the use of water for any of the purposes (Fig. 6). This analysis helped to conclude that water quality of River Ganga was suitable for at least one purpose for 89% of the time in the study duration. In this way, real-time data may be utilized for determining the use of water for a specific purpose.

4.2. RTWQMS data validation

As the utility of RTWQMS relies in the fact that, values beyond permissible limits draw immediate attention, thus supporting in taking

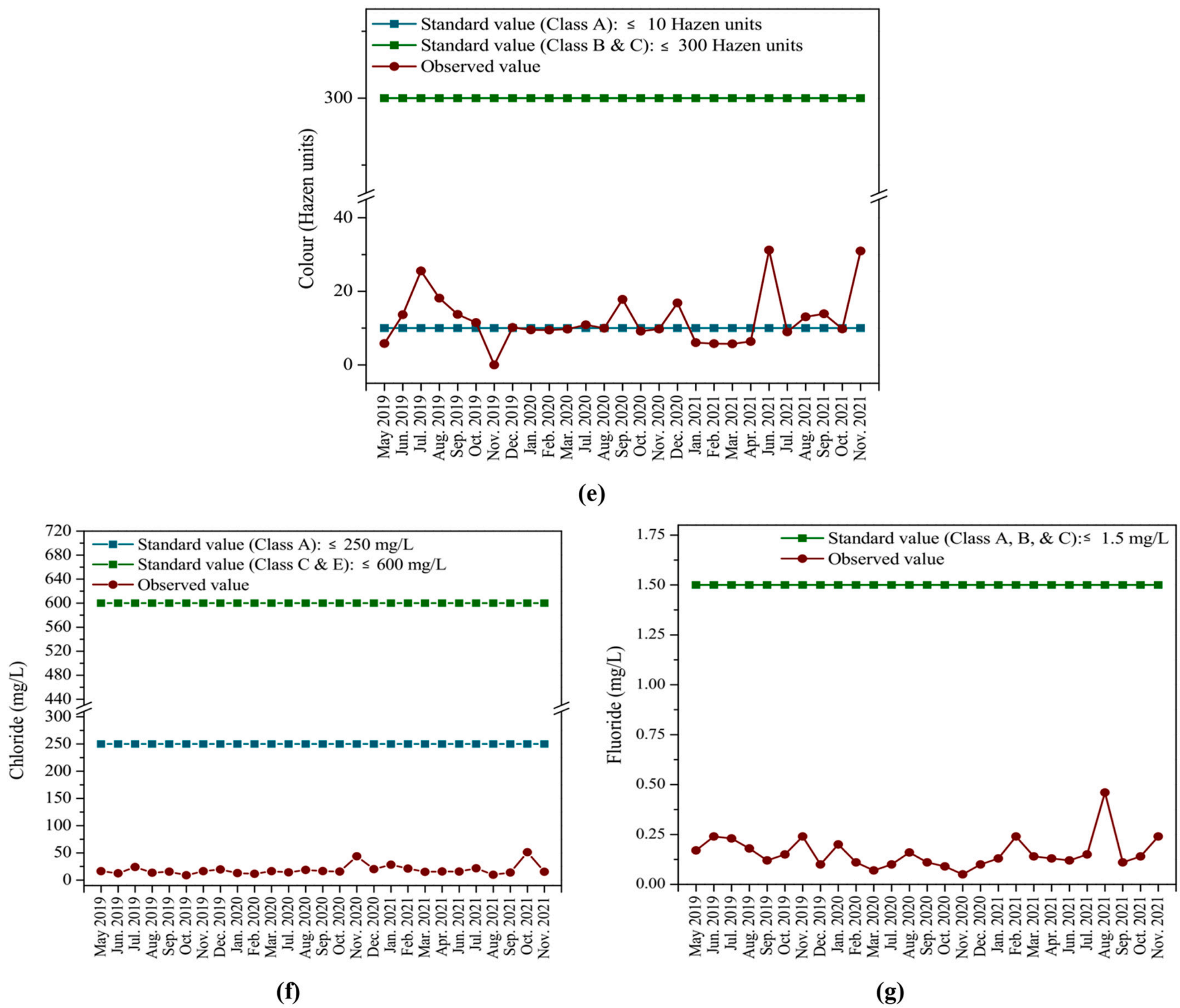


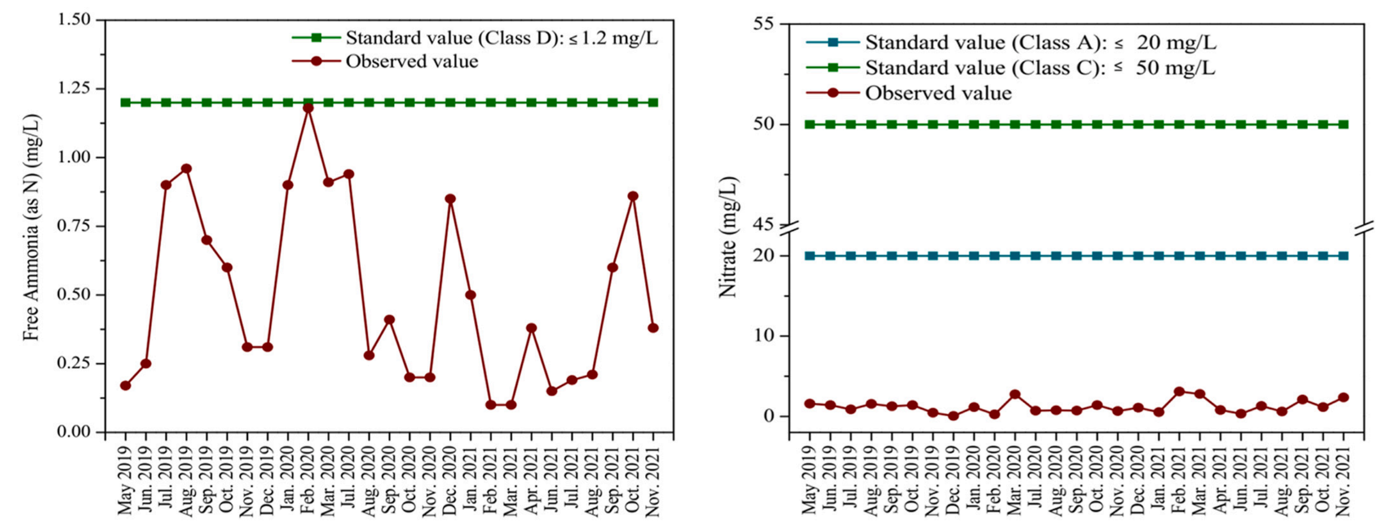
Fig. 5. (*continued*).

quick decisions and adopting appropriate control measures; the installed RTWQM network across River Ganga fulfilled this criterion. Moreover, as this was the preliminary study, accuracy and reliability of the data obtained through RTWQMS was also important to consider. Therefore, water quality data obtained from RTWQMS was compared with the values obtained in CPCB laboratory by performing manual testing procedures and analyzing the samples collected during calibrations. It is important to mention here that comparison in the data could be done only for the period of May 2019 – Jul. 2020, as rest of the time sample collection was avoided owing to restrictions imposed due to COVID-19 pandemic (Table S1).

The values obtained from RTWQMS and CPCB laboratory are shown in Fig. 7. It can be seen that not much variation was observed in the values for pH, EC, DO, and colour (Fig. 7 a – c, e). However, significant differences between the RTWQM values and CPCB laboratory values were seen for the BOD, fluoride, chloride, free ammonia, and nitrate in few of the months (Fig. 7 d, f – i). The reason for this may be attributed to the different testing procedures and stability of the concerned chemical constituent. The laboratory testing for BOD is carried out by incubating the water sample for 3 days followed by titration procedure, while in RTWQMS there is no such incubation. Therefore, differences in the results are expected. Further, in case of fluoride and free ammonia, majority of the values obtained in laboratory were below detectable limit (hence, depicted as 'zero' in graphs), as per the sensitivity of the used system, which might have differed from the sensitivity of the RTWQMS. Moreover, free ammonia (i.e. gaseous NH_3 molecules) might also convert to NH_4^+ at decreased pH and temperature conditions (Huang and Shang 2007) prevailing during sample transportation from the study site to the laboratory; thus resulting in low values. Therefore, differences were observed. The reason for the differences observed between the RTWQMS values and laboratory values in case of chloride and nitrate could not be elucidated, however, sensitivity of the used sensors and plausible errors in manual testing procedures might play a significant role in such cases. Nevertheless, real-time monitoring system offered a good approximation of the various parameters measured in River Ganga, which eventually helped in continuous monitoring of the water body.

4.3. Utility and technical competence of the installed RTWQM system

Results in the present study demonstrated that water quality data for



(h) **(i)**

Fig. 5. (*continued*).

17 parameters could be successfully obtained on continuous basis through the installed RTWQMS in River Ganga, its tributaries, and drains discharging into the river (Table S1). The received data helped in determining the usability of the river water and also supported for taking appropriate actions in order to improve the water quality. These features are considerably advanced than many other IoT based systems employed for water quality monitoring. For example, the 'Hydrobean' system designed for catchment water quality monitoring in United Kingdom was able to monitor only 3 parameters, namely, EC, temperature, and pressure (Benzon et al. 2021). Similarly, the real-time water quality monitoring system deployed in River Krishna (India) was able to monitor 7 parameters, viz. pH, temperature, DO, EC, TDS, BOD, and NO_3^- (Pujar et al. 2020). Another unmanned surface vessel was designed to monitor real-time water quality in remote locations in India (Vasudevan and Baskaran 2021). This system could monitor pH, temperature, DO, TDS, and turbidity. Chowdury et al. designed the IoT based RTWQMS in Bangladesh which was able to sense pH, temperature, turbidity, and oxidation-reduction potential (ORP) (Chowdury et al. 2019). Some other researchers have also reported the measurement of water level (Perumal et al. 2015), flow level (Cloete et al. 2016), and presence of organic compounds (Simic et al. 2016), etc. (Geetha and Gouthami 2016). Thus, simultaneous measurement of parameters like colour, chloride, fluoride, nitrate, ammonia, and others is a novel feature of the reported RTWQMS. Nevertheless, for determining the overall health of the aquatic system; measurement of cations, anions, colour, BTX, TOC etc. is highly desirable and hence these parameters were also included in the installed system.

The system was also capable to be installed either at fixed locations or on the floating platforms, thereby making it possible to gather water quality data even from the remote and/or inaccessible locations. The provision of solar powered battery further enhanced its applicability for the places where continuous supply of electrical power was critical. In the 'Hydrobean' system designed in United Kingdom, the performance of battery was a major limitation for the continuous monitoring as it was needed to be replaced every 24 h (Benzon et al. 2021). Similarly, data gap has been reported in other systems due to the episodes of power cut (Lee et al. 2022). However, such limitations could be minimized through the provision of solar powered battery in the installed system.

Apart from the large number of parameters monitored and ability to perform in the remote locations; the technical competence of the installed RTWQMS was also evident from its data quality. Significant differences could be observed in the water quality data obtained for the river and drain. It can be seen in Fig. 8, that there is sharp contrast between the water quality results obtained from the RTWQMS installed in the drain discharging into the River Ganga (Station code: UP – 46), and river water (station code: UP – 26). As expected, DO levels were low in the drain effluent as compared to the river water (Fig. 8 c). Similarly, BOD levels were high in the drain owing to pollution (Fig. 8 d). Colour, EC, chloride, fluoride, and ammonia were also found to be high in the

Table 2
Designated best uses (DBU) of water (CPCB 2019; IS 2296:1992, 1992).

Water quality class	Designated best use
A	Drinking water source without conventional treatment but after disinfection
B	Outdoor bathing (organized)
C	Drinking water source after conventional treatment and disinfection
D	Propagation of wildlife and fisheries
E	Irrigation, industrial cooling, controlled waste disposal
Below E	Not meeting any of the A, B, C, D, and E criteria

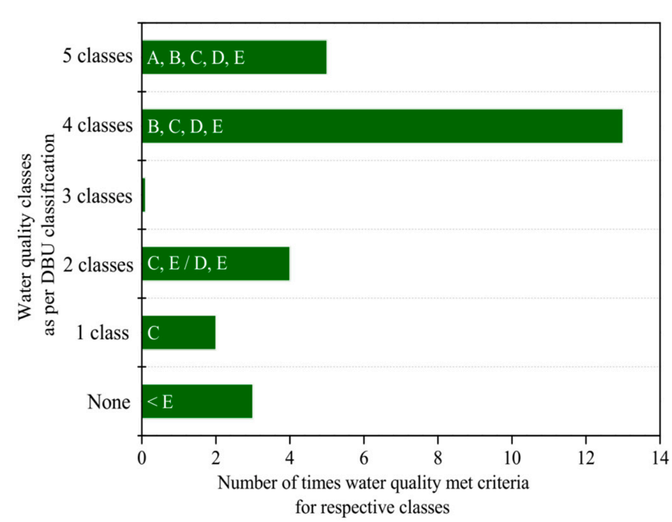


Fig. 6. Designation of water quality class in the study duration, based on DBU classification, for the station code UP-26 in Uttar Pradesh stretch of River Ganga

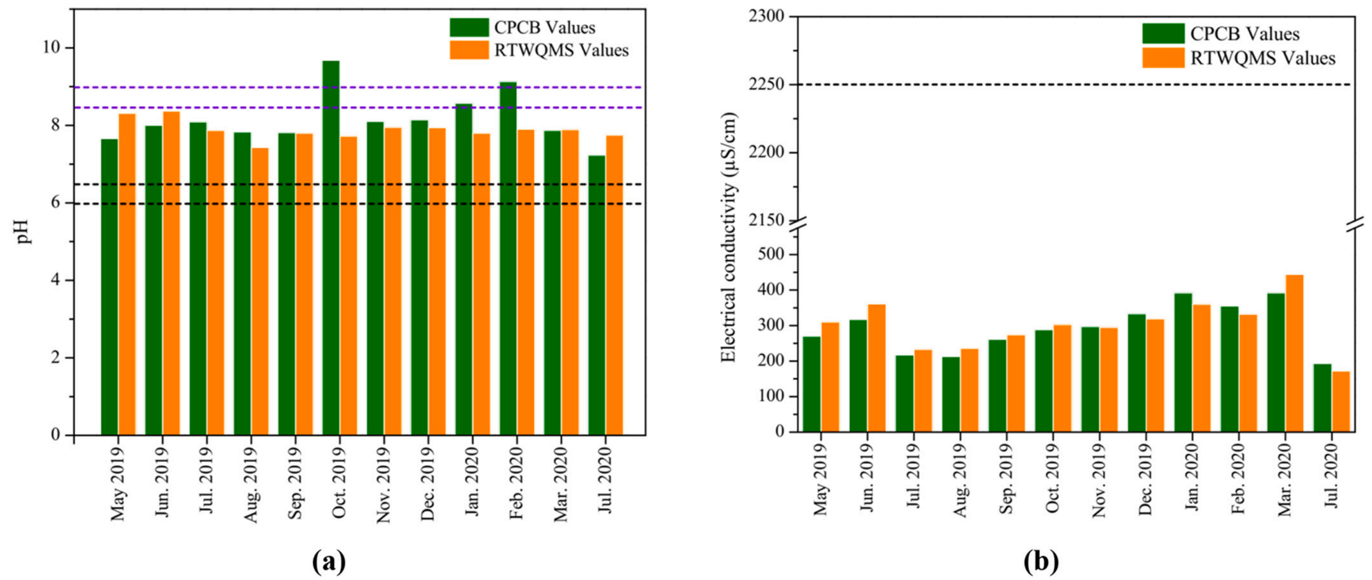


Fig. 7. Comparison of water quality data obtained from RTWQMS and CPCB laboratory for the station code UP-26 in Uttar Pradesh stretch of River Ganga (a) pH; (b) Electrical conductivity; (c) DO; (d) BOD; (e) Colour; (f) Chloride; (g) Fluoride; (h) Free ammonia (as N); (i) Nitrate.
(Dotted line in graphs indicates the standard value for the particular parameter as per IS 2296:1992, 1992)

drain effluent, indicating the pollution (Fig. 8 b, e – h). It infers that RTWQMSs were able to sense the water quality accurately and provided the information accordingly. Obtaining these data in real-time can certainly help in estimating the resultant increase / decrease in various water quality parameters, once the drain's effluent mixes into the river. Thus, it becomes possible to adopt suitable measures well in time to treat the effluent of the drain or divert the drain channel for maintaining the river water quality and aquatic ecosystem. Nevertheless, real-time monitoring enabled the authorities to keep check on the instances which could have resulted in deterioration of the river water quality.

5. Conclusions and way forward

Real-time water quality monitoring system based on internet of things was developed and employed in River Ganga, India for continuous water quality monitoring. It was seen that RTWQMS provided the water quality data in real time, measured through various sensors. The accuracy of the data was also cross-checked with the laboratory values obtained after manual testing procedures. Apart from a few parameters, the RTWQMS values were in good approximation with the laboratory values, which indicated the optimum functionality of the installed system. Thus, such a system may be utilized for continuous monitoring of the quality of many other water bodies as well. However, some limitations were also observed in the existing system, as detailed below:

a. Requirement of frequent calibrations was one of the limitations in the existing system. Need of frequent calibration at the study site forfeits the purpose of RTWQMS. Further, lack of calibration often results in considerable deviation of observed data from the actual data, in some case as high as 70–90%.
b. Drop time was observed in some cases either due to communication failure or solar power disruption.
c. Frequent cleaning of the sensors was must to avoid the disturbances caused due to the tangled aquatic plants / weeds and silt deposition in the sensors.
d. In case of floating stations, data continuity and data quality was compromised few of the times, when floods disturbed the sensors. Moreover, sometimes stations also got damaged during the flood condition and regular calibration activities also got affected. Further, in case of fixed stations, the placement of stations / sensors was needed to be re-located if the river deviated from its regular flow channel. Measurement was also affected if the water level in the river went low beyond a certain limit.
e. Security and maintenance of the RTWQMS set-up in remote areas was another aspect to be looked into, in order to deal with the issues of theft and vandalization.

Therefore, further research and technological development is required to overcome these limitations and enhancing the accuracy and applicability of the system without much inflation in the cost. Robustness of the system needs to be improved with lesser requirement of calibrations and reduction in drop time episodes. Moreover, system should be made automated in such a way that sensors and other mechanical parts could be cleaned without any human assistance. Another important feature that could be introduced in the present RTWQMS is the development and inclusion of sensors or any other mechanism for counting the total coliform organisms. Information system may also be developed to create alert, in case any parameter exceeds its permissible limit. To ensure safety, instrument may be housed in a compartment having scanner, alarm system, and/or any such protective devices. Such interventions will certainly help to minimize the complexity, thereby enhancing the applicability of the RTWQM systems for various water bodies.

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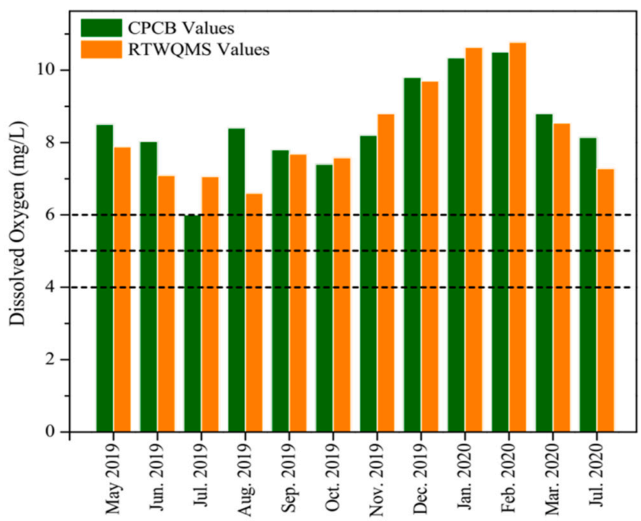
Declaration of Competing Interest

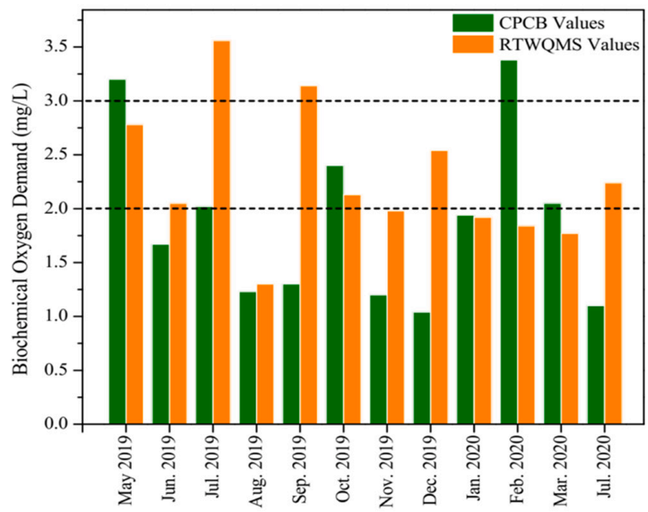
Authors declare that there are no conflicts of interests.

Data availability

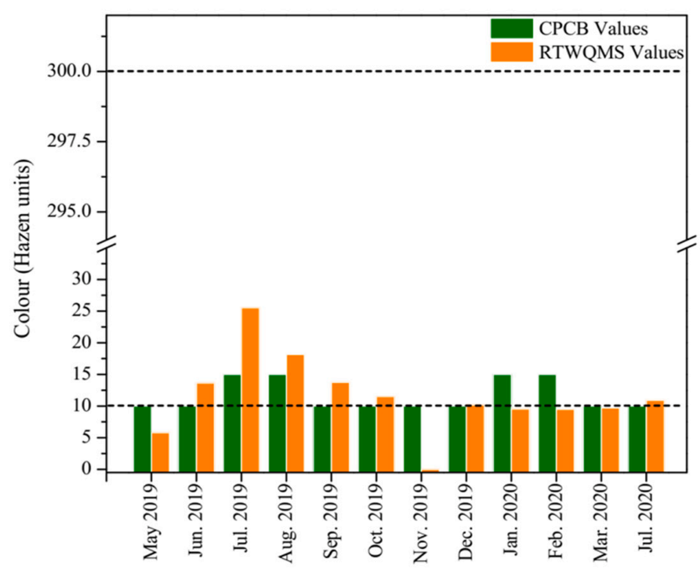
Data will be made available on request.



(c)



(d)



(e)

Fig. 7. (*continued*).

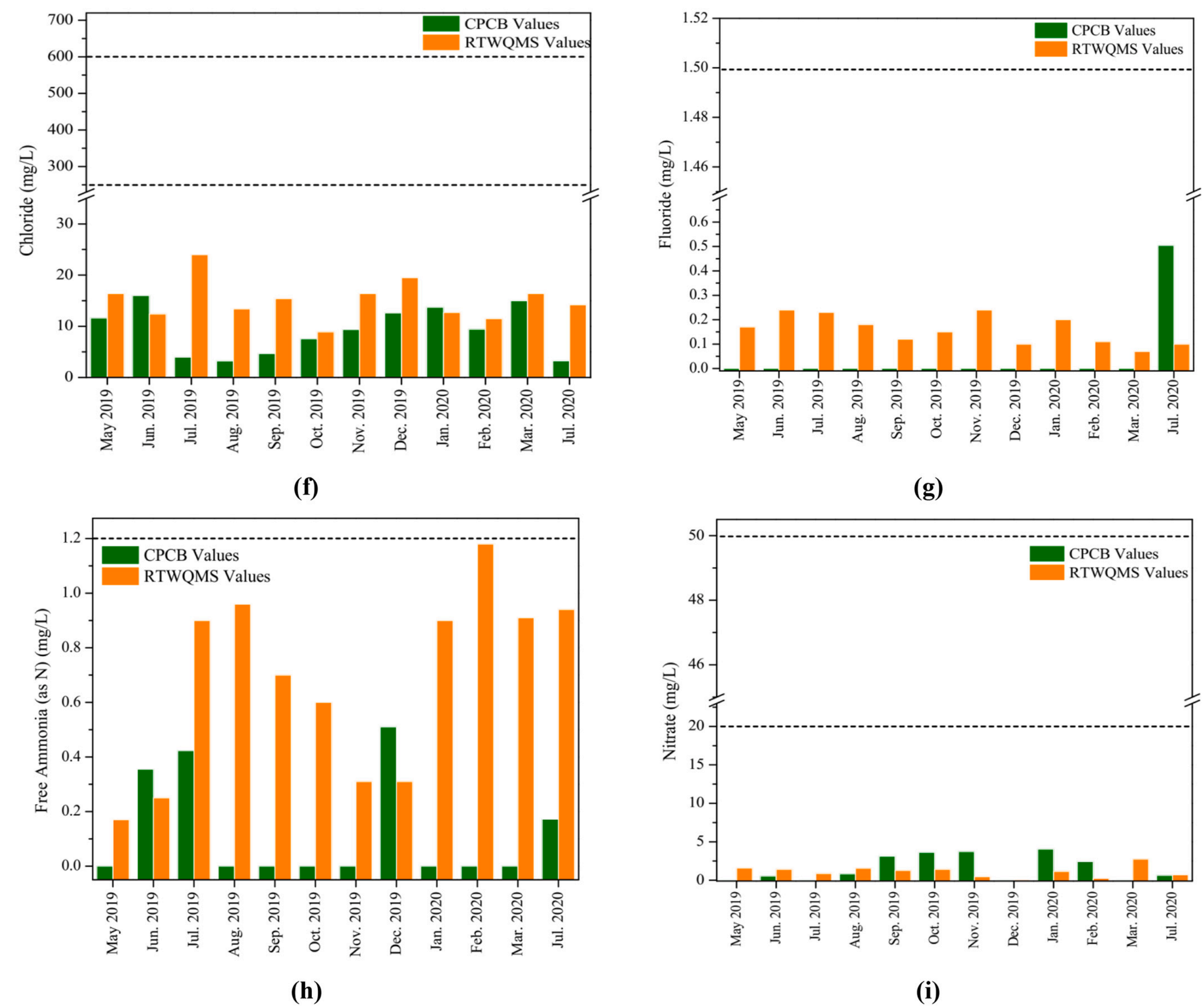


Fig. 7. (*continued*).

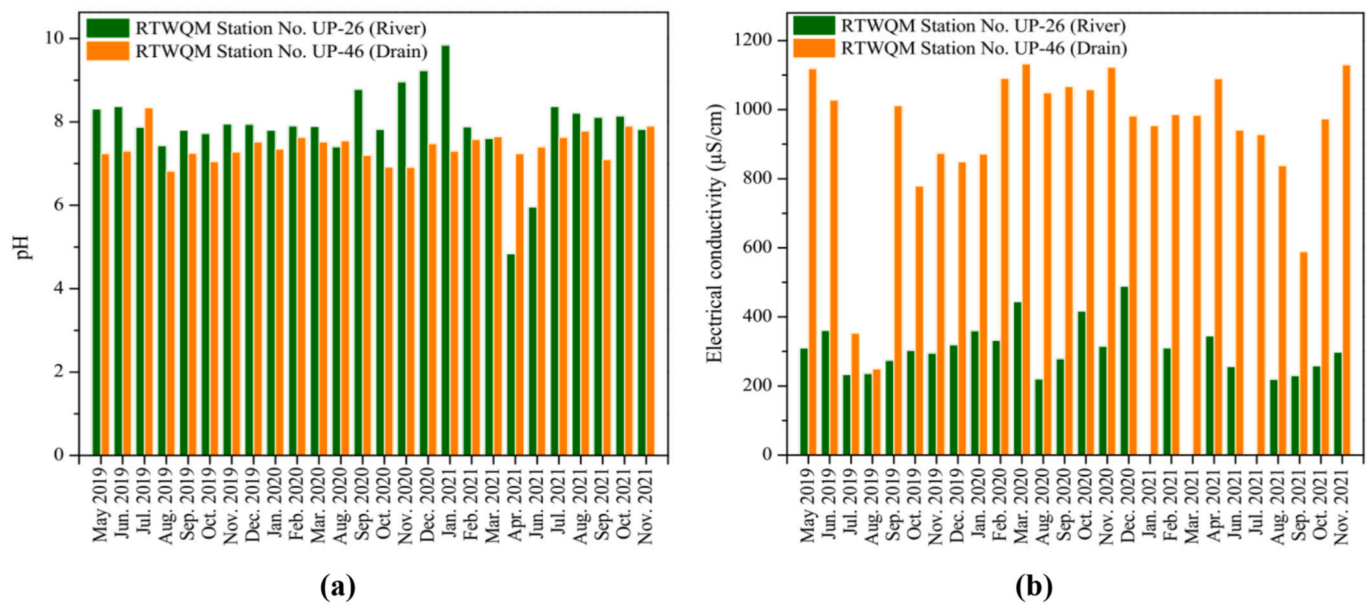


Fig. 8. Comparison of the water quality data of river (UP – 26) and drain (UP – 46), obtained through RTWQMS in Uttar Pradesh stretch of River Ganga (a) pH; (b) Electrical conductivity; (c) DO; (d) BOD; (e) Colour; (f) Chloride; (g) Fluoride; (h) Free ammonia (as N); (i) Nitrate

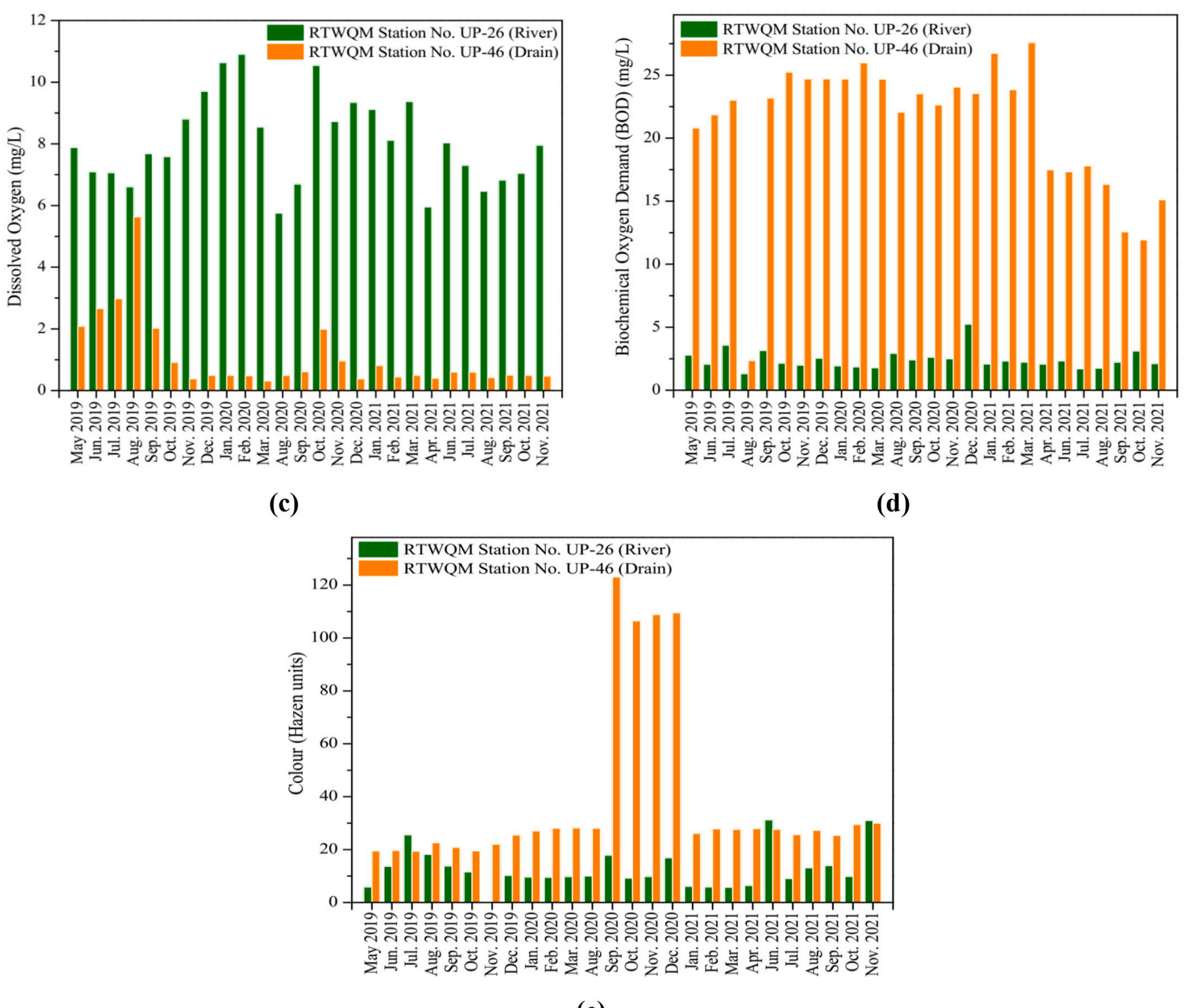


Fig. 8. (*continued*).

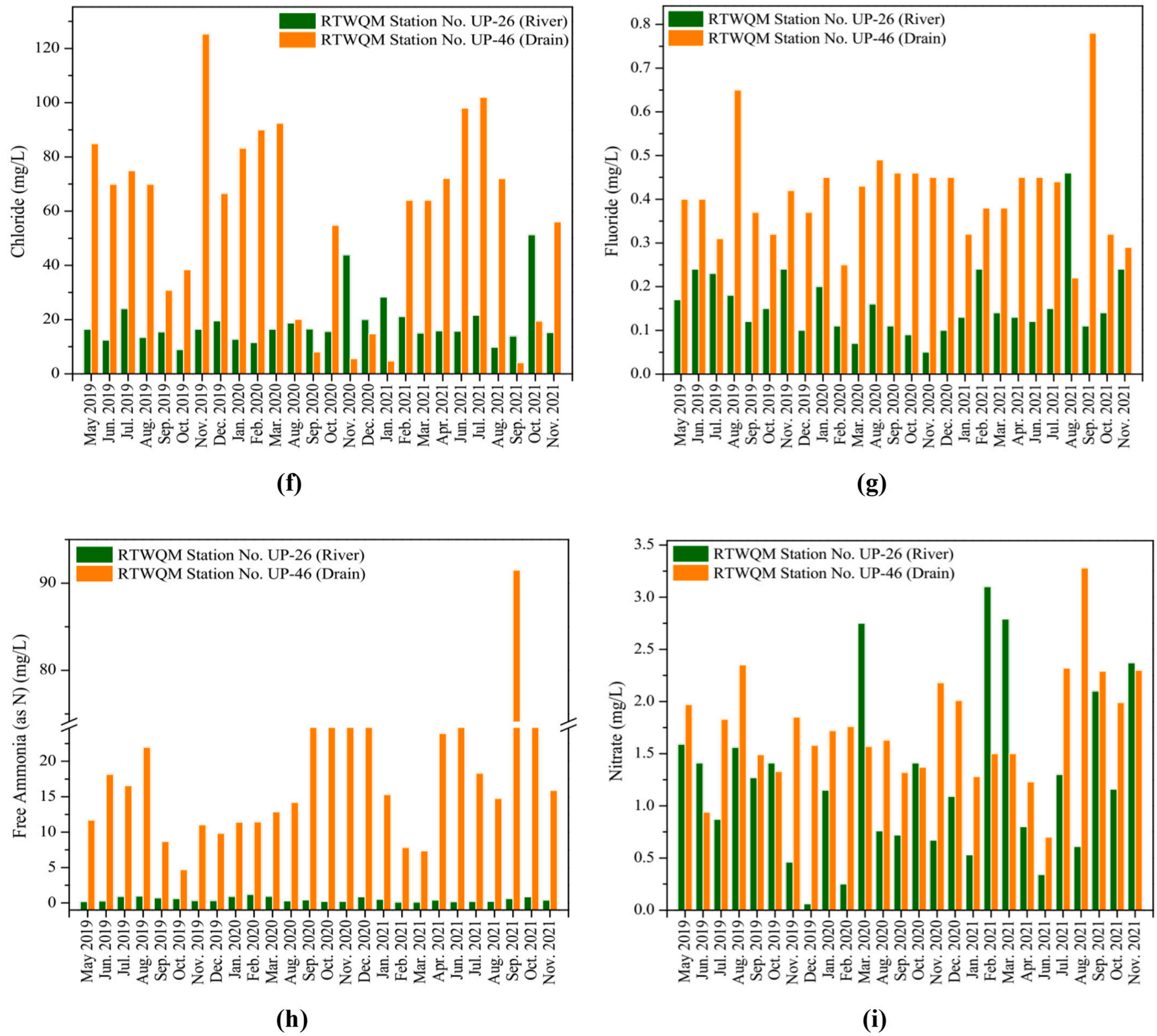


Fig. 8. (*continued*).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2022.101770.

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