Dear Reviewer 2,

Thank you for your valuable comments on this work which helps us to improve our revised manuscript quality.

Reply to Comments

Referee Comment: General comments: - The topic of the paper is quite relevant. - Language should be looked at, specifically the use of articles. - The number of samples used for validation is very limited. Also, the range of parameter values within the set of samples is both small and limited to values in the desired range. The purpose of the system is, it seems to me, to detect water quality deviations, so at least you should show that the system is capable of doing so.

Author Response: The samples are collected in real-time from the distribution network for water supply in the campus. So, there is not much variation in the sample values. But, for the validation of system we have simulate the sensor readings and used in our fuzzy model and the same has been updated in the results and discussion section. Also, the PRE plot has been updated. Page 7. Line 7-10.

Referee Comment: comment references: page. line 1.16 very essential -> essential

Author Response: Corrected. Page 1. Line 22

Referee Comment: 1.19 there must be more recent number than those from 1996

Author Response: Corrected and updated in manuscript. Page 1. Line 24

Referee Comment: 1.22 suggestion to rephrase second half of this sentence: ...and the situation may become worse in the future.

Author Response: corrected and updated. Page 1. Line 28

Referee Comment: 1.24 is IWT a measuring tool or a visualization platform?

Author Response: IWT is a visualization platform which gets data from Govt agencies and update the same in the tool at regular interval. Page 1. Line 29-30

Referee Comment: 2.29 The point of this sentence should be the ability to include vagueness or ambiguity rather than its similarity to the way humans may think.

Author Response: updated in manuscript. Page 3. Line 11.

Referee Comment: 2.30 Less mathematically intensive than what?

Author Response: the fuzzy logic comes under the category of intelligence techniques like neural network and genetic algorithms. In such case, fuzzy is less mathematically intensive as the other techniques require rigorous mathematical computation. The same has been updated in the manuscript. Page 3. Line 13.

Referee Comment: 3.3 In my opinion, there is no added value presenting this information in a figure in the way it has been done.

Author Response: the figure has been removed and information has been updated in the section 2.2.

Referee Comment: Just include it in the text. 3.4 scikit-fuzzy development team

Author Response: corrected. Page 3. Line 19.

Referee Comment: 3.7 produces **Author Response:** corrected. Page 3. Line 22.

Referee Comment: 3.8 exerts? **Author Response:** corrected. Page 3. Line 23.

Referee Comment: 3.10 please rephrase **Author Response:** corrected. Page 3 line 25-26.

Referee Comment: 3.13 functions are most commonly used; their linear nature **Author Response:** corrected. Page 3. Line 28-29.

Referee Comment: 3.14 easy implementation ability -> ease of implementation **Author Response:** corrected. Page 3. Line 29.

Referee Comment: 3.23 effect -> affect? **Author Response:** corrected. Page 4. Line 8.

Referee Comment: 3.24 What is meant by fired? Ignored, removed? **Author Response:** the rule which does not affect the output was ignored. Page 4. Line 8.

Referee Comment: 4.6 systam -> system **Author Response:** corrected. Page 4. Line 17.

Referee Comment: 4.8 than -> then **Author Response:** corrected. Page 4. Line 19.

Referee Comment: 4.8-9: unclear sentence, please rephrase **Author Response:** corrected. Page 4. Line 20.

Referee Comment: 4.24 integrated with -> coupled to **Author Response:** corrected. Page 5. Line 12.

Referee Comment: 5.24: "illation" : I had to look that word up. **Author Response:** corrected. Page 6. Line 7.

Referee Comment: 6.9: fuzzy -> the fuzzy inference system? Is that what you mean? **Author Response:** yes, it is fuzzy inference system. Corrected. Page 6. Line 8.

Referee Comment: 6.15: No work on that done yet, so I would not use the word "compatible". You might mention that making it into an IoT application will be relatively straightforward because the RPi has a wifi chip. **Author Response:** corrected. Page 7. Line 19.

6.16: looks? **Author Response:** corrected. Page 7. Line 22.

6.16: I can see the practical importance, but the academic is not clear to me. **Author Response:** for academic purpose, the developed prototype can be use for the demonstration in university/college or exhibition fair. In this aspect, it can have the academic purpose as well.

Referee Comment: Table 1 - C3: fix enumeration - Why is the requirement for untreated water 'A' stricter than for treated water 'C' in terms of total coliforms?

Author Response: These are the standards defined by WHO as well as CPCB, New Delhi. In case of total coliforms, CPCB has given maximum permissible limit of drinking water **subject to pollution**. That is why the total coliform limit is higher in type 'C' than type 'A' in drinking water. (Page 9 in reference document) (Visionary et al., 2015).

Referee Comment: Figure 6: Is there 2-way communication between the hardware platform and the sensors? The figure suggests there is.

Author Response: Yes, there is 2-way communication as the sensors are interfaced through I2C communication protocol. Every sensor has its unique address and gives response to the Raspberry Pi.

Referee Comment: Figure 9: Please indicate units and x-axis parameter. **Author Response:** Corrected.

References

Visionary, E., Goals, S., North, A. D., Services, S. M., Procurement, P., Friendly, E., Ecblab, U. and Star, E.: Environmental Standards, , 1–2 [online] Available from: https://scclmines.com/env/ENVIRONMENTAL STANDARDS.pdf (Accessed 29 March 2019), 2015.

Raspberry Pi based Smart Sensing Platform for Drinking Water Quality Monitoring System: A Python Framework Approach

Punit Khatri[1], Karunesh Kumar Gupta[1], Raj Kumar Gupta[2]

[1]Department of Electrical and Electronics Engineering, Birla Institute of Technology & Science (BITS), Pilani-333031, India
[2]Department of Physics, Birla Institute of Technology & Science (BITS), Pilani-333031, India

Correspondence to: Punit Khatri (punit.khtr@gmail.com)

Abstract. ~~Drinking or potable water quality monitoring is essential for mankind as it affects the human health directly or indirectly. This work reports a smart sensing platform for potable water quality monitoring. Five water quality parameters (pH, Dissolved Oxygen, Oxidation Reduction Potential, Electrical Conductivity, and Temperature) have been selected to monitor the water quality.~~ This paper proposes the development of Raspberry Pi based hardware platform for water quality monitoring. The selection of water quality parameters was~~is~~ made based on guidelines of the Central Pollution and Control Board, New Delhi, India. A Graphical User Interface (GUI) was~~is~~ developed for providing~~to provide~~ an interactive Human Machine Interface to~~for~~ the end user for ease of operation. Python programming language was~~is~~ used for GUI development, data acquisition and for data analysis. Fuzzy computing technique was~~is~~ employed for decision making to categorize the water quality in different classes like bad, poor, satisfactory, good and excellent. The system has been tested for various water samples from five different locations~~resources~~ and results have been displayed. For authentication, the results were compared with benchmark instrument EXO-1.

1 Introduction

~~Drinking water quality monitoring is very essential before consumption in daily life as it affects directly or indirectly human health (Bhardwaj et al., 2018). The water crisis has become a global problem in recent years, it is not limited to a particular region or country. By the end of 2025, half of the world population will be living in water-stressed areas (World Health Organization (WHO), 1996).~~ Water quality monitoring is essential before consumption in daily life as it may effect human health directly or indirectly (Bhardwaj et al., 2018). According to world health organization, half of the world's population will be living in water-stressed areas till the end of 2025 (World Health Organization, n.d.). In developing countries, as much as 80% of illnesses are linked to poor quality water and sanitation conditions (Anan, 2003). ~~India is one of the most water-challenged countries, among developing countries in the world. Groundwater levels are decreasing day by day as farmers, city residents and industries are regularly draining wells and aquifers.~~ The available water is severely polluted, and the situation may become ~~it may create the~~ worst ~~situation~~ in the future. Drinking water with pollutant concentration exceeding BIS (Bureau of Indian Standard) limits, is considered unsafe. The ~~groundwater~~water quality was measured by different govt. agencies among 632 districts in India which can be ~~by~~ accessed on IWT (India Water Tool) visualization~~2.1~~ tool (World Resources

Institute, 2016)~~ among 632 districts in India~~. Among 632 districts, 59 are above BIS limits. The yellow and red areas in figure 1 indicate places where chloride~~chlorine~~, fluoride, iron, arsenic, nitrate and/or electrical conductivity exceed national standards. This is one of the most critical reasons why drinking water quality monitoring is essential.

Traditionally, water quality measurement involves sample collection on sites and subsequent laboratory chemical based analysis, which is both the labor and cost intensive (Korostynska et al., 2013). Also, the measurement is not in real-time. Hence, to reduce the labor cost and time consumption,~~Therefore it is the~~ there is a need of the hour to have real-time monitoring of water quality for drinking applications (Bhardwaj et al., 2015). The work presented in this paper aims to provide an efficient real-time monitoring of ~~ground~~ water quality in drinking applications and can address the issues related to drinking water quality for various species.

The proposed work consists of Multi-Sensor Array (MSA), hardware platform along with a software platform (i.e. python framework). In the first stage, MSA ~~is~~was designed that consists an array of commercially available individual sensors for water quality parameters~~pH, Dissolved Oxygen (DO), Oxygen Reduction Potential (ORP), Electrical Conductivity (EC) and temperature. The Total Dissolved Solids (TDS) is derived from Electrical Conductivity (EC)~~. The selection of the parameters is based on the guidelines of the Central Pollution and Control Board (CPCB), New Delhi, India (Central Polution Control Board, 2007). In the second stage, the hardware platform was designed based on the Raspberry Pi board. An additional serial port expander was~~is~~ used since Raspberry has only one I2C channel and it ~~is~~was required to communicate with all the sensors simultaneously. In the third stage, a Graphical User Interface (GUI) was designed for Human Machine Interface (HMI) and fuzzy modeling in python. ~~software platform is designed which consists of Graphical User Interface (GUI) for interactive Human Machine Interface (HMI) and fuzzy modeling. A python framework is utilized in software and GUI development.~~ The water standard was~~is~~ defined based on calculated water quality parameters using Fuzzy Inference System (FIS) since FIS has the capability to imbibe vagueness related to observed parameters. The fuzzy approach reported in this work has been used and discussed widely in many environmental applications and helps in decision making in many real-life complex problems (Lermontov et al., 2009).

Many researchers such as~~(S.~~ Ponsadailakshmi (Ponsadailakshmi et al., 2018), ~~A.~~ Tiri (Tiri et al., 2018), ~~B. V~~ Raman (Raman et al., 2009), ~~A. M.~~ Jinturkar (Jinturkar et al., 2010), and ~~Y.~~ Icaga (Icaga, 2007)~~, etc.)~~ have implemented the fuzzy modeling in MATLAB for water quality index calculation. That process of modeling is offline for e.g. researchers have collected the data and later done the modeling in MATLAB. Whereas in this paper, we ~~are trying to~~had implement the fuzzy in real-time calculation spontaneously after the data collection with the help of libraries in the Python framework.

2 Materials and methods

2.1 Water Quality Parameter Selection Criteria

Water quality parameter selection is a critical step as this will determine the overall water quality. The Central Pollution and Control Board (CPCB) have suggested the criteria of water quality parameters for different usage of the water which is shown in table 1. CPCB have decided five different categories for the use of water in different applications such as irrigation, drinking, bathing, etc. In this work, category 'C' parameters have been considered since we are targeting drinking water source after conventional treatment and disinfection. If the water quality is monitored before the treatment and disinfection, most of the parameters will be out of permissible range. In case if the parameter is on the lower or upper edge of the permissible range, this will have the same effect as the poor quality of the parameters. This is the reason behind the selection of category 'C'. Also, Eexperimental work done by US Environmental Protection Agency (USEPA) has proven that water quality parameters such as pH, EC, and DO high or low level of DO and ORP are indirectthe indicators of contaminants such as nicotine, arsenic trioxide and Escherichia coli (Hall et al., 2007) (Power and Nagy, 1999). That's why for the detection of contamination, the samese water quality parameters havecan been considered as promising criterion.

2.2 Defining Water Quality

The fuzzy inference system (FIS) has the ability to include vagueness in decision making and reasoning mimics the way human thinks in his day to day life. Hence fuzzy logic based techniques proved to be very effective since it is less mathematically intensive as compared to neural networks and genetic algorithms etc. and supports approximate reasoning. In FIS, the knowledge is presented as linguistic rules. The inputs are converted from crisp value to linguistic variable by the process called fuzzification and these variables are fed to inference system. This inference system gives a new set of a linguistic variable which is then converted to crisp value with the help of defuzzification (MathWorks, n.d.). The basic process to design a fuzzy logic involves three (3) basic steps: 1) define membership function for each variable, 2) perform fuzzy inference based on the inference method, and 3) select defuzzification method to define water quality. shown in figure 2.

The proposed fuzzy logic was implemented in python with the help of library developed by known as scikit-fuzzy development teamlibrary (Anon, n.d.) to define the water quality from the groups of five linguistic variables defined as bad, poor, satisfactory, good and excellent. The fuzzy system uses Mamdani implication model, which takes five inputs pH, Electrical Conductivity (EC), Oxidation Reduction Potential (ORP), Dissolved Oxygen (DO) and temperature. The Mamdani Fuzzy Inference System producesproduce a more accurate response as compared to Takagi-Sugeno type model since it usesexerts the centroid method of defuzzification. The defuzzified output of the model is water quality which corresponds to five inputs of the model. In this paper, Mamdani-type FIS model wasis implemented forin a decision support system since it haspossesses spontaneous and interpretable nature of the rule base capability. To decide the water quality, five inputs and one output wereare selected, and modeling wasis performed based on these parameters. The selection of the membership function is done based on the complexity of the system considered for decision making. Triangular membership functions (MF) areis most commonly used membership functions because of theirits linear nature and ease of implementationeasy implementation ability (Zhao and Bose, 2002) (Kosko, 1993), hence we have selected triangular MF to fuzzify the crisp variable into linguistic one. The triangular membership function as shown in figure 23 depends on three parameters l, m and n and are given by equation 1.

$$f(x;l,m,n) = \begin{cases} 0 & \text{for } x < l \\ \dfrac{x-l}{m-l} & \text{for } l \le x \le m \\ \dfrac{n-x}{n-m} & \text{for } m \le x \le n \\ 0 & \text{for } x > n \end{cases} \quad (1)$$

The logic operations used in the fuzzy logic are *min, max* and *compliment* and these are defined by the equation (2), (3) and (4) respectively. Let A and B are two subsets.

$$\mu_{A \cup B}(x) = \max\left[\mu_A(x), \mu_B(x)\right] \quad (2)$$

$$\mu_{A \cap B}(x) = \min\left[\mu_A(x), \mu_B(x)\right] \quad (3)$$

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \quad (4)$$

After the logic operations, 'if-then' rule wasis applied. All the rules were are applied in parallel and the rule which does not aeffect the output wasis ignoredfired. The outputs of all rules wereare then aggregated and all fuzzy sets that affect the output, wereare combined into a single fuzzy set. Finally, the fuzzy set wasis converted into a crisp set by means of defuzzification in which a single number wasis generated. There are several methods for defuzzification such as centroid, maximum, mean of maxima, height and modified height. In this work, the centroid defuzzification method wasis used which is the most popular method. The output wasis calculated by averaging individual centroids, weighted by their heights as given by equation 5 (Zadeh, 1988).

$$U_o = \frac{\sum_{i=1}^{n} u_i \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)}$$

(5)

Where $\mu(u_i)$ is the min/max value of the membership degree of the input values (depends on min/max operator). The overall fuzzy inference systemsystam used in this work is shown in figure 34.

As per the acceptable range of water quality parameters, we have assigned two groups to each parameter which are desirable (DES) and undesirable (UNDES) as described in table 2. If the parameters are in the desirable range, thenthan only fuzzy has been applied otherwise thate sample has been rejected. After checking the desirable acceptable range, we have assigned individual membership functions to each parameter as shown in figure 45. Also, we have defined the membership function for water quality on the scale of 0 to 100. After assigning the membership functions, "if-then" rule wasis applied and overall quality wasis defined on the basis ofbased on adopted rule base formulation.

3 Hardware Platform Design

The hardware platform plays a vital role in any system development since data acquisition and data processing is done with the help of the hardware platform itself. The main task of the hardware platform design is MSA design and its interfacing with the raspberry pi board followed by python framework. The details of the design are given below.

3.1 Multi-Sensor Array (MSA) Design

For the proposed work, Multi-Sensor Array (MSA) is designed using the industrially manufactured sensors from Atlas Scientific, USA. The individual sensors are arranged in an array form to make the MSA. The sensors used are pH sensor, Electrical Conductivity (EC) sensor, Dissolved Oxygen (DO) sensor, Oxidation Reduction Potential (ORP) sensor and a temperature sensor. Total Dissolved Solids (TDS) parameter was derived from EC. The block diagram of MSA and its interfacing with hardware followed by software framework is shown in figure 56.

3.2 Integration of MSA with Raspberry Pi board and interfacing with Python

Once the MSA is designed, it must be coupled to integrated with the Raspberry Pi for data acquisition and further data processing. Raspberry Pi is a single board credit card size micro-computer with ARM cortex A-53 processor (Raspberry Pi Foundation, 2014). It is an open hardware with many on-board running components like CPU, graphics, memory, USB controller etc. Nowadays, Raspberry Pi board is being used in many real-time applications (for e.g. real-time video surveillance system (MathWorks, n.d.), real-time paper currency recognition of new Indian notes after demonetization (Anilkumar and Srikanth, 2018), automatic traffic control system (Talukder et al., 2017), smart traffic system (Kumar et al., 2017), energy management system based on real-time electricity pricing model (Qureshi et al., 2017), self-driving system (Sumardi et al., 2018), 3D wavelet transform (Bernabé et al., 2018), and air quality monitoring system (Alkandari and Moein, 2018)).
Bhardwaj implemented the Cyber-Physical System (CPS) based water quality monitoring (Bhardwaj et al., 2018) using Arduino Uno board which has got some limitation with computational capabilities. Although Arduino is user-friendly, the reason for selecting the Raspberry Pi for this work is its computational capabilities that cannot be done in the Arduino platform. Apart from the computational capabilities, Raspberry Pi is bundled with inbuilt Bluetooth module, Wi-Fi module, HDMI interface, camera interface, display slot, SD card slot, USB slot, etc. which has tomust be interfaced externally in case of Arduino depending upon application.
For stand-alone applications, we can use a display panel and interface it with the python framework. We have used a 7″ touch screen and interfaced it with the python programming. Python is an open source programming platform and supports the data processing and computing. The only drawback that we are facing with raspberry Pi board is a limited number of I2C channel, so we have interfaced external serial port expender with the board to enhance the number of I2C channels. The experimental setup of MSA integrated with Raspberry Pi board is shown in figure 67. It includes MSA connected to serial port expender and Raspberry board followed by python programming.

4 Results and Discussion

4.1 Experimental Procedure

The proposed system has been tested for water samples from five different locations. In order to get accurate readings, each sensor node has been calibrated before going for measurement. The calibration was performed with the reference solution given for each sensor. Initially, the measurement iteration was carried out for at least five minutes so that sensor reading gets stabilized because the original readings must be recorded only after the sensor attains stability in order to make any conclusive decision ~~illation~~ out of data. The system was tested for the total duration of 21 hours over seven days. The results obtained from MSA were accumulated through fuzzy inference system implemented in python framework. The average values of the experiment for all locations are shown in table 3.~~The data readings obtained from MSA were fed to the fuzzy decision support system implemented in python with the help of available libraries. The complete procedure of data acquiring, and fuzzy decision support system was implemented in python for real-time measurement.~~

4.2 Interactive User Interface

The graphical representation was ~~is being~~ provided for real-time data obtained from various sensors with the help of GUI platform for the interactive ~~user interface~~HMI. An interactive ~~Graphical User Interface (~~GUI~~)~~ has been designed in python framework with touch interface as ~~where the user can select the individual parameter to be measured as well as check overall water quality. A screenshot of GUI is~~ shown in figure 7~~8~~. The touch interface is provided for the ease of operation for operator. In the GUI, the operator can select the measurement from menu whether it is individual parameter or water quality with a single touch. The acquired data was kept for future use by means of saving in memory drive provided with Raspberry board. The live plotting of data is shown in figure 8~~9~~. The X-axis represents time and Y-axis represents the sensor node reading.

4.3 Validation and Performance Comparison

The validation of results acquired from the proposed system was done by comparing the results obtained from available benchmark equipment YSI EXO-1 sonde monitoring system and calculating the percentage relative error (PRE) (Lee, 2016). PRE expresses the error in percentage to determine the accuracy and is given by

$$\mathbf{PRE} = 100 * \left(\frac{\mathbf{actual - observed}}{\mathbf{actual}} \right) \tag{6}$$

~~The system was tested for the total duration of 21 hours over seven days. The results obtained from MSA were accumulated through fuzzy implemented in python framework. The average values of the experiment are shown in table 3.~~ The calculated PRE plot is shown in figure 9~~10~~. Based on the results of the parameters obtained from MSA, water quality has been defined for all the locations using fuzzy libraries as shown in table 4. The input and output membership functions shown in figure 4 were implemented in MATLAB. The same has been used for the validation of the fuzzy model implemented in python.

The acquired results are from the distribution networks in real-time and hence, there is not much variation in sensor reading within the desirable range. To validate the system for water quality parameter deviation, parameters acquired from the benchmark equipment for different water sample has been used as input to the fuzzy model. The output of the fuzzy model has been observed and same has been shown in table 3 and 4.

5 Conclusion

Water quality monitoring is essential before consumption and its real-time monitoring will reduce the risk of illness in the human being. Traditional methods for water quality monitoring are being replaced by online water quality monitoring. The developed system has the facility for online water quality monitoring as compared to traditional methods. This reduces the labor-cost as well as time-consumption. The developed GUI has touch functionality which can help operators to operate the developed system easily and in decision making based on the results displayed on the screen. The system can be deployed in remote locations as it can run on a 12 V battery. In terms of the cost, the developed system is low cost as the benchmark which we are using costs approximate 11,000 USD and the proposed setup costs less than 1000 USD.

The developed system can be used for the fault detection of the sensors as well. We can scan the sensors if they are giving the right measurement value or not. The pH and ORP sensors need to dip into the reference solution, so these two sensors will give a fixed measurement value for the solution. The Do and EC sensors do not need any reference solution. They will have a certain amount of measurement value and can be observed. We can also scan the temperature sensor for the measurement. Based on the scanning of the sensors we can conclude that if the sensors are giving genuine sensor value or fake sensor value or not giving any value.

Internet of Things (IoT) can be implemented in the system as the Raspberry Pi has built-in Wi-Fi module which is missing in this work and~~This paper reported a smart sensing platform for real-time water quality monitoring and to collect a large database. The designed platform is compatible with IoT networks as the Raspberry Pi used here has a built-in Wi-Fi module and~~ will be implemented in future~~future looks~~. The work presented here has both academic as well as~~and~~ practical importance. Currently, the calibration of the sensor is time-consuming and requires a certain time period to get stabilized. In future looks, the focus will be on auto-calibration of the sensors ~~and also~~and the drift analysis and compensation by means of algorithms.

Formatted: Font: Not Bold, Complex Script Font: Not Bold

Formatted: Font: Not Bold, Complex Script Font: Not Bold

Formatted: Font: Not Bold, Complex Script Font: Not Bold

Acknowledgments

The authors are pleased to acknowledge the Department of Science and Technology, Govt. of India, New Delhi for their financial support (DST/TM/WTI/2K16/103) and Birla Institute of Technology and Science for providing an enabling environment to carry out the research work.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

Alkandari, A. A. and Moein, S.: Implementation of Monitoring System for Air Quality using Raspberry PI : Experimental Study, Indonesian Journal of Electrical Engineering and Computer Science, 10(1), 43–49, doi:10.11591/ijeecs.v10.i1.pp43-49, 2018.

Anan, K.: ‘Water-Related Diseases Responsible For 80 Per Cent of All Illnesses, Deaths In Developing World’, Says Secretary-General In Environment Day Message, UN, 1 [online] Available from: http://www.un.org/press/en/2003/sgsm8707.doc.htm (Accessed 6 February 2018), 2003.

Anilkumar, B. and Srikanth, K. R. J.: Design and development of real time paper currency recognition system of demonetization New Indian Notes by using raspberry Pi for visually challenged, International Journal of Mechanical Engineering and Technology, 9(3), 884–891, 2018.

Anon: SciKit-Fuzzy — skfuzzy v0.2 docs, [online] Available from: http://pythonhosted.org/scikit-fuzzy/overview.html (Accessed 20 March 2018), n.d.

Bernabé, G., Hernández, R. and Acacio, M. E.: Parallel implementations of the 3D fast wavelet transform on a Raspberry Pi 2 cluster, The Journal of Supercomputing, 74(4), 1765–1778, doi:10.1007/s11227-016-1933-2, 2018.

Bhardwaj, J., Gupta, K. K. and Gupta, R.: A review of emerging trends on water quality measurement sensors, in 2015 International Conference on Technologies for Sustainable Development (ICTSD), pp. 1–6, IEEE., 2015.

Bhardwaj, J., Gupta, K. K. and Gupta, R.: Towards a cyber-physical era: Soft computing framework based multi-sensor array for water quality monitoring, Drinking Water Engineering and Science, 11(1), 9–17, doi:10.5194/dwes-11-9-2018, 2018.

Central Polution Control Board: Central Polution Control Board; Environmental Standards; Water Quality Criteria, [online] Available from: http://cpcb.nic.in/Water_Quality_Criteria.php (Accessed 25 November 2017), 2007.

Hall, J., Zaffiro, A. D., Marx, R. B., Kefauver, P. C., Radha Krishnan, E., Haught, R. C. and Herrmann, J. G.: On-line water quality parameters as indicators of distribution system contamination, American Water Works Association, 99(1), 66–77, doi:10.1002/j.1551-8833.2007.tb07847.x, 2007.

Icaga, Y.: Fuzzy evaluation of water quality classification, Ecological Indicators, 7(3), 710–718, doi:10.1016/j.ecolind.2006.08.002, 2007.

Jinturkar, A. M., Deshmukh, S. S., Agarkar, S. V. and Chavhan, G. R.: Determination of water quality index by fuzzy logic approach: a case of ground water in an Indian town, Water Science and Technology, 61(8), 1987–1994, doi:10.2166/wst.2010.095, 2010.

Korostynska, O., Mason, A. and Al-Shamma’a, A. I.: Monitoring pollutants in wastewater: Traditional lab based versus modern real-time approaches, in Smart Sensors, Measurement and Instrumentation, vol. 4, pp. 1–24, Springer, Berlin, Heidelberg., 2013.

Kosko, B.: Fuzzy thinking : the new science of fuzzy logic, Hyperion. [online] Available from: https://books.google.co.in/books/about/Fuzzy_Thinking.html?id=SdsQAQAAIAAJ (Accessed 18 September 2018), 1993.

Kumar, K. K., Durai, S., Vadivel, M. T. and Kumar, K. A.: Smart traffic system using raspberry pi by applying dynamic color changer algorithm, in 2017 IEEE International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials (ICSTM), pp. 146–150, IEEE., 2017.

Lee, S.: PERCENTAGE ERROR, MathWorld, 1 [online] Available from: http://mathworld.wolfram.com/PercentageError.html (Accessed 25 March 2018), 2016.

Lermontov, A., Yokoyama, L., Lermontov, M. and Machado, M. A. S.: River quality analysis using fuzzy water quality index: Ribeira do Iguape river watershed, Brazil, Ecological Indicators, 9(6), 1188–1197, doi:10.1016/j.ecolind.2009.02.006, 2009.

MathWorks: Fuzzy Inference System Modeling - MATLAB & Simulink - MathWorks India, [online] Available from: https://in.mathworks.com/help/fuzzy/mamdani-fuzzy-inference-systems.html (Accessed 14 March 2018a), n.d.

MathWorks: Fuzzy Logic Toolbox - MATLAB, [online] Available from: https://in.mathworks.com/products/fuzzy-logic.html (Accessed 11 March 2018b), n.d.

Ponsadailakshmi, S., Sankari, S. G., Prasanna, S. M. and Madhurambal, G.: Evaluation of water quality suitability for drinking using drinking water quality index in Nagapattinam district, Tamil Nadu in Southern India, Groundwater for Sustainable Development, 6, 43–49, doi:10.1016/j.gsd.2017.10.005, 2018.

Power, K. N. and Nagy, L. A.: Relationship between bacterial regrowth and some physical and chemical parameters within Sydney's drinking water distribution system, Water Research, 33(3), 741–750, doi:10.1016/S0043-1354(98)00251-6, 1999.

Qureshi, M. U., Girault, A., Mauger, M. and Grijalva, S.: Implementation of home energy management system with optimal load scheduling based on real-time electricity pricing models, in 2017 IEEE 7th International Conference on Consumer Electronics - Berlin (ICCE-Berlin), vol. 2017–September, pp. 134–139, IEEE., 2017.

Raman, B. V, Bouwmeester, R. and Mohan, S.: Fuzzy Logic Water Quality Index and Importance of Water Quality Parameters, Air, Soil and Water Research, 2, ASWR.S2156, doi:10.4137/ASWR.S2156, 2009.

Raspberry Pi Foundation: Raspberry Pi Documentation, , 1 [online] Available from: https://www.raspberrypi.org/documentation/ (Accessed 15 March 2018), 2014.

Sumardi, Taufiqurrahman, M. and Riyadi, M. A.: Street mark detection using raspberry pi for self-driving system, Telkomnika (Telecommunication Computing Electronics and Control), 16(2), 629–634, doi:10.12928/TELKOMNIKA.v16i2.4509, 2018.

Talukder, M. Z., Towqir, S. S., Remon, A. R. and Zaman, H. U.: An IoT based automated traffic control system with real-time update capability, in 2017 8th International Conference on Computing, Communication and Networking Technologies (ICCCNT), pp. 1–6, IEEE., 2017.

Tiri, A., Belkhiri, L. and Mouni, L.: Evaluation of surface water quality for drinking purposes using fuzzy inference system,

Groundwater for Sustainable Development, 6, 235–244, doi:10.1016/J.GSD.2018.01.006, 2018.
World Health Organization: Drinking-water, [online] Available from: https://www.who.int/news-room/fact-sheets/detail/drinking-water (Accessed 25 March 2019), n.d.
World Resources Institute: India Water Tool Version 2.1, [online] Available from: http://maps.indiawatertool.in/iwt/av/IWTUserGuide.pdf (Accessed 5 December 2017), 2016.
Zadeh, L. A.: Fuzzy logic, Computer, doi:10.1109/2.53, 1988.
Zhao, J. and Bose, B. K.: Evaluation of Membership Functions for Fuzzy Logic Controlled Induction Motor Drive, IEEE 2002 28th Annual Conference of the Industrial Electronics Society, 229–234, doi:10.1109/IECON.2002.1187512, 2002.

Table 1. Central Pollution and Control Board criteria for Water Quality (Central Polution Control Board, 2007)

Type of Water	**Category**	**Quality Parameter Criteria**
Drinking Water Source without conventional treatment but after disinfection	**'A'**	1. Total Coliforms Organism MPN/100ml shall be 50 or less 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 6mg/l or more 4. Biochemical Oxygen Demand 5 days 20°C 2mg/l or less
Outdoor bathing (Organised)	**'B'**	1. Total Coliforms Organism MPN/100ml shall be 500 or less 2. pH between 6.5 and 8.5 ~~1.~~3. Dissolved Oxygen 5mg/l or more ~~2.~~4. Biochemical Oxygen Demand 5 days 20°C 3mg/l or less
Drinking water source after conventional treatment and disinfection	**'C'**	1. Total Coliforms Organism MPN/100ml shall be 5000 or less 2. pH between 6 to 9 3. Dissolved Oxygen 4mg/l or more 4. Biochemical Oxygen Demand 5 days 20°C 3mg/l or less 5. TDS 2000 mg/l
Propagation of Wildlife and Fisheries	**'D'**	1. pH between 6.5 to 8.5 2. Dissolved Oxygen 4mg/l or more 3. Free Ammonia (as N) 1.2 mg/l or less
Irrigation, Industrial Cooling, Controlled Waste disposal	**'E'**	1. pH between 6.0 to 8.5 2. Electrical Conductivity at 25°C micromhos/cm Max.2250 3. Sodium absorption Ratio Max. 26 4. Boron Max. 2mg/l

Table 2. Groups defined for water quality parameters

Range / Parameters	UNDES	DES	UNDES
pH	< 6.5	6.5-8.5	> 8.5
EC	< 300	300-1000	> 1000
ORP	< 200	200-800	> 800
DO	< 3	3-11	> 11
Temperature	< 2	2-35	> 35

* UNDES = undesirable
DES = desirable

Table 3 (a). Average values of samples for pH, DO & EC and their calculated PRE

Location	pH			DO (mg/l)			EC (µS/cm)		
	MSA	Commercial System	PRE (%)	MSA	Commercial System	PRE (%)	MSA	Commercial System	PRE (%)
1	7.45	7.51	0.8	8.20	8.16	0.49	385	387	0.51
2	7.62	7.68	0.78	7.90	7.89	0.13	435	426	2.1
3	6.95	6.99	0.57	9.50	9.47	0.32	510	515	0.97
4	8.1	8.2	1.2	9.23	9.21	0.22	390	385	0.13
5	7.8	7.87	0.88	8.05	7.98	0.88	445	455	0.22
6	8.2	8.21	0.12	7.8	7.7	1.2	1582	1576.2	0.36
7	8.1	8.04	0.75	7.5	7.4	1.35	1635	1621.8	0.81
8	8.1	8.01	1.12	7.5	7.4	1.35	1672	1662.1	0.59

Table 3 (b). Average values of samples for ORP & Temperature and their calculated PRE

Location	ORP (mV)			Temperature (ºC)		
	MSA	Commercial System	PRE (%)	MSA	Commercial System	PRE (%)
1	213	212	0.47	22.5	22.7	0.88
2	212	210	0.95	21.5	21.3	0.93
3	185	187	1.06	19.6	19.7	0.50
4	206	208	0.96	18.9	19.1	1.04

5	191	194	1.54	23.8	24.1	1.24
6	170.5	168.5	1.18	29.2	28.98	0.76
7	170.9	168.7	1.30	30.1	29.84	0.87
8	171.1	168.4	0.58	30.5	30.21	0.96

Table 4. Fuzzy water quality for all locations

Location	Fuzzy Water Quality (FWQ)
1	Good
2	Good
3	Satisfactory
4	Good
5	Good

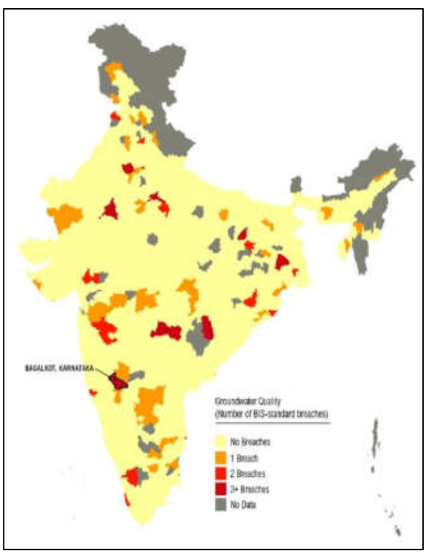


Figure 1 Groundwater Quality (Number of BIS standard breaches) (World Resources Institute, 2016)(Central Polution Control Board, 2007)

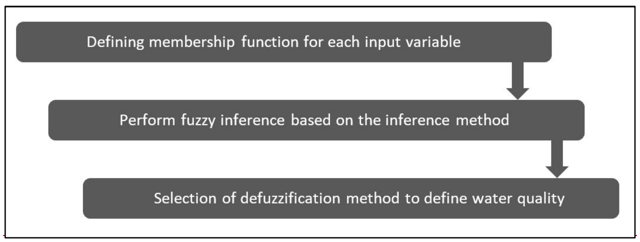


Figure 2 Fuzzy logic designing process

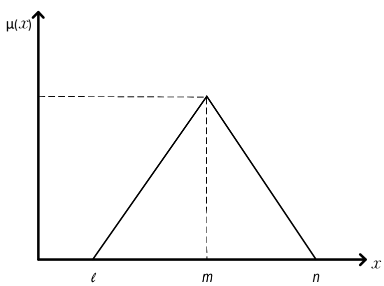
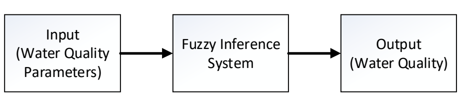
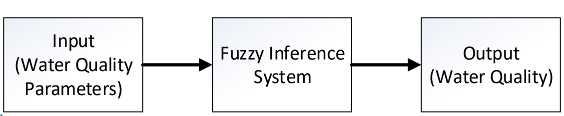


Figure 23 Triangular Membership Function

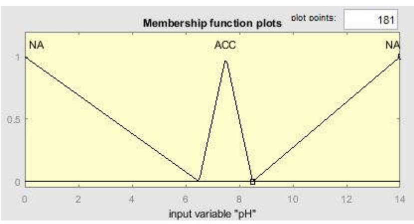




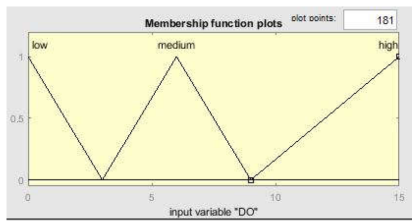
Field Code Changed

Figure 34 Block Diagram of FuFISzzy Inference System used in the work

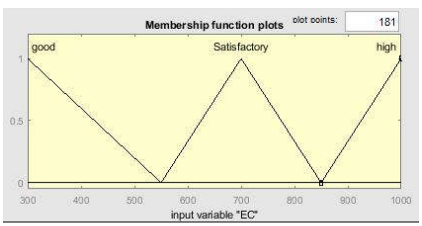
Formatted: Line spacing: 1.5 lines



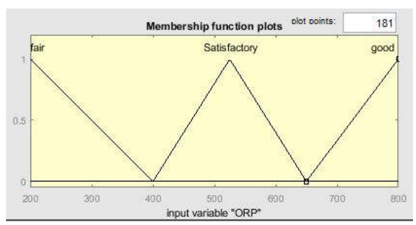
(a)



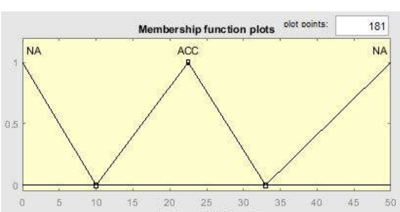
(b)



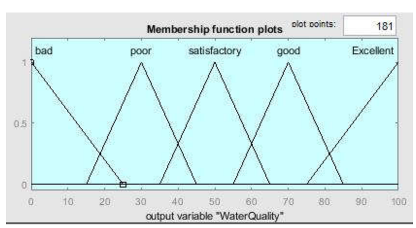
(c)



(d)



(e)



(f)

Figure 45 Input and output membership functions

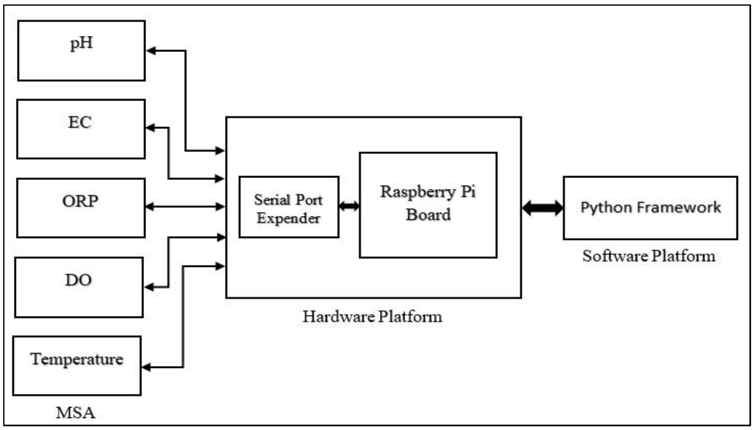
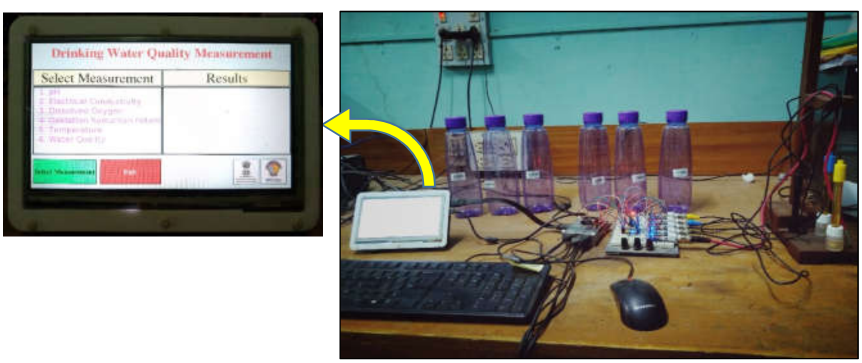
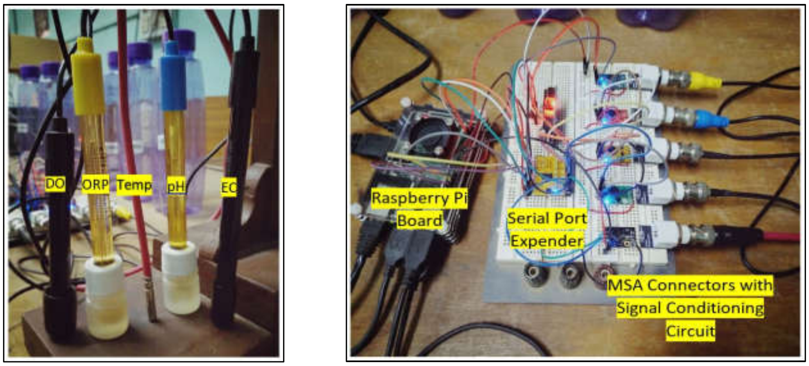


Figure 56 Block Diagram of Multi-Sensor Array (MSA) and It's Interfacing with Hardware and Software



(a)



(b) (c)

Figure 6~~7~~ (a) The proposed System (b) Multi-Sensor Array (MSA) (c) MSA integration with serial port expender and Raspberry Pi board

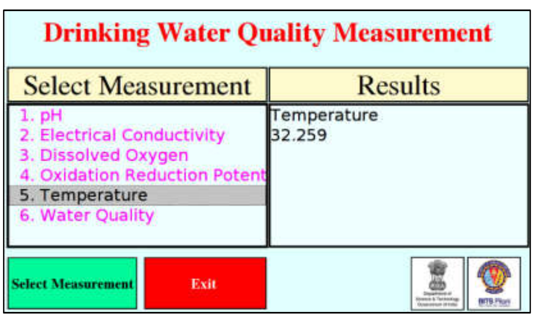


Figure 7~~8~~ Graphical User Interface

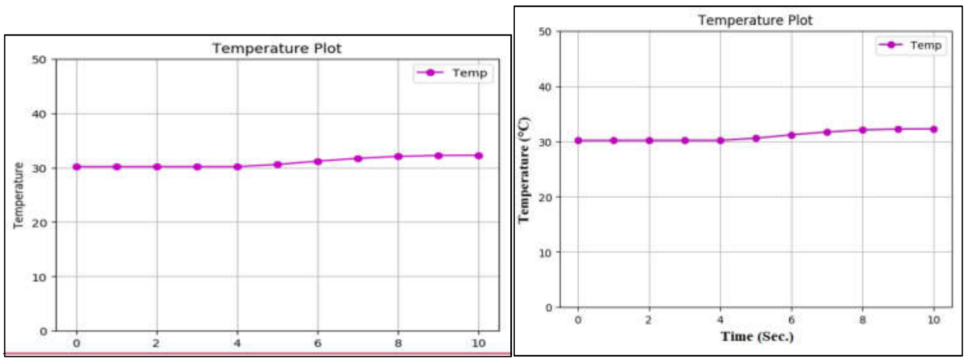


Figure 8 9 Temperature plot in GUI

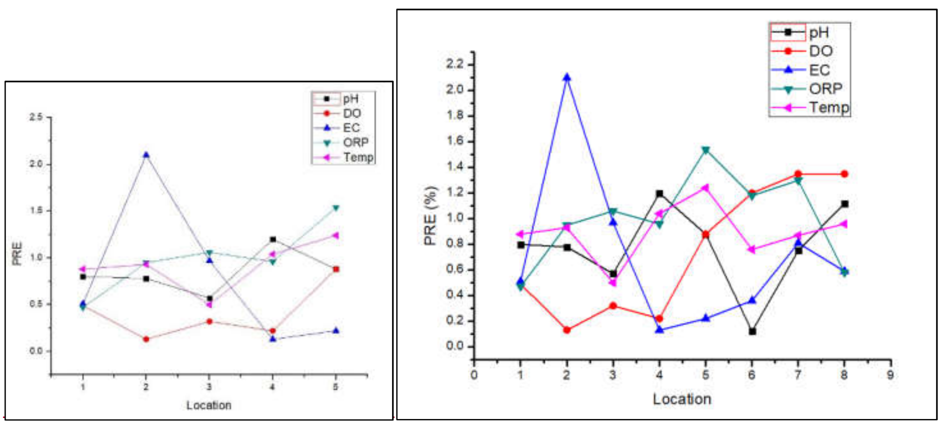


Figure 9 10 Percentage Relative Error (PRE) Plot for different water quality parameters