An Integrated Water Quality Sensing System: A Review and Analysis of Critical Parameters and an Evaluation of Contact and Non-contact Sensors

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Abstract

Several methodologies and standards exist for the measurement of water quality. The use of established water quality indices is embedded in these methodologies/standards and the measurement approach of these indices involves several different techniques and sensor technologies. Recent development in the field of water quality measurement has moved towards wireless sensor network systems to enable the monitoring of multiple bodies of water in any given geographical region, with most of the research focussing on the use of the Internet of Things (IoT) for the associated water quality sensing systems.

There exists a small amount of research into combined sensor technologies that enable measurement simultaneously of multiple parameters. There is currently, however, no analysis available on the feasibility of developing a fully integrated system to measure all desirable water quality parameters simultaneously. Sensor solutions and analysis techniques for such a fully integrated system are therefore lacking. This research analyses common water quality measurement methods, comparing them particularly to non-contact alternatives to determine the viability of a cost effective and fully integrated water quality sensing system. In parallel it seeks to determine which types of sensors are best for effective analysis of water quality in distributed bodies of water.

Literature analysis determined that a cost-effective, fully integrated water quality sensing system was feasible if the water quality parameters being measured were limited. As a result, an analysis of contact and non-contact sensors for the selected parameters was conducted. The results of this analysis were varied, and it was concluded that the types of sensor that should be used in an integrated water quality sensing system are dependent on the design of the critical parameter set being measured.

Keywords: Water quality sensing systems, pH, Electrical conductivity, Temperature, Turbidity, Total Dissolved Solids (TDS), Contact Sensors, Non-Contact Sensors

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1.0 Introduction

Water quality is a major environmental and health issue around the world, which has resulted in the extensive quality monitoring of sources of drinking water to ensure compliance with universal safe drinking water standards. Less widespread, however, is the monitoring of water quality of the multiple bodies of water in geographic areas that are not used for drinking water specifically but often used for other human activities including food reserves. This has not been traditionally viewed as critically important and monitoring activity is typically irregular at best. With the recent understanding of the importance of integrated environmental issues surrounding water quality, the importance of widespread water quality measurements has increased and as a result the need for deployment of cost-effective water quality systems has similarly increased.

Water quality systems are used throughout both industry and government to determine the standard of water quality of any given sample or body of water. There is, however, a wide range of parameters that set the standard for water quality analysis for various types and bodies of water. The issue with most water quality systems, outside of the price, is that they often only look at a single specific water quality parameter, and to get a complete overview of water quality multiple water quality parameters are needed. Furthermore the primary parameters of water quality vary between different countries with different associated environmental standards for different bodies of water, and the issue with setting a standard set of parameters that determine the quality of water is that there is a wide range of water quality indices (WQI) that are used throughout the world and each of these WQIs has different water and sediment quality variables that make up the WQI [1]. When trying to determine what is classified as safe drinking water, most of the international community refers to the standards provided by the World Health Organization (WHO). These standards provide the maximum accepted values (MAV) of all chemicals found in drinking water. WHO also provides values for the highest concentration of any chemical in drinking-water that, based on what we currently know, is considered not to cause any significant risk to the health of the consumer who is consuming 2 litres per day of that water over 70 years of consumption [2]. However, there are still some differences in the standards between the regulations imposed by different countries; for example, Table 1 shows the differences between New Zealand, India, and the USA on some key water quality parameters. Table 1 shows that despite there being universal standards on drinking water provided by WHO, individual countries can have standards that allow for flexibility in water quality by adding limits for what is permissible in the absence of alternative sources of water. As a result, different countries have different standards of water quality.

Table 1: Differences in the water quality standards between countries

	New Zealand	**India**	**USA**
Turbidity	2.5 NTU	5 NTU	5 NTU
Total dissolved solids	1000 mg/L	2000 mg/L	500 mg/L
pH	7.0–8.5	6.5–8.5	6.5–8.5
Escherichia coli	Less than one ppm in 100 mL of sample	Less than one in 100 mL of sample	0 mL
Nitrogen	50	45	10
Fluoride	1.5 mg/L	1.5 mg/L	2.0 mg/L
References	[3]	[4]	[5]

Because of this range of standards for water quality, it is difficult to provide a conclusive list of water quality parameters required for a full analysis of any body of water for an integrated water quality system. The water quality parameters that are measured by New Zealand's National Institute of Water and Atmospheric Research (NIWA) are shown in Table 2. These parameters align well with an overview of all the major water quality parameters that are discussed in the available literature on this topic. From this comparison, a defined primary set of water quality parameters can be extrapolated that can determine the water quality of a given body of water with reasonable accuracy.

Table 2: Water quality parameters measured by NIWA [6]

Physio–chemical variables	**Optical variables**	**Nutrients**	**Microbial Indicator**	**Biological indicators**
Dissolved oxygen	Visual clarity	Total nitrogen	*E. Coli*	Macroinvertebrates
Temperature	Turbidity	Total phosphorus		Periphyton
pH	Coloured Dissolved Organic matter	Dissolved nitrogen		
Conductivity		Dissolved phosphorus		

Table 3: Standard water quality parameters and the typical sensing method used to measure them.

Water Quality Parameters			
Target Analyte	**Unit of Measure**	**Standard Sensing Method**	**References**
Dissolved oxygen	mg/L	Optical sensor	[7] [8]
Conductivity	μS/cm	Electrode sensor	[7] [9]
pH		Electrode sensor	[7] [9]
Total phosphorus	μg/L	Colorimetric sensor	[7] [10]
Dissolved phosphorus	μg/L	Colorimetric sensor	[7] [10]
Total nitrogen	μg/L	Electrode sensor	[7] [9]
Dissolved nitrogen	μg/L	Electrode sensor	[7] [9]
Turbidity	NTU	Optical sensor	[11] [12]
Temperature	°C	Thermistor probe	[11] [13]
Chlorophyll-a	μg/L	Optical sensor	[11] [12]
Total suspended solids	mg/L	Optical sensor	[11] [12]
Inorganic suspended solids	mg/L	Optical sensor	[11] [12]
Organic suspended solids	mg/L	Optical sensor	[11] [12]
Biochemical oxygen demand	mg/L	Biosensor	[14] [15]
Faecal coliform	#/100 mL	Fluorescence sensor	[14] [16]
Escherichia coli	cfu/100mL	Fluorescence sensor	[14] [16]
Ammonia	mg/L	Fluorescence or optical sensor	[1] [17]

A cost-effective integrated water quality system would have to be able to measure all the water quality parameters needed to determine the quality of any given body of water using methods that are cheap and efficient. There are multiple methods for measuring the water quality parameters of a given body of water but the most common is method is to take water samples and have them lab tested for the required water quality parameters, although in some cases the measurements can be taken on-site with handheld sensors. In New Zealand, it is common practice to measure the dissolved oxygen, temperature, and visual clarity on-site and then have all the other required indicators measured by the analysis of water samples [18]. The current methods of water quality analysis are neither cheap nor efficient and allow an opportunity to provide an all-inclusive sensing unit that is cheaper and easier to use than the multiple probes, meters, and lab analysis required by current practices. To evaluate the feasibility of an all-inclusive water quality sensing unit, an analysis of the required measurement methods is needed along with the evaluation of a non-contact or low maintenance alternative that can be used in an all-inclusive water quality sensing unit. Through this analysis, it can be determined if a cost-effective integrated water quality sensing is feasible and, if so, how, while also determining the best types of sensing methods to use in such a system. A review of previous research into this topic will provide the necessary insight into how water quality is measured, whether a cost-effective integrated water quality sensing is feasible by analysing how the required parameters are measured, and if those measurement systems can be incorporated into an all-inclusive water quality sensing unit.

2.0 Water Quality Assessment Models

Water quality assessment models are the criteria that grade the quality of any given body of water; this is typically done using a water quality index (WQI) that is used to evaluate the overall water quality of a body of water, typically to rate the water against safe drinking water standards. There are multiple water quality assessment models that are used throughout the world to evaluate different types of parameters, from the chemical pollutants in water to the macroinvertebrate contamination [19].

A water quality index (WQI) is made by ranking water quality parameters according to the significance placed on them by water quality standards. Most developed countries have their own modelling systems that are used to determine the water quality of bodies of water within their territories as well as to predict various other indicators. Two good examples of WQIs used by governments today are the Canadian Council of Ministers for the Environment water quality index (CCME) [20] and Aggregation Functions [21]. The CCME is primarily used in New Zealand and Canada while the use of aggregation functions has been popularised in the United States of America (USA).

2.1 Canadian Council of Ministers Water Quality Index (CCME)

The reason that the CCME is popular is that it provides a very good mathematical framework that is flexible with input variables and so can be used for all water quality evaluations across all bodies of water and still provide an accurate representation of the water quality. The CCME WQI requires that there be a minimum of four water quality parameters being measured but puts no restriction on what those parameters must be, so the appropriate parameters can be used in varying environments [22].

The CCME WQI calculation gives a representation of water quality based on the chosen water quality parameters by evaluating three key aspects of the analysis, as shown in Equation 1 [22].

$$CCMEWQI = 100 - \left(\frac{\sqrt{F1^2+F2^2+F3^2}}{1.732}\right) \qquad (1)$$

The first aspect of the CCME equation ($F1$) is the scope, which is calculated as shown in Equation 2 [22]. This represents the percentage of water quality parameters that had failing conditions met during the period that the water quality test took place.

$$F1 = \left(\frac{Total\ number\ of\ failed\ variables}{Total\ number\ of\ variables}\right) \times\ 100 \qquad (2)$$

The second aspect of the CCME equation (*F*2) is the frequency, which is calculated as shown in Equation 3. This represents the percentage of individual water quality tests taken that had failing conditions met.

$$F2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) \times\ 100 \qquad (3)$$

The final aspect of the CCME (*F*3) is the amplitude, which is calculated as shown in Equation 4. This represents the degree to which the water quality tests that had failing conditions failed, as seen in Equation 4: this is calculated in three steps.

$$F3 = \left(\frac{nse}{0.01nse + 0.01}\right) \qquad (4)$$

The first part of calculating F3 is to find the “excursion”, this is the number of times that an individual concentration in a water quality test falls outside the allowable range of the objective. When the test must not exceed a certain objective then Equation 5 is used and when the test must not fall below a certain objective Equation 6 is used.

$$excursion\ i = \left(\frac{FailedTestValue\ i}{Objective\ j}\right) - 1 \qquad (5)$$

$$excursion\ i = \left(\frac{Objective\ j}{FailedTestValue\ i}\right) - 1 \qquad (6)$$

The second part of calculating *F*3 is to find the normalized sum of excursions or the “*nse*”. The *nse* is calculated using Equation 7 and then the third and final step to calculate *F*3 is to put all the results into Equation 4.

$$nse = \frac{\sum_{i=1}^{n} excursion\ i}{Number\ of\ tests} \qquad (7)$$

2.2 Aggregation Functions

Four main aggregation functions are used when calculating a WQI, the arithmetic mean, the geometric mean, the harmonic mean, and the minimum operator [21], all of which are shown in Table 4. All aggregation functions take data of specified water quality parameters that have been weighted based on the significance of the parameters to a body of water and put the data into an equation to determine the forecast for change in the water quality. This is a good forecasting method that helps adjust for changes in water quality over time and analyse methods to improve water quality. However, it has a strong reliance on the weights given to individual water quality parameters that are determined by a survey of water quality data; this means that consistent updates to the weights are necessary.

Table 4: Summary of Aggregation Functions [21]

Aggregation Function	Formula
Arithmetic mean	$WQI_A = \sum_{i=1}^{n} q_i w_i$
Geometric mean	$WQI_G = \prod_{i=1}^{n} q_i^{w_i}$
Harmonic mean	$WQI_H = \sqrt{\frac{n}{\sum_{i=1}^{n} 1/q_i}}$
Minimum operator	$WQI_M = min(q_1, q_2 \dots, q_n)$

In aggregation functions q_i is the 0–100 rating for each variable and w_i are the weights where $\sum_{i=1}^{n} w_i = 1$ [21]. The number n is the number of sub-indices aggregated and because of how each of the functions treats the w_i and the n, different functions will give varying results. An example of the variation in results is shown in Table 5 where the same data from the USA's Environmental protection agency regulatory impact report for the 2003 CAFO rule [23] was used in each of the aggregation functions as an example.

Table 5: Policy Forecast for Change in WQI [21]

WQI	Mean	Std. Dev.	Min	Max
Geometric	0.2983	1.4793	-46.4499	52.0442
Harmonic	0.4577	2.5227	-75.0607	77.2153
Arithmetic	0.1004	0.5325	-25.8412	23.2690
Minimum	0.3072	1.9282	-69.1100	65.9200

3.0 Water Quality Monitoring Systems

The traditional approach to monitoring water quality has been to gather water sample of a given body of water and analyse the samples in a lab; however, this method is inefficient due to the labour involved and can be inaccurate as the results of the water samples only give a snapshot of the water quality at the time when the samples were taken [24]. With the advent of the Internet of Things (IoT) new novel ways have been developed that allow for water quality to be monitored more often and give a more complete overview of the water quality in any given body of water.

One of the most popular monitoring methods is the wireless sensor network (WSN). This type of monitoring method consists of a range of sensor nodes that are situated in different bodies of water. These sensor nodes have a wireless transmitter that sends water quality data to the main server that sorts and displays the data –usually a General Packet Radio Service (GPRS) network or a low-power wide-area network (LPWAN) is used to send the data [25]. A general overview of how this system works is shown in Figure 1.

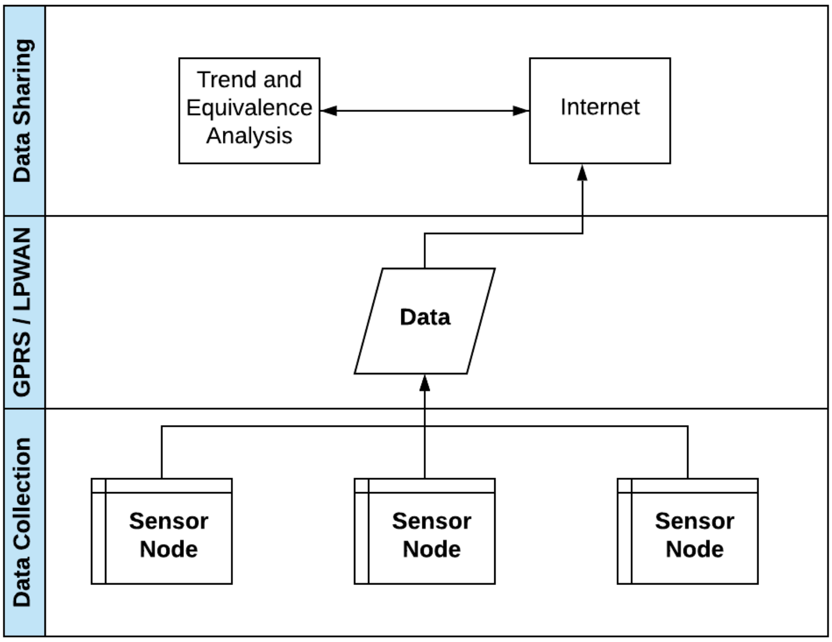
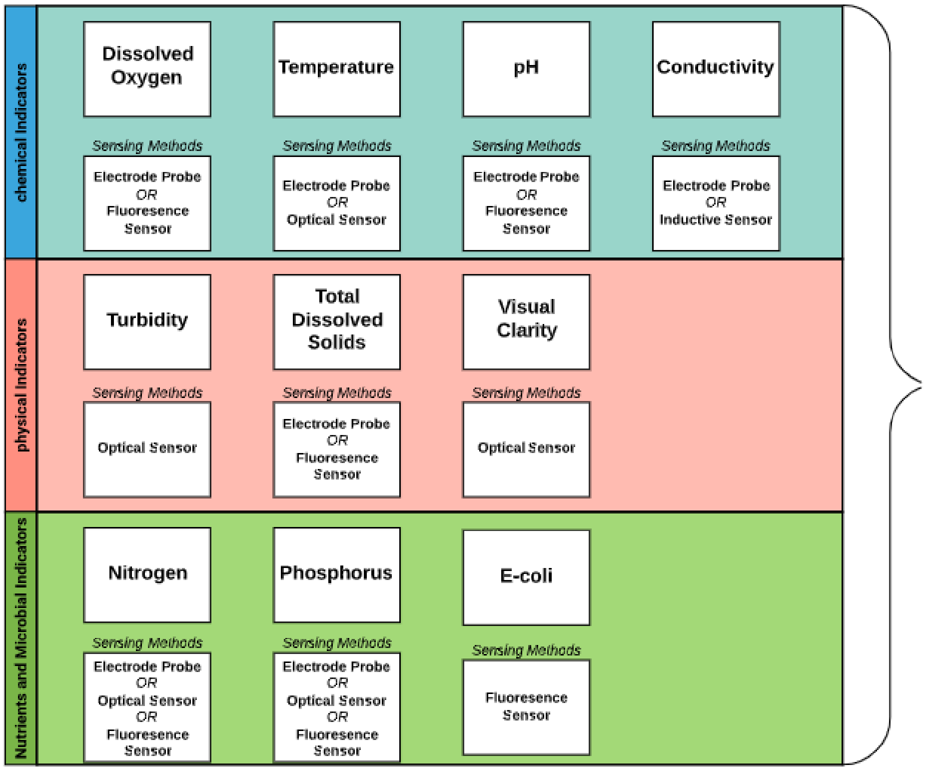


Figure 1: Water quality WSN system

A good example of a water monitoring system is described in “IoT Application in River Monitoring: Methods and Challenges” [26]. This system has sensor nodes that consist of multiple sensors to measure a range of water quality parameters that input data into a microcontroller that correlates the data so that it can be sent to an application server every 15 minutes via an LPWAN. This system is very good for continuous water quality monitoring and large-scale data gathering; however, the accuracy of this system is dependent on how well the sensors used in the nodes react to long exposure to water and whether their reliability decreases over time.

4.0 Water Quality Sensors

When evaluating the water quality of a given body of water often there are multiple methods and sensors used depending on the type of WQI that is being calculated to determine the water quality. After an in-depth analysis of current literature and cross-referencing the results with the environmental standards of a few major countries [2] focusing on safe drinking water standards, the wide range of water quality parameters have been narrowed down to a set of critical indicators. These critical indicators make up the necessary parameters required to determine the general water quality of a body of water, not looking at individual situations that require a specific indicator to be measured. The critical indicators are dissolved oxygen, temperature, pH, conductivity, turbidity, nitrogen, phosphorus, and *E. coli*. These indicators are shown in Figure 2 along with the current sensing methods that are most commonly used to measure them.



A typical water quality index (WQI) that would be Used to evaluate theses parameters is the Canadian Council of Ministers for the Environment water quality index (CCME) and WQI forecasting for changes in these parameters is done by the use of simulations and aggregation functions.

Figure 2: An overview of the critical water quality parameters

4.1 Dissolved Oxygen Sensors

Dissolved oxygen refers to the measurement of the gas or liquid oxygen transfer and oxygen uptake rates. The concentration of dissolved oxygen is a vital parameter, as it is used for measurements in industrial, physiological, and environmental studies to determine the water quality [8]. Having a healthy level of dissolved oxygen in water is vital, as it is essential for the survival of fish and other aquatic organisms. Table 6 gives an overview of the commercially available dissolved oxygen sensors, as of 2020.

Table 6: Commercially available sensors

Sensor	Sensing method	Supplier
Optical dissolved oxygen sensor	Fluorescence quenching	METTLER TOLEDO [27]
Polarographic dissolved oxygen sensor	Electrode membrane	METTLER TOLEDO [28]
Amperometric oxygen sensor	Electrode	Krohne Messtechnik [29]
Polarographic sensor	Electrode	LTH Electronics Ltd [30]
Optical dissolved oxygen sensor	sensing membrane	Hamilton [31]
Electrochemical dissolved oxygen sensor	electrochemical	Xylem Analytics Germany Sales GmbH & Co KG – WTW [32]

As of 2020 most of the current research into dissolved oxygen sensors is done looking into novel ways of measuring dissolved oxygen and the effects that different detection method has on the readings of dissolved oxygen in different environments.

4.1.1 Common Dissolved Oxygen Sensors

The Measurement of Dissolved oxygen in water is typically done using a probe that either use optical or electrode sensing methods with the electrode sensing methods being affordable. there are two main types of electrode probe sensors Amperometric and Voltammetric, with Amperometric being the most common [33]. A good example of an Amperometric Probe is described in [33] "Development of a reliable microelectrode dissolved oxygen sensor", this probe uses a carbon fibre electrode system that has a fine membrane that controls the rate of oxygen transport to the electrode, this electrode detects ions in a body of water using an electric current or changes within an electric current. This sensor is not the perfect system that has several areas that can be improved.

There are different types of dissolved oxygen sensors are used for different environments, the electrode system described in “Development of a reliable microelectrode dissolved oxygen sensor” is a good example of a generalised dissolved oxygen sensor. However, when measuring the dissolved oxygen of a body of water it is prudent to consider the type of water that is being measured and choose the dissolved oxygen sensor appropriately. For example, there are if the body of water being measured has been exposed to Microbial Fermentation then it Nitrogen and Boron-Doped Reduced Graphene Oxide Membrane-Less Amperometric Sensor [34] as this sensor has been proven to give accurate readings of dissolved oxygen in microbial fermentation. The main advantage of this sensor is that the use of a metal-free N, B-doped reduced graphene oxide as an electrode material is cheap and the electrode has a high chemical stability t to withstand harsh environments [34]. The use of Nitrogen and boron-doped reduced graphene oxide as an electrode for a dissolved oxygen sensor allows for accurate measurements to be taken without the interference of any chemical reactance in the water.

Not all dissolved oxygen electrodes are Amperometric sensors the are some that are Voltammetric probes. Where Amperometric Sensors that detect the oxygen ions in the water-based of changes in the electric current of the electrode probe Voltammetric sensors measure the electrical activity from the electrode probe and use electroanalytical methods to determine the amount of dissolved oxygen in water, a subtle but important difference. An example of a Voltammetric probe is given in “A glassy carbon electrode modified with an iron N4-macrocycle and reduced graphene oxide for voltammetric sensing of dissolved oxygen” [35]. The sensor described uses a glassy carbon electrode to measure the electrical activity in the water and then uses cyclic voltammograms and differential pulse voltammetry to determine the dissolved oxygen in the water. This sensor provides accurate results and has serval desired properties of a sensor including a low detection limit, satisfactory linear concentration range, and excellent stability, however, to achieve the optimum results from this sensor requires the glassy carbon electrode surface to be polished and cleaned by sonication to remove any adsorbed species [35].

Despite the difference in measurement system both Voltammetric and Amperometric Sensors use electrodes, an illustration of which is shown in Figure 3, and the use of membranes on probes can cause poor sensor performance because membranes are easily blocked and fragile so damage is not uncommon and this leads to the probe being regularly replaced [33]. This limitation on the probe reliability and the sampling method that probe-based sensors require, as well as the fact that Common Dissolved Oxygen meters are expensive, provides an option to explore another method to measure Dissolved Oxygen.

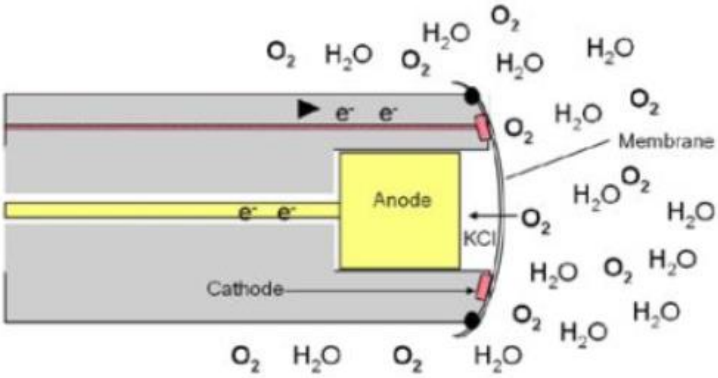


Figure 3: Layout of a dissolved oxygen electrode [36]

4.1.2 Non-contact Dissolved Oxygen Sensors

There have been serval sensors developed to detect the dissolved oxygen concentration in water without using a probe the most common and accurate of these sensors is a Fluorescence sensor. Fluorescence sensors are often superior to other optical and electrochemical sensors because they have a high sensitivity which leads to very accurate measurement results [37].

However, Fluorescence sensors are not perfect and fluctuations in light intensity and detector sensitivity along with light scattering can lead to inconsistencies in the measurement results [8]. Despite the difficulties of a fluorescence sensor, it is a cheaper and easier method to measure Dissolved oxygen when compared to a probe sensor, the difference being that a probe method will have more consistent results.

4.2 Water Temperature Sensors

Water temperature is an important parameter in water quality assessment as it is often used as an indicator for many different issues with the water quality of a body of water [38]. Temperature impacts a wide range of chemical and biological parameters of water, it can affect the dissolved oxygen level of the water, the aquatic life in a body of water, and the sensitivity of a given body of water to different types of pollutants. Table 7 gives an overview of the commercially available water temperature sensors as of 2020.

Table 7: Commercially available sensors

Sensor	**Sensing method**	**Supplier**
Thermistor probe	Thermistor	Campbell Scientific [39]
Analog sensor	Electrode conductivity cell	Envco [40]
Temperature probe	Resistance Temperature Detector (RTD)	Krohne Messtechnik [41]
Temperature probe	Resistance thermometers	WIKA Alexander Wiegand SE & Co. KG [42]
Resistance temperature sensor	Resistance Temperature Detector (RTD)	Danfoss Industrial Automation [43]
Thermocouple	Thermocouple	SIMEX Sp. z o.o. [44]

As of 2020 most of the current research into water temperature sensors is into different types of temperature sensing and analysing their performance at water temperature detection.

4.2.1 Common Water Temperature Sensors

Temperature is a water quality parameter that is typically measured in the field, using a probe to measure the temperature at multiple depths, with the most common probes used being thermistor probes [38]. Conventional thermistor probes typically consist of an electronic temperature control system that maintains the device at a constant temperature allowing a calculation of temperature based on the change in temperature of the probe.

The disadvantage of a thermistor probe is the sampling method of the probe, as it requires direct contact with the water, which can lead to issues in measurements, since aquatic organisms can interfere with the probe. However, it is still used in field testing because a thermistor probe is cheaper than a pyrometer. Thermistor probes also allow for measurements to be taken at different depths and have an advantage over pyrometers with measurements that are carried out in environments where the temperature is below 0 °C [38].

A good example of how a thermistor probe works is described in “A dual-thermistor probe for absolute measurement of thermal diffusivity and thermal conductivity by the heat pulse method” [45]. A thermistor probe works by connecting a voltage source across a thermistor and measuring the change in resistance: this relationship is shown in Equation 8 [45] where, R_{S0} is a variable resistor, R_B are matched 10 kΩ resistors, E_S is the voltage source, V_1 is the voltage output and B is coefficient of the thermistor which can be measured experimentally. The way that a thermistors probe is designed is shown by the layout of Figure 4.

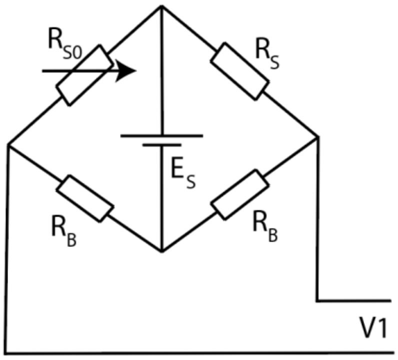


Figure 4: Thermistor a Wheatstone bridge design

$$\Delta T = B\frac{(R_{S0}+R_B)^2}{R_B R_{S0} E_S}V_1 \tag{8}$$

Another good example of a water temperature sensor is a resistance temperature detector (RTD) probe, typically made by having a glass core that is wrapped with a fine wire made out of a pure material like copper or nickel. A good example of an RTD sensor is provided by “A flexible resistive temperature detector (RTD) based on in-situ growth of patterned Ag film on polyimide without lithography” [46]. This RTD uses an Ag-PI film that acts as an RTD to measure the temperature, this gives the RTD high sensitivity values and excellent mechanical properties with no obvious change occurring even after 5000 bending cycles [46].

4.2.2 Non-contact Water Temperature Sensors

The most common non-contact water temperature sensor is a pyrometer, a type of remote-sensing thermometer that measures the temperature of a surface. Non-contact water temperature sensors typically use infrared or near infrared sensors to determine the thermal radiation emitted by the water to calculate the temperature [47].

Two significant issues exist in the field use of pyrometers, however, where measurements are carried out below 0 °C, causing the optical system to freeze over, and at high air humidity where moisture can penetrate the optical system. In both these circumstances, temperature measurement proves impossible [47].

4.3 pH Sensors

The parameter of pH is a very important when evaluating water, since it determines the acidity or alkalinity of water. It is especially important for drinking water, as the recommended range for pH of drinking water is 6.5–8.5; any further outside this range of pH, water is deemed too acidic or basic for general consumption [9]. Table 8 gives an overview of the commercially available pH sensors as of 2020.

Table 8: Commercially available sensors

Sensor name	Sensing method	Supplier
Water pH sensor	Electrode	Krohne Messtechnik [48]
Durable pH probe	Electrode	METTLER TOLEDO [49]
Redox pH sensor	Electrode	Knick [50]
Redox pH sensor	Electrode	AQUALABO [51]
Redox pH sensor	Electrode	LTH Electronics Ltd [52]
Water pH sensor	Electrode	Palintest [53]

As of 2020 most of the current research into pH sensors is done by developing different versions of pH sensing methods and improving on existing detection methods to enhance and analyse pH detection under different circumstances.

4.3.1 Common pH Sensors

Excluding pH paper, the most common water pH sensor is a reduction potentiometer electrode probe sensor or redox probe. A redox probe uses an electrode to measure the pH in water; a common type of electrode would be a glass electrode sensor, shown in Figure 5. This type of electrode is used because it is cheap, effective and almost ideal for pH sensing; however, it presents some drawbacks such as its fragility, difficulty of use in micro-electrodes and it requires frequent recalibration before use to be effective [54]. To overcome the limitations of the glass electrode there are alternatives based on solid-state electrodes, but the most common electrode in use is still the glass electrode due to them being significantly cheaper. Electrode-based pH sensing works by measuring the potentiometric response towards the pH, which is caused by a local variation of electric charge in the water that is a result of the proton exchange between the surrounding solution and the surface of the electrode [55]. This method gives semi-consistent measurement of pH in water which is reliable if minor variation is allowed in the measurement.

A good example of a redox pH is described in “Application of ruthenium oxide pH-sensitive electrode to samples with high redox interference” [56]. This sensor attempts to overcome some of the shortcomings of a redox pH probe, which are that the presence of oxidising and reducing agents in the tested sample can affect the measurement of pH and the accuracy of the sensor. The use of a ruthenium oxide electrode does improves upon this weakness, as the pH response is not suppressed by redox agents [56].

Another type of pH sensor that is less widely used due to being more expensive without any major benefits over electrode pH sensors is the fibre-optic pH sensor, a good example of which is described in "All-polymer fibre-optic pH sensor" [57]. The fibre-optic pH sensor measures the change in swelling of a polymer that is connected to a fibre-optic cable to determine the pH. This is done by the swelling exerting stress on the polymer to induce a wavelength shift in the UV light in the fibre optic cable and the magnitude of the shift is used to determine the pH value [57].

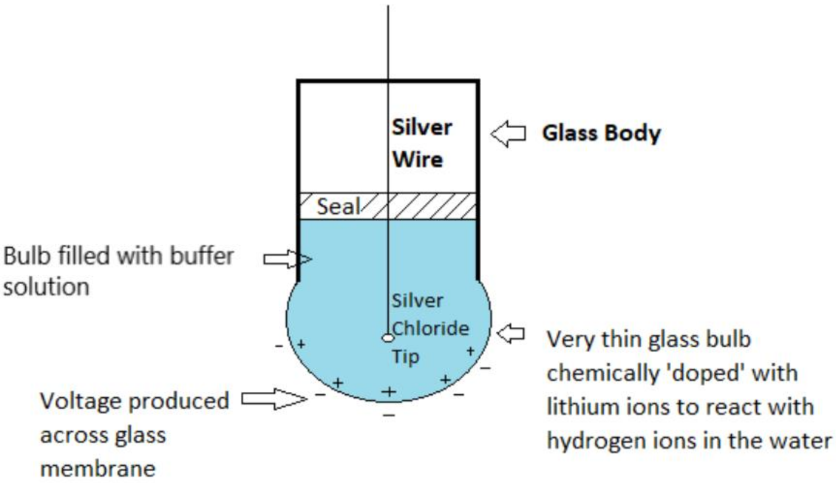


Figure 5: pH electrode probe layout

4.3.2 Non-contact pH Sensors

Non-contact pH sensors are not common, because it is easier and cheaper to use the contact methods. There are sensors, however, based on the ion-induced changes in fluorescence. These sensors have a high detection limit of fluorescence and result in very accurate pH readings [58]. The technical limitations of the fluorescence sensors include their susceptibility to variations in the background light, which can give inconsistent readings. This, and the necessity for an expensive meter to analyse the inputs of the fluorescent sensors has led to there being very few non-contact pH sensors on the market.

4.4 Conductivity Sensors

Water conductivity can be a difficult water quality parameter to quantify, as its measurements are often nonselective in the sense that they do not distinguish between individual concentrations of different ionic chemicals mixed in water. Water conductivity is a vital measurement in water quality assessments, since high or low conductivity levels can be used to detect environmental changes and pollution [59]. Table 9 gives an overview of the commercially available water conductivity sensors, as of 2020.

Table 9: Commercially available sensors

Sensor name	Sensing method	Supplier
Water conductivity sensor	Electrode	Krohne Messtechnik [60]
Inductive conductivity sensor	Inductive	Krohne Messtechnik [60]
2-electrode conductivity sensor	Electrode	Swan [61]
Inductive conductivity sensor	Inductive	LTH Electronics Ltd [62]
4-electrode conductivity sensor	Electrode	Innovative Sensor Technology IST AG [63]

As of 2020 most of the current research into water conductivity sensors is done by investigating how water conductivity can be used to determine different aspects of water quality, such as the detection of pollutants, and by the development of novel water conductivity sensors that are based on existing detection methods.

4.4.1 Common Conductivity Sensors

There are two main types of water conductivity sensors: the electrode sensor and toroidal sensors, with the main difference being that the electrode sensor requires contact with the water whereas the toroidal sensor is an inductive sensor so does not [9]. The most common of the two sensors is the electrode sensor; the main advantages associated with this sensor are its wide measurement range, low cost of the sensor and the linear response of its measurements [59]. The main disadvantage of the electrode sensor is that it must come into contact with the sample water; this increases the chance of fouling in the measurement results and risk of the sensor being damaged.

A good example of how an electrode sensor measures the conductivity of water is given in "Performance study of a two-electrode type aqueous conductivity sensor for smart farming" [64]. To measure the conductivity of the water, the sensor measures the AC impedance across the electrodes and from the measured impedance data the sample conductivity is calculated using Equation 9 [64] where $|Z|$ is the magnitude and θ is the phase, k is the cell constant, k_0 is the offset term that accounts for nonideality and t is the measurement temperature.

$$\sigma_t = k\frac{\cos\theta}{|Z|} + k_0 \tag{9}$$

As of 2020, most of the industrial market for water conductivity sensors is split evenly between electrode and inductive sensors. A good example of the common type of electrode sensor is described in "A Microfabricated 4-Electrode Conductivity Sensor with Enhanced Range" [65]. The 4-electrode conductivity sensor uses a 4-point probe system and is ideal because it decreases the influence that the resistance of the material used in the leads has over the measured conductivity, so allowing for more accurate results [65].

The difference between a two-electrode and a four-electrode sensor is shown below in Figure 6.

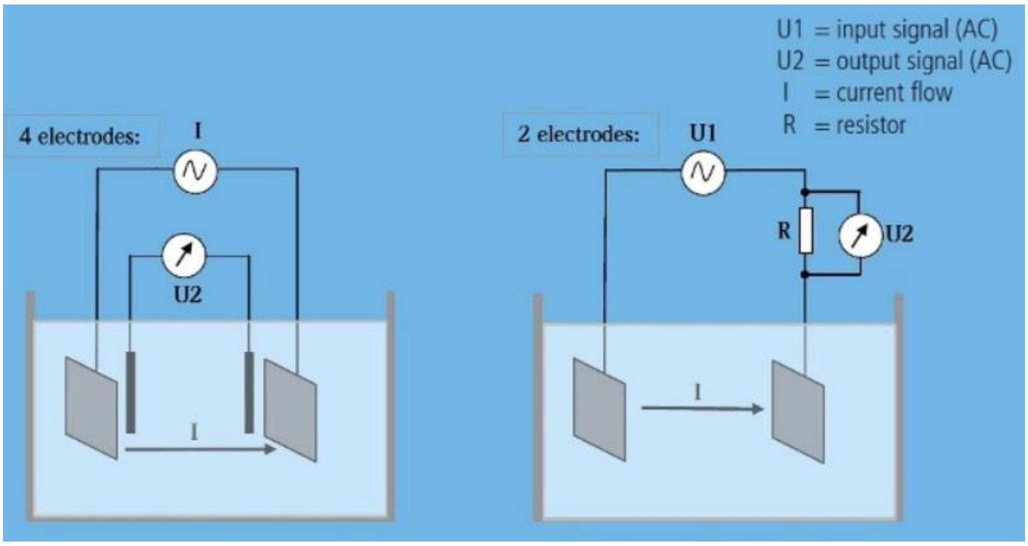


Figure 6: Electrode sensor layout [66]

4.4.2 Non-contact Conductivity Sensors

The primary non-contact water conductivity sensor is the toroidal (inductive) sensor, typically more expensive than the contact electrode sensors, but as the toroidal sensor does not have to come into contact with the water sample it reduces the probability of fouling and the lifespan of the sensor [59]. Toroidal sensors calculate the water conductivity by measuring the phase change between two signals and converting to an output voltage that gives the conductivity of the water [67], as shown in Figure 7. The toroidal sensor is a very precise method of sensing; however, electrical interference and signal loss can occur for toroidal conductivity sensors, which will result in inconsistency in the measurements.

A good example of how an inductive conductivity sensor works is given in "The Development of a Novel Capacitive Water Conductivity Sensor" [68]. A typical inductive water conductivity sensor works by magnetic induction or capacitance. The example provided measures water conductivity through capacitance: this is done by having a parallel plate capacitor connected to a circuit that acts as an electrical resonator and compares the resonant frequency changes that come from the parallel plate capacitor to determine the conductivity of the water.

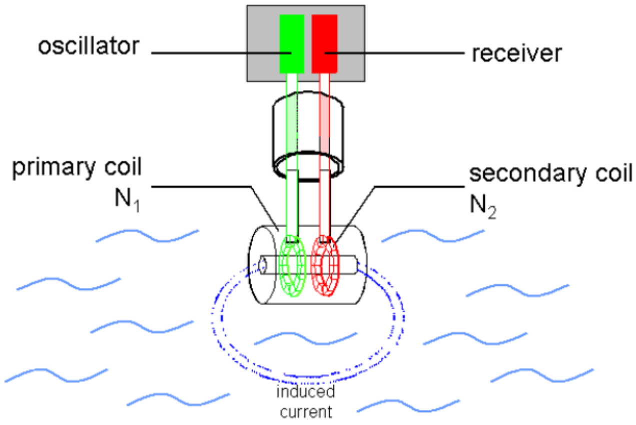


Figure 7: Inductive sensor layout [69].

4.5 Turbidity Sensors

Turbidity is an optical property of water that is caused by the dispersion of rays of light through suspended material in the water. The suspended material in water is typically made up of a mixture of sand, silt, clay, particulate organic matter, plankton, and other microorganisms [12]. Turbidity is a vital parameter of water quality as it measures the total suspended soils (TTS) in the water and is typically measured with optical sensors. Table 10 gives an overview of the commercially available water turbidity sensors as of 2020.

Table 10: Commercially available sensors

Sensor name	Sensing method	Supplier
Turbidity sensor	Optical sensor	ABB Measurement & Analytics [70]
Turbidity sensor	Optical sensor	Krohne Messtechnik [71]
Turbidity sensor	Optical sensor	METTLER TOLEDO [72]
Turbidity sensor	Optical sensor	Endress+Hauser AG [73]
Turbidity sensor	Optical sensor	KOBOLD Messring GmbH [74]
Turbidity sensor	Optical sensor	Xylem Analytics Germany Sales GmbH & Co KG – WTW [75]

As of 2020 most of the current research into turbidity sensors is into the design and development of novel turbidity sensors and turbidity monitoring systems, typically done through IoT.

The common turbidity sensor is a non-contact optical sensor that uses a photodetector which registers the intensity of the light scattered by solid particles suspended in the sample. The light emitted by the source collides with the suspended material in the water and is scattered without undergoing any change in its wavelength. The photodetector on the optical turbidity sensor receives the signal from the scattered light and converts this signal into electrical impulses [12]. The linear relationship between electrical impulse and the signal registered by the sensor makes it possible to use the scattered light signal to estimate the turbidity of water [76].

A good example of how a water turbidity sensor works is described in “Low-Cost Turbidity Sensor for Low-Power Wireless Monitoring of Fresh-Water Courses” [77]. Turbidity is typically measured using a phototransistor, positioned orthogonally to the direction of the original light [77]. The phototransistor measures the scattered light intensity, which is used to determine the turbidity. Turbidity is proportional to the scattered light intensity as described in Equation 10 [77], where T is the turbidity, I_{90} is the intensity of the light and k_1, k_2 are parameters that are set when calibrating the sensor.

$$T = k_1 I_{90} + k_2 \tag{10}$$

A novel type of turbidity sensor that is not as widely used as the standard photo-optic sensor is a chromatic sensor: a good example of this is described in “Turbidity and RI Dependency of a

Polymer Optical Fibre-Based Chromatic Sensor” [78]. The chromatic sensor is based on the air-gap multimode fibre-to-fibre transmission principle. When light transitions between two fibre optic cables the resulting air gap will create a conical dispersion of light where only a fraction of the light successfully transitions between the two cables, as shown in Figure 8.

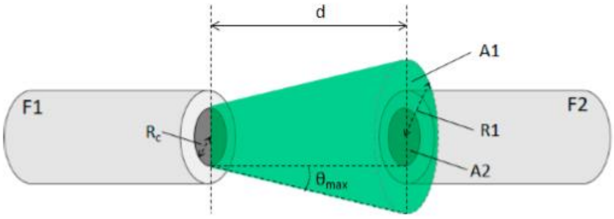


Figure 8: The light transitions between two fibre optic cables [78]

By submerging two perfectly aligned fibre optic cables in water the existence of suspended particles in the water will result in the scattering or absorption of light in the gap between the cables. Having a photodetector at 90 degrees to the gap will allow the sensor to determine the turbidity by comparing the expected light intensity with the recorded wavelength [78].

4.6 Nitrate and Phosphate Sensors

It is important to measure the levels of nitrate and phosphate (which are forms of Nitrogen and Phosphorus) in water bodies as excessive levels lead to algae growth and anoxia, which is a lack of oxygen caused by excessive nutrients in the water. There is a wide range of techniques used to measure the nitrate and phosphate levels in the water, with it commonly being performed by taking samples for lab testing. There is, however, a variety of field meters that can be used to measure the nitrate and phosphate levels in water in situ [79].

Table 11 gives an overview of the commercially available nitrate and phosphate sensors, as of 2020.

As of 2020 most of the current research into Nitrogen and Phosphorus Sensors is the development and analysis of different Nitrogen and Phosphorus Sensors and remote sensing method used to determine the Nitrogen and Phosphorus quantities in water.

Table 11: Commercially available sensors

Sensor name	Sensing method	Supplier
Nitrate analyser	Wavelength analyser	ABB Measurement & Analytics [80]
Nitrate analyser	Wavelength analyser	Aquas Inc. [81]
Nitrate analyser	Wavelength analyser	Teledyne Analytical Instruments [82]
Phosphate analyser	Colorimetric analyser	ABB Measurement & Analytics [83]
Phosphate analyser	Colorimetric analyser	Apura s.r.l. [84]
Phosphate analyser	Colorimetric analyser	Swan [85]

4.6.1 Common pH Nitrate and Phosphate Sensors

Typically, an electrode sensor is used to measure the nitrate and phosphate content in water. One of the common electrodes used to measure nitrogen and phosphorus is a copper electrode. Copper is used because its surface improves the electroanalytical performances of these electrodes, allowing the direct detection of nitrates and phosphates in the ten micromolar range [86]. The disadvantage of these electrodes is that they require an independent meter to measure the levels of nitrate and phosphate and an electrode sensor is limited to its sampling method, so the accuracy of the measurement decreases with the size of the body of water.

A good example of how a nitrate sensor works is described in “Nanowire-based Cu electrode as electrochemical sensor for detection of nitrate in water” [87]. Nitrate electrode sensors work by the reduction of nitrate at different electrodes, the correlation of the ‘cathodic peak current’ is used to calculate the concentration of nitrate in the water. Unfortunately, nitrate reduction can be influenced by the pH value of the water sample, which is why wavelength analysers are more commonly used than electrochemical electrode sensors.

A good example of how a phosphate sensor works is described in “A Portable and Accurate Phosphate Sensor Using a Gradient Fabry–Pérot Array” [88]. The levels of phosphate in water can be measured using a Fabry–Pérot array; the array consists of several optical reflectors that are spaced micrometres apart. When water is passed though the array the reflected emitted light changes its wavelength and the wavelength-dependent absorbance can be measured [89]. The phosphate in water causes a wavelength-dependent absorbance which can be measured by different types of colorimetric analysers.

4.6.2 Non-contact Nitrate and Phosphate Sensors

An optical colorimetric sensor can be used to measure the nitrate and phosphate content in samples of water by measuring the fluorescence. The fluorescence spectra of different metal ions in water differ sufficiently such that by measuring the fluorescence a meter can fingerprint spectrum data of various metal ions and also determine the quantities of nitrate and phosphate in water, an example of this is shown in Figure 9. A fluorescence array can identify up to 11 metal ions and distinguish different minerals in water with 100% accuracy [10].

The disadvantage of this sensor is that it is expensive and is best used on collected samples of water, however, this sensor can be handheld and so as long as it is connected to a meter to fingerprint the nitrate and phosphate quantities it is often easier to use on larger bodies of water than an electrode probe.

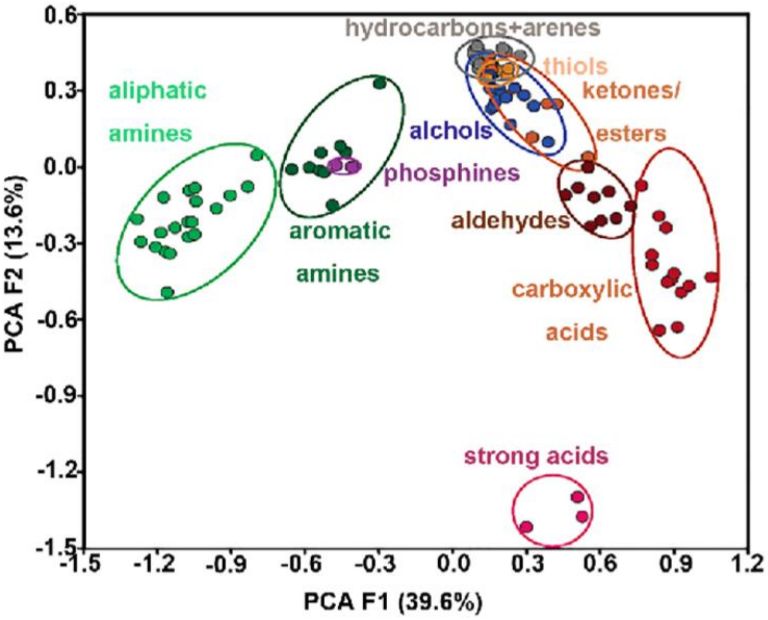


Figure 9: Example of an optical colorimetric showing the discrimination of the volatile organic compounds which can be used to measure nitrates and phosphates [10]

4.7 Escherichia coli Sensors

Escherichia coli (*E. coli*) is the best bacterial indicator of faecal contamination and is an important parameter for the hygienic bacteriological evaluation of fresh water, which is a vital standard in water quality assessments [90]. The detection of *E. coli* in water is important to predict the infection risk associated with surface waters and the water quality of recreational and industrial water facilities [16]. Table 12 gives an overview of the commercially available *E. coli* sensors, as of 2020.

As of 2020, most of the current research into *E. coli* sensors is into the detection of *E. coli* through different types of sensing methods and the development of novel sensors to measure *E. coli*.

Table 12: Commercially available E. coli sensors

Sensor name	Sensing method	Supplier
MicroSnap	Bioluminogenic test	Hygiena [91]
ELISA Kit	Enzyme-linked Immunosorbent	Bomatik [92]
ELISA Kit	Enzyme-linked Immunosorbent	MyBioSource[93]

4.7.1 Common E. Coli Sensors

Typically, *E. coli* is measured in a lab or clinical environment by taking a sample of water and using the b-D-glucuronidase chromogenic or the fluorogenic substrates of the water sample to find the biomarker of the *E. coli* [94]. Despite *E. coli* typically being measured in a lab, there are still sensors that can measure it in the field; for example, an electrochemical biosensor has been proven to be able to accurately detect *E. coli*. Electrochemical sensors work by measuring the metabolic activity of the *E. coli*. The electrochemical sensor has its surface specifically designed to measure the metabolic activity of the *E. coli* in water. The disadvantage of using an electrochemical sensor is that it requires samples to be taken and put through the sensor, which limits the accuracy in large bodies of water.

A good example of an electrochemical sensor for the detection of *E. coli* in water is described in "An electrochemical biosensor for rapid detection of *E. coli* O157:H7 with highly efficient bifunctional glucose oxidase-polydopamine nanocomposites and Prussian blue modified screen-printed interdigitated electrodes" [95]. The sensor described in this paper uses amperometric detection to characterize and detect the concentrations of *E. coli* in water; this method of detection is ideal as it gives accurate measurements within short detection times and can be used on-site, which excludes the need to transport water samples.

Despite the electrochemical sensors that have been proposed in multiple papers, the common method of measuring is still the lab method, a good example of which is described in "Elimination of Escherichia coli in Water Using Cobalt Ferrite Nanoparticles: Laboratory and Pilot Plant Experiments" [96]. The method described in this paper is one of the ways to test for

E. coli in a lab: to determine the concentration of *E. coli* in the water, samples are successively diluted by a ratio of 1:10. One millilitre of the final dilution is then filtered into a sterile membrane filter. The filter is then placed onto an absorbent sterile pad and embedded in a culture broth made from a lauryl sulphate solution. From this, the concentration of the *E. coli* in water can be determined after an incubation process at 40 °C for 16 h [96].

4.7.2 Non-contact E. coli Sensors

A fluorescence sensor can be used to measure the number of *E. coli* in water by using biochemical detection However, this method requires the incubation of water samples to get good linearity of the fluorescent signal [16]. The reason that *E. coli* measurements are done in the lab is that it is easier and more accurate through the clinical method. More research could be done in this area to develop a non-contact field sensor for the measurement of *E. coli*, but currently, it remains necessary to take the measurements in a lab environment.

5 Summary of Literature

The critical indicators that make up the necessary parameters required to determine the water quality of any given body of water are currently measured primarily using probe-based sensing. This method is very popular because the probe-based sensors are typically cheaper than their non-contact sensor counterparts and do not require long wait times that lab testing needs. However, water samples often need to be sent to labs for elements of the total testing programme, so investing in high-quality sensor technologies for field evaluations is often not deemed an acceptable expense. Each water quality parameter has a unique sensor and meter already on the market; however, there is no complete integrated system that allows for the full set of required parameters to be measured by the same device. A single device capable of reliably measuring the complete set of required parameters would significantly reduce the overall cost of water quality monitoring, increase field efficiency for the user and allow for autonomous water quality data collection and analysis.

When collecting water quality data, the sensors used need to be active for very long periods of time to collect a proper data set. This can be an issue for contact sensors as they can be interfered with or damaged by pollutants in the water. Non-contact sensors are ideal for collecting water quality data because the long exposure to water will not affect the data samples, and so to make an integrated water quality parameter measurement system it would be ideal to use non-contact sensors because they require less maintenance. However, non-contact sensors are significantly more expensive than the contact sensors and so an evaluation of the actual maintenance the contact sensors would need and the feasibility of some of the low-end non-contact sensors is needed. The water quality parameters of temperature and turbidity have simple non-contact sensors that can be easily integrated into a single system; however, the non-contact sensors for conductivity, dissolved oxygen, pH, nitrogen, phosphorus and *E. coli* are more complex and require a more complete system to analyse their outputs. It is possible that the dissolved oxygen, temperature, and visual clarity can be directly and readily measured while in the field, so these could be integrated into a single measurement system.

In summary, a staged approach at developing an integrated field device is recommended. Initially, it is recommended that the measurements of nitrogen, phosphorus, and *E. coli* be excluded from the device/system design at this stage. Lab testing would still be required for nutrient and biological indicators like the macroinvertebrates and periphyton and adding them to an integrated measurement system adds an unneeded level of complexity.

6 Research Methodology

To facilitate the development of an integrated sensing unit that can be deployed in the field for long periods of time collecting water quality data, an analysis is required of what types of sensors are the optimal solutions to use. To determine if low-end non-contact sensors can be recommended to make a cost-effective system, an analysis on how the sensors perform over long periods of time and a comparison between contact and non-contact sensors is required, as well as analysis of the sensor data looking at the variations of the sensors over time. To acquire the necessary data an experiment was proposed that would simulate the collection of surface water quality data in a controlled environment and give the opportunity to test the feasibility of a single integrated system that can collect the required water quality data.

The first part of this experiment was to determine the water quality parameters that would be measured and select the sensors that would measure them; this was based on the research done into contact and non-contact water quality sensors that has been summarised in Section 5.0. From this research it was decided to do a comparison of the contact and non-contact sensors for pH, electrical Conductivity, and temperature, while doing a comparison of the variation of the sensors for turbidity and total dissolved solids (TDS) which is an alternative measurement to measuring the nitrogen and phosphorus in the water. TDS does not tell you if the water is safe to drink as there are healthy minerals in water such as potassium, magnesium, and calcium that contribute to the TDS value. However, TDS is still an important measurement of water quality to measure having too much TDS in water no matter what they are can be hazardous.

The second part of the experiment was to set up an environment that would simulate a source of surface water that could be analysed in a controlled environment where the actual values of the water quality parameters would remain consistent. That way, measurements of the water sample could be done and variations in the measurements could be analysed to determine the optimal sensor type to use.

The third part of the experiment was to assemble all the sensors into a single integrated unit that could output the sensor data to a single source. This was done by designing a custom sensor box that held all the sensors such that they could measure the flowing sample water. The data collection of the sensors was set up by connecting to a microcontroller that converted the sensor readings to a string of serial data that was appended to a CSV file every minute. The exception to this was in the use of the inductive conductivity sensor, which required MODBUS communication, so the sensor was set up as a MODBUS slave and connected to a MODBUS master that appended its value to a CSV file every minute. The layout for this setup is shown in Figure 10.

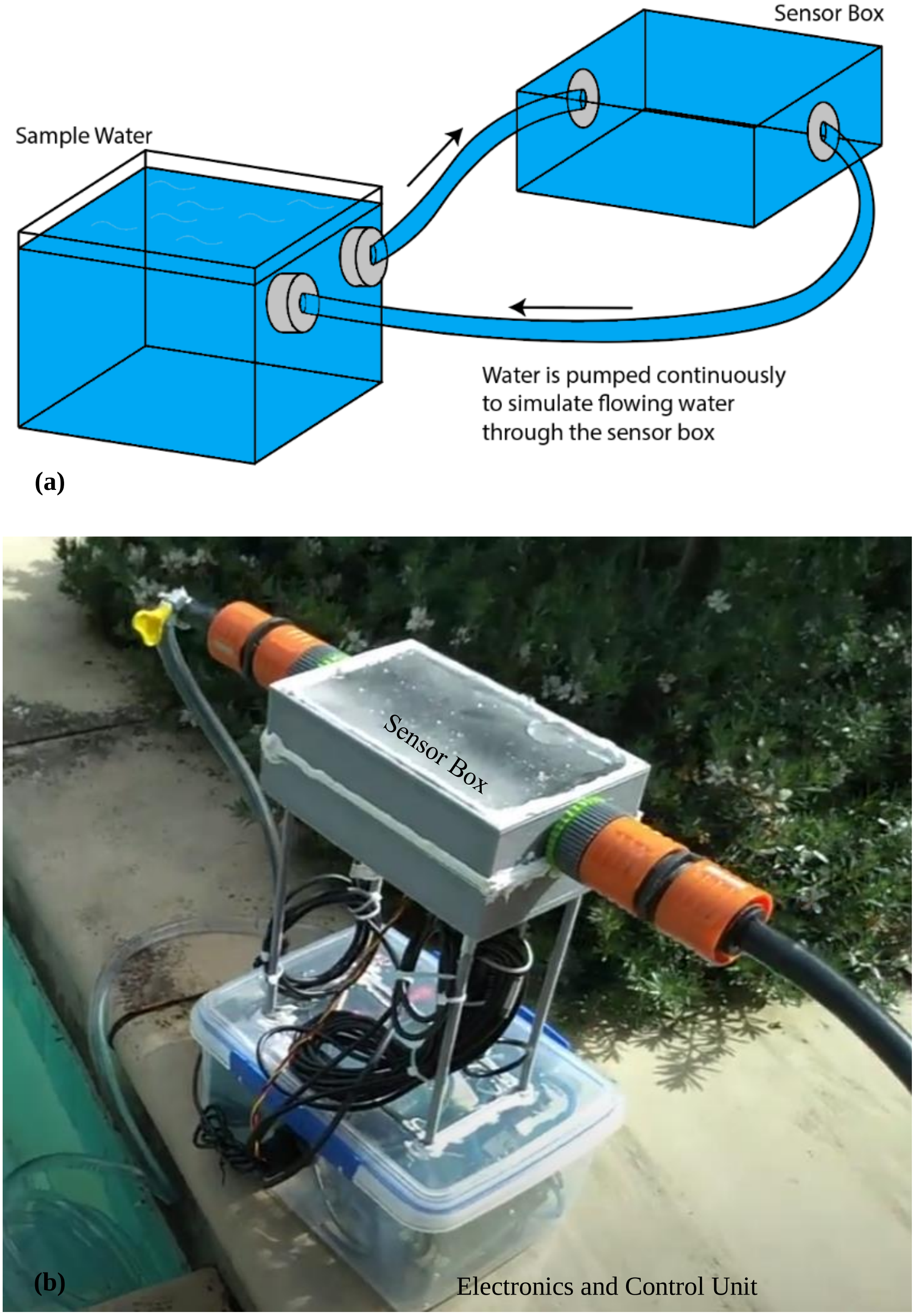
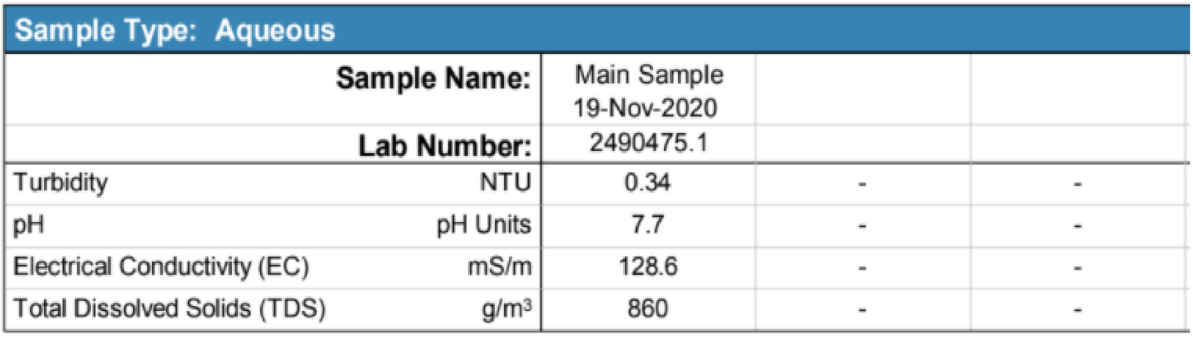


Figure 10: Experimental setup. a) Basic function diagram, b) Actual measurement system

The final part of the experiment was to source a sample of surface water to be used in this experiment and determine the actual values of the water quality parameters that were being analysed. This would allow for there to be a reference to compare the sensor values against. A sample of the surface water was taken and sent to Hill Laboratories, a privately owned analytical testing laboratory, which independently measured the water quality parameters of the sample water, the results of which are shown in Table 13.

Table 13: Results from lab test of sample water



Sample Type: Aqueous				
	Sample Name:	Main Sample 19-Nov-2020		
	Lab Number:	2490475.1		
Turbidity	NTU	0.34	-	-
pH	pH Units	7.7	-	-
Electrical Conductivity (EC)	mS/m	128.6	-	-
Total Dissolved Solids (TDS)	g/m^3	860	-	-

For the selection of the sensors to be used in the proposed experiment, a wide range of commercial sensors were reviewed, and the choice of the selected sensors was based on how well they fit into wah could be consider cost effective for long term data collection. The validity of the ‘Sensor Type’ criterion was based on the research into existing literature and the current commercially available sensors. The criterion ‘Recommended Use’ was based on the sensor specifications provided by the manufacturer which outlines the conditions the sensor should be used in. The ‘Sensor Price’ criterion was added due to most of the commercially available sensors having prices that are outside the budget range for this research, and such considerations had to be made. An overview of the analysis of the sensors considered is shown in Table 14.

Table 14: Sensors considered for research comparison

	Sensor Type	**Price (*NZD)***	**Recommended Use**	**Source**
pH Sensor	Optical pH Sensor	6630	Moderate and Versatile Applications, Limited pH Range	Pyro Science
pH Sensor	Electrode Sensor	80	Swimming pools	Sensorex
pH Sensor	Electrode Sensor	78	Moderate and Versatile Applications	Gravity
pH Sensor	Differential pH Sensor	1073	Wastewater	Sensorex
pH Sensor	Process Electrode Sensor	330	Versatile use, Long-term submersion	Sensorex
Conductivity Sensor	Toroidal Conductivity Sensor	729	Harsh immersion Applications	Sensorex
Conductivity Sensor	Titanium Pressure Resistance Electrode	1047	Harsh immersion Applications	Mettler Toledo
Conductivity Sensor	Analog Electrical Conductivity Sensor	140	Laboratory Applications	Gravity
Conductivity Sensor	Inductive Conductivity Sensor	1256	Chemical and industrial Applications	Mettler Toledo
Temperature Sensor	Infrared Temperature Sensor	415 NZD	Versatile Applications, −20 °C to 500 °C	Calex Electronics Limited
Temperature Sensor	NTC Thermistor	43 NZD	Versatile Applications, −60 °C to 150 °C	RS Pro

	Sensor Type	**Price (*NZD)***	**Recommended Use**	**Source**
Temperature Sensor	RTD Probe	140 NZD	Versatile Applications, −30 °C to 180 °C	Intech Instruments
Temperature Sensor	MEMS (Micro-Electro-Mechanical-Systems) Photoelectric Sensor	70 NZD	Versatile Applications, 5 °C to 50 °C	Omron
Temperature Sensor	Type K Thermocouple	75 NZD	Versatile Applications, −60 °C to 350 °C	RS Pro
TDS Sensor	Analog TDS electrode Sensor	17 NZD	Versatile long-term immersion applications	Gravity
TDS Sensor	HM Digital Single TDS Meter	50 NZD	Versatile long-term immersion applications	TRU Water
TDS Sensor	Analog TDS electrode Sensor	12 NZD	Versatile applications	Grove
Turbidity Sensor	Analog Turbidity Sensor	25 NZD	Versatile long-term immersion applications	Gravity
Turbidity Sensor	Optical turbidity sensor	8500.00	Industrial wastewater Use	METTLER TOLEDO

This experiment was set up to run for a total of 20 days with a measurement reading taken every minute, totalling around 30,000 recorded water quality measurement from each sensor used. This data was then correlated into graph to view the variations over time. In conjunction with this experiment an analysis of the physical sensor was performed before, during and after the experiment to evaluate if there was any fouling on the sensor due to it having long-term exposure to the sample water. This was done by taking photos of the measurement instrument of the sensor before and after the experiment, as well as a photo of the sensors instrument every five days of the experiment.

The purpose of the experiment was to determine which types of sensors are best to be used in an integrated water quality measuring system, rather than using pre-existing literature which describes the benefits and disadvantages of contact and non-contact sensors. The literature on this topic does not account for an integrated system of sensors being used nor for potential defaults in the low-end sensor market. As a result, literature on the benefits of contact and non-contact sensors fails to consider whether the sensors will affect each other’s readings and the individual sensor defects. Therefore, if the recommendations of existing literature were used without an independent test the result would be a very expensive sensing unit that has not been fully validated. Similar approaches have been taken in similar research such as “Measuring surface water quality using a low-cost sensor kit within the context of rural Africa” [97] and “Design of Smart Sensors for Real-Time Water Quality Monitoring” [98], both of which have similar methods to this experiment, and have taken a sensor recommended in the literature but understood the need to test the sensors for a specific use. The proposed research method looks to not only validate some of the existing literature on contact and non-contact sensors but also examine if the best sensors that are recommended in the literature are in fact the best to use in practice by analysing them against their counterparts. This experiment also looks at the variations that can be expected in some of the more affordable sensors and if those variations are acceptable to bring down the price of water quality sensing.

6.1 pH Sensor Comparison

The two types of pH sensor chosen were two variant types of pH electrodes, the first being the most common pH electrode currently used (the glass bulb pH electrode) and the second a flat glass electrode which is designed to be resistant to external fouling on the sensor and damage to the electrode. The pH sensors that were selected for comparison were the NZD 78 Electrode sensor from DF Robot and the NZD 330 Process Electrode Sensor from Sensorex. These sensors were chosen because they are not overly expensive and provide a good comparison between a common glass bulb electrode sensor and a commercial grade flat glass electrode sensor. From this comparison of sensors, we can analyse how significant the impact of external fouling is on the sensor and the difference in internal reference decay between the sensors. This should provide a good reference as to whether the improved performance in measuring surface water is worth the extra cost of the Sensorex sensor. One of the biggest supposed issues with the cheaper electrode sensor is external fouling of the bulb, as the glass of the bulb is very thin to allow the ions in the electrode to react with the ions in the water. As a result, external fouling and damage to the bulb is an issue that affects the accurate measurement of the pH value. The hypothesis of the evaluation of this sensor was that there would be external fouling on the glass bulb electrode sensor that would affect the measurement of the pH value, resulting in a large variation in the result between the two sensors.

The non-contact type sensor chosen for this experiment was a flat glass electrode sensor. This sensor was chosen as the non-contact alternative because true non-contact methods of pH sensing is done via fluorescent sensors, as described in Chapter 2, and using such a sensor for this experiment is not practical. Instead, the flat glass electrode sensor was chosen for the comparison specifically to see how much of an issue external fouling is in the long term. It is a flat glass pH sensor which is resistant to external fouling because the flat surface allows for the natural flow of the water to clean the surface of the electrode, and the reduced surface area reduces the risk of damage. The hypothesis of the evaluation of this sensor was there would be no external fouling on this sensor and that there would be no deviation in its results.

The purpose of this comparison is to see if the standard glass bulb electrode pH sensor weakness of being susceptible to external fouling affecting the measurements of the pH value is an issue when used for water quality testing over long periods of time.

Some important considerations to be made when evaluating the results of the pH sensors is that the pH electrodes used in this case study are the type that have an internal reference electrode and, as such, the pH reading might degrade over a long period of time, which should not be an issue in this experiment. This degradation happens because the internal electrode calibration and the electrolyte solution will, over time, deviate from its set value as the electrolyte solution is contaminated or diluted. This can be fixed by simply re-calibrating the sensor, and most sensors of this type are designed for a certain number of cycles before maintenance is required to recalibrate the sensor. There are ways around this issue with a popular one being a differential pH sensor; this type of sensor has a measurement system that removes the ground loop error and combined with a buffered electrolyte solution compensates for the internal reference change, and an accurate pH reading can be measured even with some continuation and/or some dilution.

6.1.1 Glass Bulb Electrode

The glass bulb pH electrode has a bulb-like shape to maximise the surface area of the sensor. It works by having a glass bulb that is filled with a buffer solution of a known pH value. An electrode connected to a fixed voltage supply is then submerged in the solution to act as the anode. The cathode of this sensor is the glass bulb itself, which is made of a sensitive glass membrane with low impedance. This allows the ions in the buffer solution to react with the ions in the water. The reaction between the ions produces a change in voltage that is measured to calculate the pH value of the water, as shown in Figure 11.

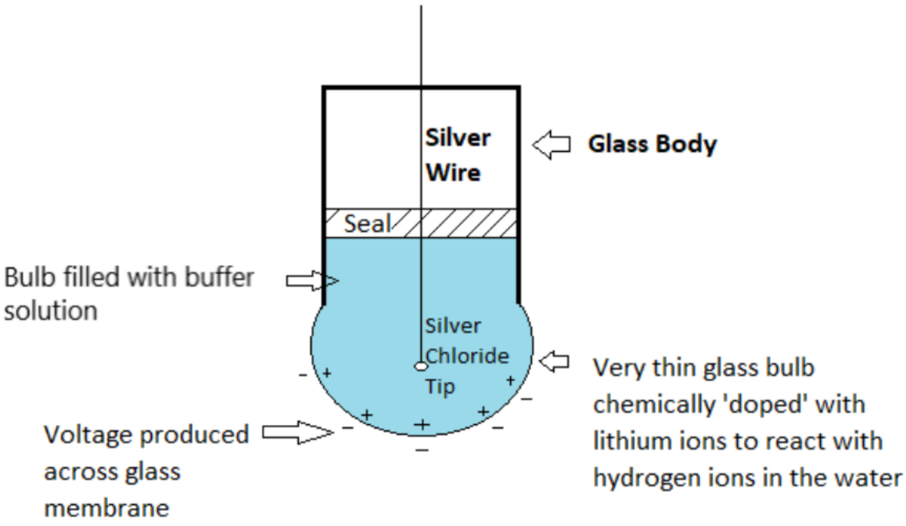


Figure 11: Glass bulb pH electrode

6.1.2 Flat Glass Electrode

The flat glass electrode has the same measurement system as the glass bulb electrode except where the glass bulb electrode is made of a thin glass membrane that is vulnerable to external fouling, the flat glass electrode is designed with its measurement surface flat, shown in Figure 12. This reduces the surface area making its sampling ratio smaller; however, it removes the vulnerability to external fouling.

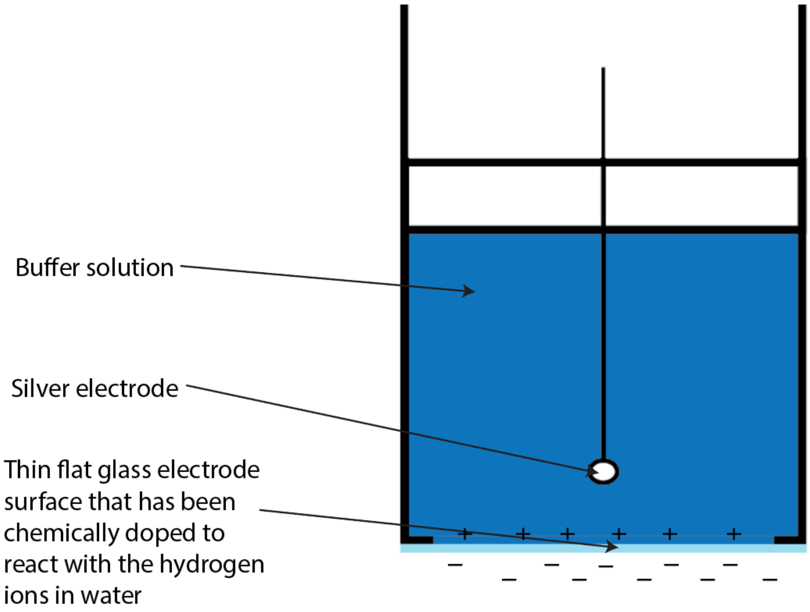


Figure 12: Flat glass pH electrode

6.2 Conductivity Sensor Comparison

The two types of conductivity sensors that were chosen for this experiment were a common electrode electrical conductivity sensor and an inductive coil electrical conductivity sensor. The conductivity sensors that were selected for comparison were the Toroidal Conductivity Sensor from Sensorex and the Analog Electrical Conductivity Sensor from Gravity. These sensors were chosen because they are representative of the low-end sensors on the market for their sensor type and will provide a good comparison between an electrode conductivity sensor and an inductive conductivity sensor. The purpose of this test will be to compare how the sensor readings are affected by long-term immersion in water and to see what benefits the inductive sensor provides for its extra cost. From this it will be possible to recommend if it is necessary or beneficial to have a non-contact electrical conductivity sensor as part of an integrated water quality system. The hypothesis of this comparison was that the electrode conductivity sensor would have a gradual deterioration in its results because of electrode decay resulting in an inaccuracy in the conductivity calculation of the sensor since the initial calibration of the sensor is no longer valid. This will result in a large variation between the results of the two sensors.

An important consideration when comparing the results of the two electrical conductivity sensors is that both sensors require a manual pre-calibration before use, which is susceptible to variation as the calibration is based on knowing the exact electrical conductivity of the calibration solution.

6.2.1 Electrode conductivity sensor

The electrode electrical conductivity sensor works by connecting the first electrode to a direct current source and then measuring the change in current output from the second electrode using an equation like the one shown in Equation 11. Figure 13 shows a standard layout for how this works.

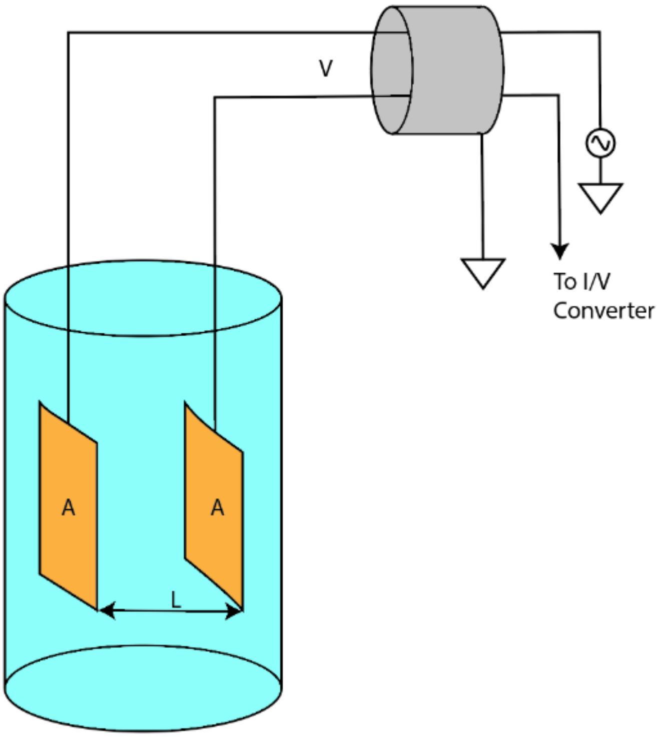


Figure 13: Electrode conductivity sensor layout

L = Distance between electrodes

A = surface area of the electrodes

I = Direct current value

V = Output voltage

$$E_C = (L \div A) * (I \div V) \tag{11}$$

6.2.2 Inductive Conductivity Sensor

The inductive (toroidal) conductivity sensor works by having two coils: one to induce a current in the liquid and one to measure the current: the difference between the induced current and the received one is how the inductive toroidal sensor measures the electrical conductivity, which is shown in Figure14.

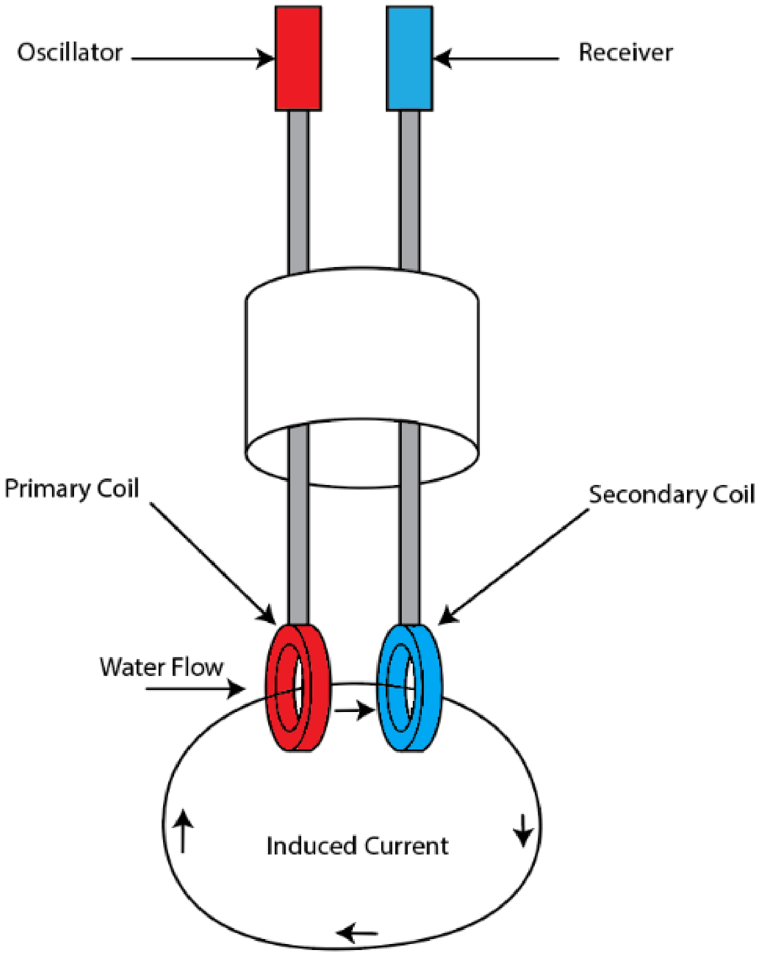


Figure 14: Inductive conductivity sensor layout

6.3 Temperature Sensor Comparison

The two types of temperature sensors used in this comparison were a common negative temperature coefficient (NTC) thermistor probe and a photoelectrical temperature sensor. The temperature sensors that were selected for comparison were the NTC thermistor sensor from RS Pro and the MEMS Photoelectric Sensor from Omron. These sensors were chosen because they are representative of the low-end sensors on the market for their sensor type and will provide a good comparison between a standard contact temperature probe and a non-contact temperature sensor. The purpose of this comparison is to see if there is any variation between the contact and non-contact readings and to see if there is any benefit to using the non-contact sensor type, an example of this being no external fouling on the contact probe. The hypothesis of this comparison is that the non-contact photoelectric sensor will not be sensitive to minor changes in the water temperature and so its results will have a much smoother and less accurate trend curve than the thermistor's results.

6.3.1 Thermistor Temperature Sensor

The thermistor used in this experiment was sourced from RS Components and is an NTC liquid temperature probe. This type of thermistor works by being connected to a direct voltage source and measuring the voltage change across the thermistor. Because this sensor is an NTC thermistor the resistance of the thermistor decreases with increasing temperature. The electrical layout of how this works is shown in Figure 15.

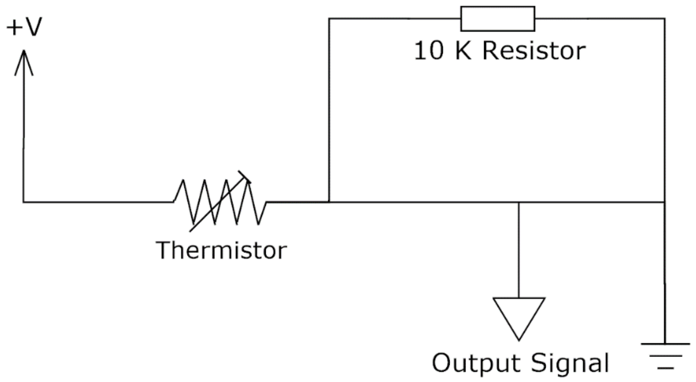


Figure 15: Thermistor electrical layout

6.3.2 Photoelectric Temperature Sensor

The sensor chosen for this test is the Omeron D6T-44L-06 thermal sensor; this is a photoelectric sensor that works by having 4 × 4 array of sensor readings that output a total of 16 temperature values. The total temperature is calculated by taking an average of the total.

The D6T-44L-06 thermal sensor is a Micro Electro-Mechanical System (MEMS) that has 16 output channels in a 4 × 4 array that detects the change in infrared radiation, as shown in Figure 16. The calculation of temperature is based on an average of all the cells, which is compared against a reference heat source in the sensor.

An issue with this measurement method is that distance becomes a factor in the fluctuations in temperature values, since the area of the field of view affects the number of channels in the array that are recording a heat source.

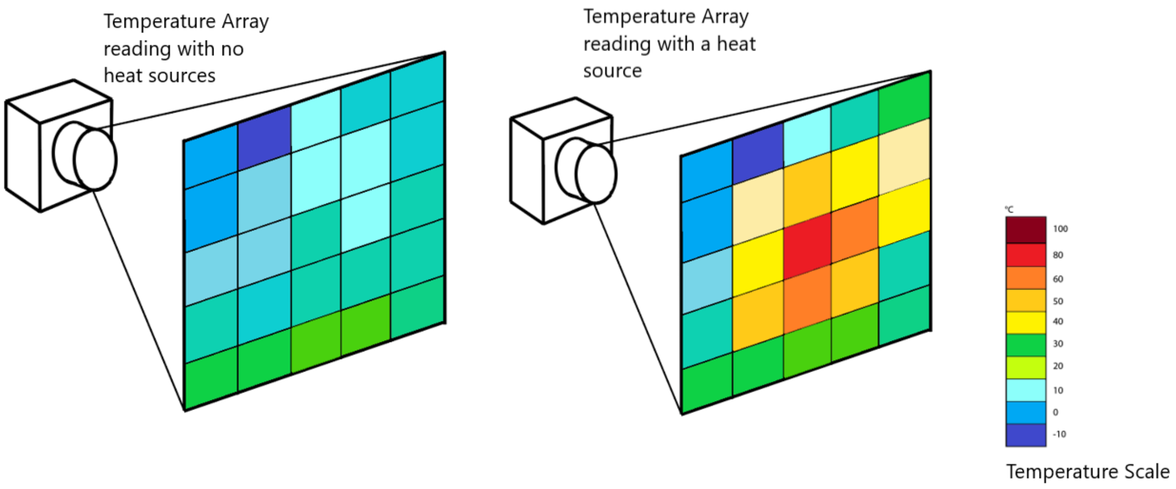


Figure 16: MEMS temperature detection array

6.4 Turbidity Sensor

The turbidity sensor that was chosen to test the reliability of the more affordable options for turbidity sensing was the Analog Turbidity Sensor from Gravity. This sensor was chosen because it is a cheap sensing solution that is designed for long-term immersion in water, making it the perfect sensor to test if there are any drawbacks to this cheaper range of turbidity sensor. The purpose of this comparison is to look for defects in the sensors to see if it is necessary to have industrial grade turbidity sensor or if the cheaper range of turbidity sensor would be an acceptable substitute in an integrated water quality system. The hypothesis of this comparison was that there would be minimal or no variation in the results and that the cheaper range of turbidity sensor would be satisfactory for use in an integrated sensor system.

The turbidity sensor works by shining a light or laser beam through the water and measuring the scattering in the diffraction ratio. The circuit is shown in Figure 17.

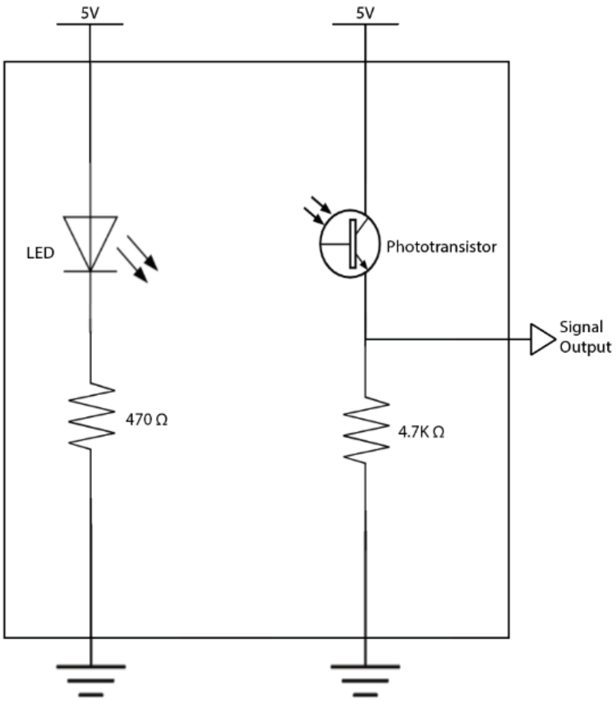


Figure 17: Turbidity sensor electrical layout

6.5 TDS Sensor

The TDS sensor that was chosen to test the reliability of a cheap contact electrode was the Analog TDS Electrode Sensor from Gravity. This sensor was chosen because not only is it a cheap solution, but it is also designed for long-term immersion in water, making it the perfect sensor to test if there are any variation issues in the sensor readings. This comparison was done between two of the same sensors from Gravity, the purpose of this comparison is to see if the cheaper sensing solution has any drawbacks that would exclude it from substituting for a more expensive option in an integrated water quality system. The hypothesis of this comparison was that there would be minimal or no variation in the results, because both were the same make, and that the cheaper range of TDS sensors would be satisfactory for use in an integrated sensor system.

The TDS works by measuring the conductivity between the electrodes and determining the TDS based on the difference between the anode and the cathode, as shown in Figure 18. Dissolved solids increase the conductivity of the water so the total dissolved solids can be determined by the conductivity.

It is important to note that the TDS does not measure contaminants, nor does it tell you if the water is safe to drink as there are healthy minerals in water such as potassium, magnesium, and calcium that contribute to the TDS value. However, TDS is still an important measurement of water quality to measure having too much TDS in water no matter what they are can be hazardous. The purpose for the TDS sensors in this experiment is to compare the differences in the sensor result to see what type of variation can be expected between sensors.

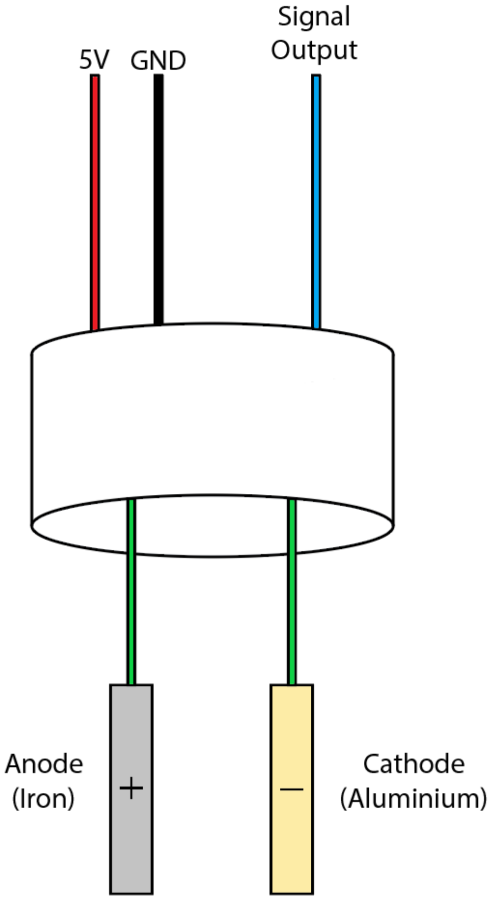


Figure 18: Total dissolved solids (TDS) electrode

7 Results

7.1 pH Sensor Results

An evaluation of the two pH sensors before during and after use showed that there was no external fouling on either of the sensors; this suggests that for analysis of water that does not have high amounts of corrosive chemicals (such as wastewater) then external fouling will not be an issue that will affect the sensors' measurements.

The results of the two sensors, shown in Figure 19, have both sensors within an acceptable pH measurement range from 7.85 to 8.02, and with the lab test of the sample water measuring a value of 7.7, the overall measurement of both sensors was consistent and accurate. The only major difference between the two types of pH sensor shown in the results is that the glass bulb pH sensor is more sensitive to minor changes in the pH value.

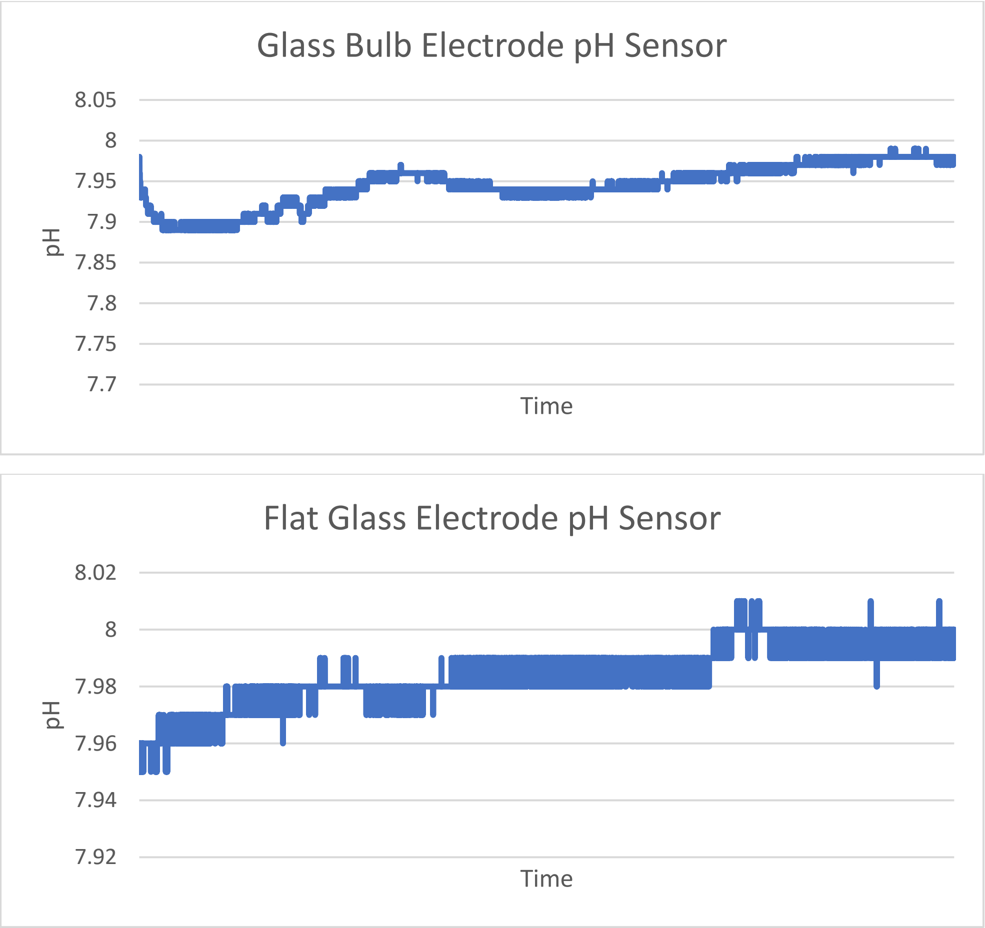


Figure 19: Results from the pH sensor comparison

7.2 Conductivity Sensor Results

An evaluation of the conductivity electrode sensor before, after and during use showed some very minor external fouling on the surface of the glass shield of the electrode, which appeared 15 days into the experiment. This fouling was in the form of a very minor build-up of particulates on the electrode, which could be cleaned off during the post-test examination of the sensor. This fouling may have contributed to the variation in the sensors results as shown in Figure 20; however, it was too minor to affect the results in a major way. The data collected from the experiment was correlated into graph form and is shown in Figure 20, showing a large variation between the two sensors.

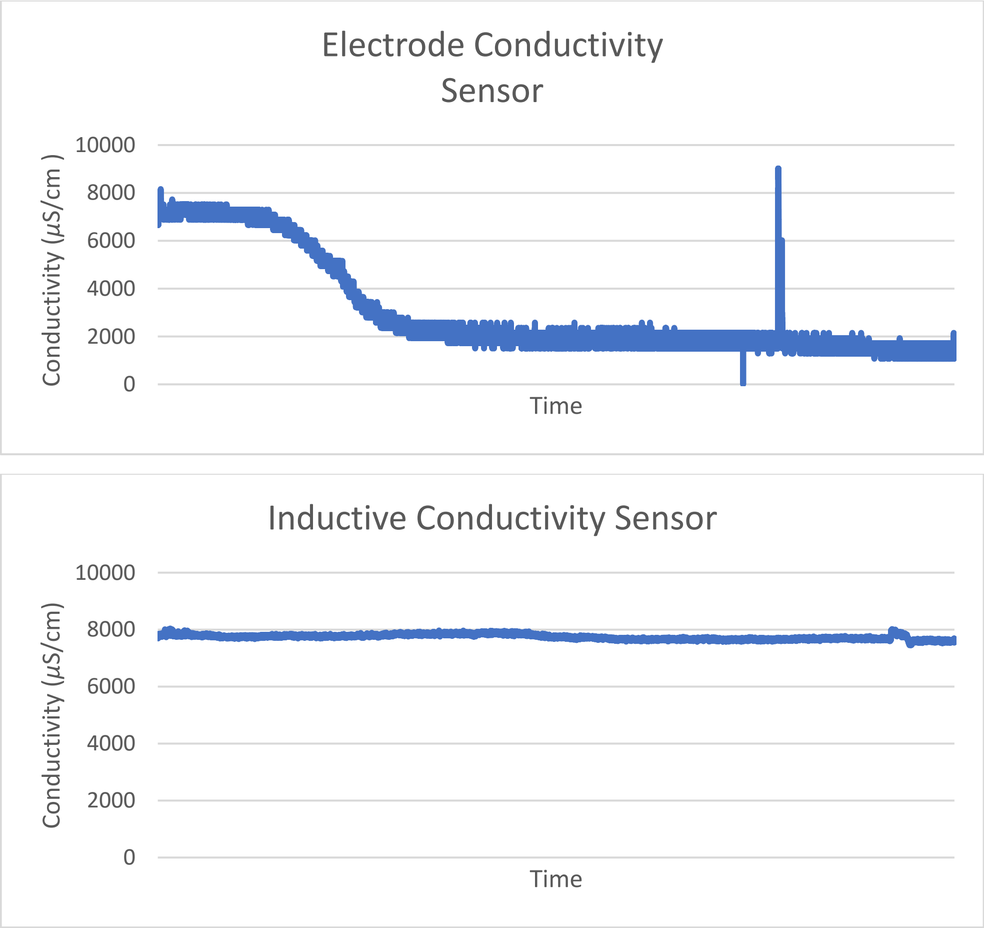


Figure 20: Results of the conductivity sensor comparison

The electrode conductivity sensor’s result showed a decay over time, where it started at the correct electrical conductivity (EC) value of between 7000 and 8000 μS/cm but within the first five days of the experiment it started to drop down to 2000 μS/cm where it remained for the rest of the test time with two major outlying measurements that can be seen as spikes in the data.

The inductive conductivity sensor showed a consistent measurement trend with the sensor readings fluctuating between 7500 and 8000 μS/cm, an acceptable range of variation given the possibility for other factors affecting the EC value of the sample water.

Also, the sensor results are different from the lab tested sample of the water. The lab tested water shows that the EC of the water used in this experiment was 1286 μS/cm and the base sensor reading of the water was 7800 μS/cm.

7.3 Temperature Sensor Results

An evaluation of the thermistor temperature sensor before, after and during use showed that there was no fouling on the surface of the sensor affecting the results of the temperature readings. An evaluation of the photoelectric sensor when setting up the experiment showed that because the sensor looks for changes in the infrared radiation, there could be issues with results, as water is a clear liquid that produces minimal infrared radiation to be observed. To compensate for this, it was proposed to put a thin piece of copper submerged in the water stream that took up all the sensors field of view so that the sensor would be measuring the temperature of the copper sheet, which in turn would be determined by the water temperature. However, it was decided to run it without the copper sheet to see if the result of the contact and non-contact sensor were vastly different.

The results of the two sensors' measurements over 20 days are shown in Figure 21, and it can be seen that, contrary to the hypothesis, the non-contact photoelectric sensor would not perform well when used to measure water temperature. The comparison between the results of the two sensors, shows that the temperature readings between the two sensors were consistent with the thermistor being more susceptible to minor changes in temperature than the photoelectric sensor.

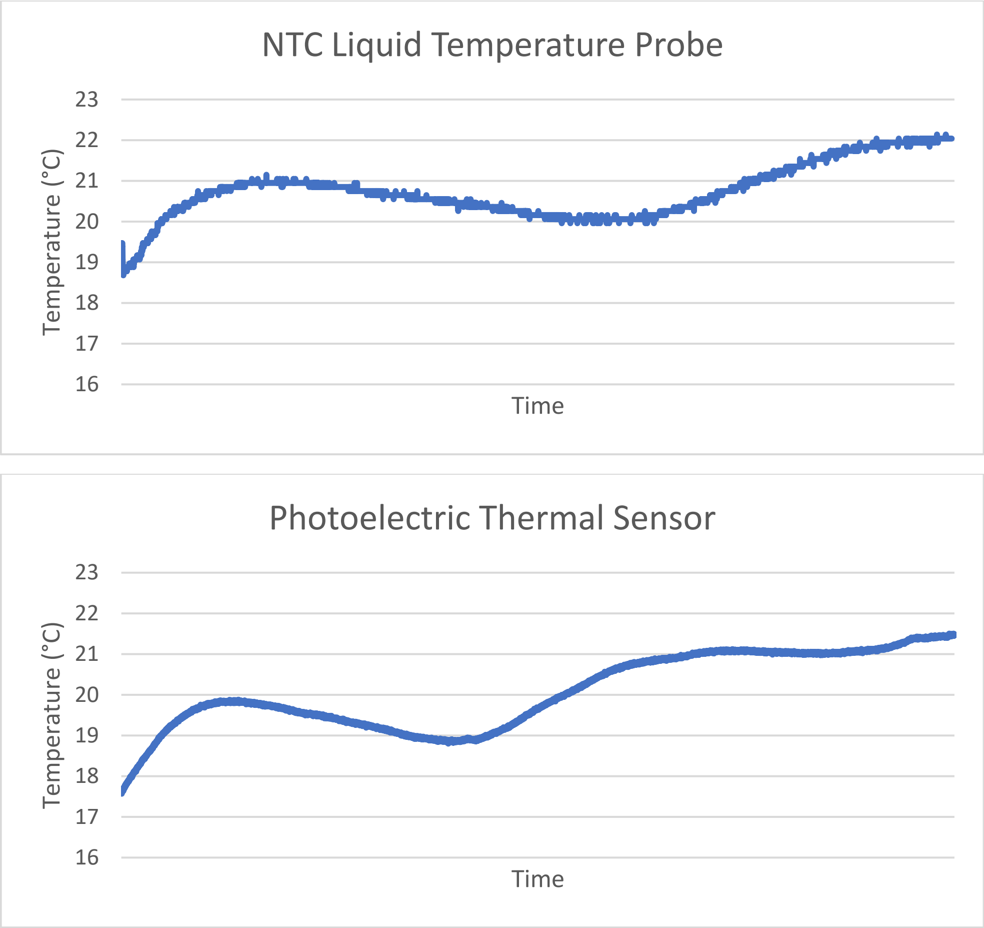


Figure 21: Results of the temperature sensor comparison

7.4 Turbidity Sensor Results

An evaluation of the turbidity sensor before use showed that the cheaper turbidity sensor does not come without issues, as it is not properly water sealed and water can get into the electronics from where the wires attach, shown in Figure 23. A water sealant paste was applied to the back of the two identical sensors being used in this experiment, which fixed the issue. The results of those sensors are shown in Figure 22, and show a variation range of 0.2 NTU, which, despite not being insignificant on the NTU scale, is not a major variation.

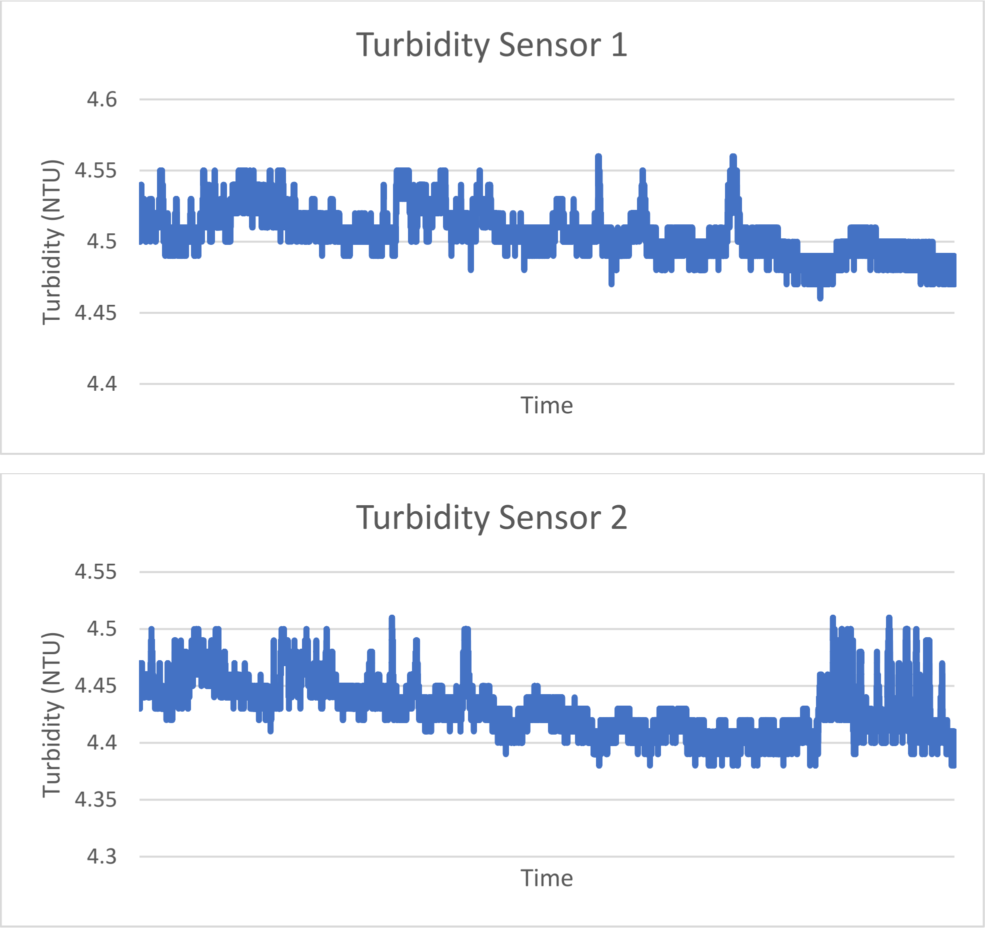


Figure 22: Results of the turbidity sensor comparison

To test if the water sealant was a necessary, a third turbidity sensor was added to the sensor box without the sealant. When the experiment started, the flowing water resulted in a small amount of water getting into the exposed parts of the turbidity sensor. The result shown in Figure 24 show that due to the sensor having exposed elements the small amount of water that gets into it ruins its measurement capability.

Figure 23: Flaw in the turbidity sensor

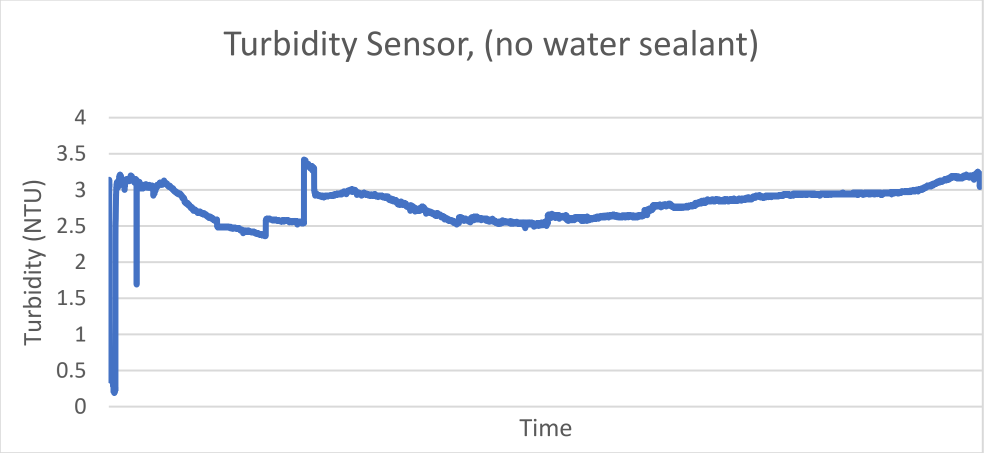
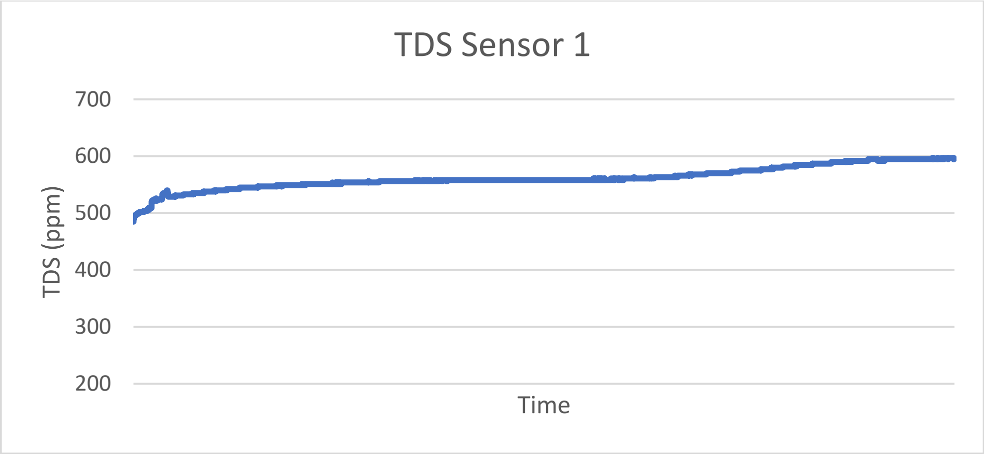


Figure 24: Results of the turbidity sensor without added water seal

7.5 TDS Sensor Results

The comparison between the two identical TDS sensors showed a surprising amount of variation between the sensors. As shown in Figure 25, the first sensor started its measurements at 500 ppm and over the 20-day trial incrementally increased to 600 ppm, whereas the second sensors result started its measurements around 320 ppm and incrementally increased to 500 ppm by the end of the 20-day trail. While the sensors follow similar trends, their reading are significantly different and with no signs of external fouling and both sensors sampling the same water there is variation between the sensor reading themselves.



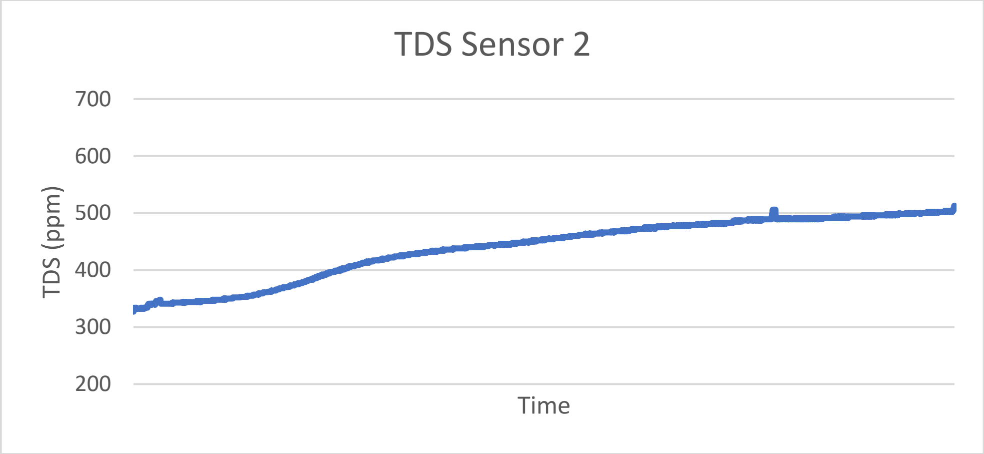


Figure 25: Results of the TDS Sensor Comparison

8 Discussion

The purpose of this experiment was to determine what type of sensors were better to use in an integrated water quality sensing unit, contact or non-contact sensors. The result of the sensors indicate that it may be necessary to use non-contact sensors in integrated sensor systems for some variables like conductivity and that the extra expense of a non-contact sensor is sometimes not justified, as in the case of temperature.

8.1 pH

The results of the pH sensor comparison, described in Section 7.1, show that there is minimal variation between the two sensor results and no external fouling on the sensors. This did not match the hypothesis of this comparison as external fouling was expected to happen on the glass bulb electrode sensor and this would affect the pH measurements. Since external fouling did not happen the hypothesis of this comparison was wrong and, as shown in the results, there was very little variation between the sensors. This means that for water quality measurements of surface water there is no need to have a flat glass electrode to minimise the effects of contaminants in the water affecting the measurements. When selecting the pH sensor to be used in an integrated water quality sensing unit, a standard glass bulb pH electrode is an acceptable sensor to be used and the extra expense of an industrial grade pH sensor, which can measure pH in a highly contaminated environment, is not justified.

The results from this comparison conform with existing research such as “pH effects on the adherence and fouling propensity of extracellular polymeric substances in a membrane bioreactor” [99], which comments that fouling happens at a significantly higher rate when in high pH liquids such as wastewater, and that the relation between pH elevation and is shown to be a result of extracellular polymeric substances conformation and swelling, which means that in average surface water such as rivers and lakes, fouling on the pH sensor should not be an issue. However, unlike what has been done in previous research this comparison was done between two different types of glass electrode sensors, looking at whether external fouling is an issue and currently there is a lack of research looking at this specific issue.

This comparison provides insight into the effects of external fouling on glass electrode sensors, as it suggests that external fouling is not an issue for glass pH electrode sensors when measuring surface water. However, this comparison was done as part of an experiment that only lasted 20 days, and as such it cannot be conclusively shown that external fouling does not have an effect on glass electrodes when measuring surface water, as it might take effect after a longer period.

Also, the sample used was a standard sample of surface water that might be found in rivers or lakes, and it is possible that under more extreme conditions a sample of surface water might produce external fouling on the glass electrode. However, it is beyond the scope of this study to examine how different samples of surface water affect the pH sensors, although it is an area of further research that needs to be done to determine conclusively if it is better to use a glass bulb electrode sensor for an integrated water quality sensing system.

8.2 Conductivity

The results of the conductivity sensor comparison described in Section 7.2, show a major variation between the results of the two sensors. The reason that there is such a major variation in results between the contact and non-contact sensors could be ascribed to several reasons, the first being the external fouling found in the evaluation of the sensor. There could have been a discrepancy in the calibrations of the sensors that resulted in the two sensors running at different scales, however both sensors' readings started at the same value and vary over time, suggesting an issue with the sensing method rather than the calibration. The results from the comparison are in line with the hypothesis, which was that the electrode conductivity sensor would have a gradual deterioration in its results, although the hypothesis predicted a gradual decay. What we see in the result of the electrode sensor is a steep initial decay that levels out, which happened much faster than has been previously reported in literature. This is most likely due to the sensor used in this experiment, which is not designed for long-term submersion.

The results also showed a discrepancy between the lab results and the sensor results, due to a calibration error of the sensors. There are two reasons why the EC measured by Hill labs is different to the sensor readings: the first is a difference in the calibration of the sensors, which has to do with scale, as there was only two points of reference in the calibration the sensors which had a uniform scale between EC values. Because of this, the trends shown in the results of this comparison are accurate; however, the actual values differ from those measured at Hill Labs. The second reason for a difference between the EC results of the Hill labs and the sensor readings is that the electrical conductivity of the water increases as temperature increases, and there are compensations in the conductivity sensors to account for the temperature variable. However, the matrices used in the sensors may have variation between them which would result in the temperature of the water having different effects on the EC value.

What the results of this comparison show is that the inductive sensor is more sensitive to minor changes in the EC value of the water, due to the induced current of the sensor measuring a larger area of the water than the electrode sensor, and that the electrode sensor requires periodic calibration, and, as such, the electrode sensor is not suited to long-term submersion. The results suggest that it is best to use non-contact sensors when measuring the electrical conductivity of the water for long periods of time, hence it is recommended that the inductive conductivity sensor in the integrated water quality sensing system is used. Research has been done in previous studies to make an electrode sensor that is affordable and suitable for long-term data gathering applications, and this research confirms that measurement deviation begins to happen after a time with electrode conductivity sensors. The result of this comparison agrees with the previous research; however, in this comparison the deviation in the result began much sooner than in other research such as in "Cost-effective autonomous sensor for the long-term monitoring of water electrical conductivity of crop fields" [100] where deviation in the result did not happen until day 70. This is most likely because unlike in previous research the sensor used in this research comparison is a standard commercially available sensor and most of the other previous researchers on this topic developed their own sensor specifically for this test.

This comparison provides insight into how significant the deviations in the measurement of electrical conductivity using an electrode conductivity sensor are when compared with an inductive conductivity sensor which is an area of research that has been overlooked. However, this comparison was done over a 20-day period, which might not have been enough time to show the complete analysis for the comparison, and the electrode sensor used in this comparison was not specially designed for long-term submersion measurements. A future area of research might look at designing a cost-effective electrode sensor for long-term submersion and comparing how that sensor performs against the inductive conductivity sensor.

8.3 Temperature

The results of the temperature sensor comparison, described in Section 7.3, show minimal variation between the two sensor results. The hypothesis of this comparison suggested that that non-contact photoelectric sensor would not be sensitive to minor changes in the water temperature and so its results would have a much smoother and less accurate trend curve than the thermistor's results. This did happen to a very minor degree, as the results for the non-contact temperature sensor did have a smoother graph; however, there was no accuracy lost in the trend curve of the results. The results also showed no external fouling on the thermistor, which was due to the material used for the external shell of the thermistor (stainless steel) and because the probe has a conservative design that limits its surface area. These results mean that contact with the water has a very minimal if not negligible effect on the temperature readings over long periods of time.

The results for the temperature sensors confirm that non-contact sensors can be used to accurately measure the temperature of water over long periods of time, but show that unless there is a specific situation where non-contact sensors are required it is better to use the contact type sensor to measure water temperature as it reacts faster to changes in the temperature, is typically cheaper, and contact with the water does not present any major issues that will affect the temperature measurements. The results of this comparison agree with previous research into making an affordable and practical non-contact temperature sensor in that a non-contact temperature sensor does provide a valid alternative sensing solution. However, unlike the previous research on this topic, this comparison was specifically looking at what type of sensor would be better to use in an integrated water quality sensing system and it is simply more practical to use the contact thermistor sensor.

This comparison provides insight into the accuracy of non-contact temperature sensors and contact type temperature sensors. However, this comparison was only done between two of the many variations of temperature sensor available commercially, and so an area of future research might be to compare all the contact type temperature sensors such as RTD, thermistor and thermocouple sensors to determine which type is better for long-term submersion measurements.

8.4 Turbidity

The results of the turbidity sensor comparison, described in Section 7.4, show minimal variation between the two sensor results, which is in line with the hypothesis of this comparison that there would be minimal variation. However, what does not support the hypothesis is that the cheaper range of turbidity sensors would be acceptable to use in an integrated sensor system, because a flaw in the sensor design was discovered that would negatively affect its measurements. The water seal issue of the sensors, which is described in Section 7.4, does not specifically exclude the sensors from being accepted into the integrated water quality sensing system, because the results show that when a common water sealant is added to cover up the flaw, the sensors work in optimal condition. Based on the result of this comparison and the price difference between an industrial turbidity sensor and the cheaper range, it is recommended that the cheaper turbidity sensor in the integrated water quality sensor system is used, with the caveat that a water sealant is added to the sensor to prevent water getting inside it.

The results from this comparison agree with similar research done using the same turbidity sensors, such as “Water Quality Measuring Station” [101] which found that the turbidity sensor used in this experiment was able to measure turbidity accurately enough for it to be used in water quality measuring station. However, unlike the previous research [101], the comparison in this study was between two of the same turbidity sensors to study any deviation of the measurements. This comparison validates the decisions of previous research to use this sensor by confirming that the deviation between the sensors was minimal. However, this comparison was done between only two of the sensors, with a third used to test what would happen if water got into the sensor. For a more complete analysis of the deviation in this more cost-effective sensing solution, a further experiment needs to be done analysing the results of several sensors. Also, an area of future development that could be explored is taking this cheaper technology and integrating it into a sensor body that can be fully submerged without any sealant issues.

8.5 TDS

The results of the turbidity sensor comparison, described in Section 7.5, show a major variation between the two sensors. The hypothesis of this comparison was that, there would-be minimal variation in the results because the two sensors were the same type, but this did not happen and there are two possible reason. The first has to do with the nature of charged positive ions. Charged positive ions are always moving and when the sensor is submerged in water the ions begin to move between the electrodes using the water as a conduit, and so any minor difference in the conductivity of the water will result in a different TDS reading. However, since the two TDS sensors used are the same sensor type, using the same code, measuring the same water, any differences in the measurement due to the conductivity of the water should be minimal. The second reason is that there was quality control issue with the TDS sensors used. This is probably the case, as the sensor used was a cheaper sensing solution. The purpose of this comparison was to determine if there were any drawbacks to adding the cheaper sensing solution for TDS into the integrated water quality sensing solution, and the results show that there are major variations between what should be identical sensors, and so it is recommended that they are not used in the integrated solution. Not much research has been done into the comparison of cheap TDS sensors, so the results of this comparison show some unique findings that differ from previous research into TDS sensors. Unlike previous research this comparison shows that there is room for major variation in sensor results between different sensors of the same type, providing insight into a potential issue with low-end TDS sensors. However, this comparison was only done between two TDS sensors so it cannot be conclusively stated that this is a common issue. Thorough analysis needs to be done into this issue by comparing the results for several TDS sensors to determine the average deviation between the sensors.

9 Conclusion and Future Work

This research aimed to determine the feasibility of a cost-effective integrated water quality sensing system and determine what types of sensor are best suited for the long-term submersion required for such a system. Many considerations were evaluated including cost, accuracy, durability and age sensitivity. Ultimately the results of this research suggest that a cost effective fully integrated water quality sensing system is feasible if the water quality parameters being measured are limited to a set of critical parameters. In researching the best types of sensors used to analyse water quality parameters, specific attention has been given to the performance of sensors exposed to long-term submersion and whether non-contact sensors were superior in such cases. The results of this research on sensor type are varied with the results suggesting a different answer depending on the parameter being measured.

For pH and temperature this research concludes that there is little justification in using the more complex and expensive non-contact sensor, as there is insufficient evidence to suggest that such sensors provide a significant improvement over the standard contact type sensors. With respect to the parameter of electrical conductivity, this research concurs with the finding of previous research into electrical conductivity sensors. It concludes that the non-contact inductive conductivity sensor is the superior sensing method for long-term submersion measurement, and the use of this non-contact sensor type is recommended in any fully integrated system. For the measurement of turbidity, this research concludes that there is little justification in using the more expensive sensor types rather than the cheaper optical turbidity sensors. These standard sensors are a fraction of the cost of an industrial grade turbidity sensor and the data sets showed very little performance variation when measuring turbidity for long periods of time. When measuring the parameters for TDS, the results of this research found there to be a large amount of variation between the two identical electrode sensors used and concludes that this needs to be investigated further to determine if this is a common issue in these sensor types. Until such research is done it is recommended that the TDS sensor is not used in an integrated water quality sensing system.

9.1 Research Evaluation

The approach this research took when evaluating the feasibility of a cost effective fully integrated water quality sensing system was to initially review existing research on this topic, determine how water quality parameters are typically measured, and investigate whether existing measurement techniques and hardware could be integrated into a single system. The outcome of this research aligns with what was discovered from the initial review, that it was just not practical to measure some of the water quality parameters outside a lab environment. Further findings from this review did determine, however, that it was possible to have an integrated water quality sensing system if the parameters being measured were specified and limited. This led to the configuring of a set of critical parameters and the evaluation of the sensor technologies appropriate for the measurement of these parameters.

One of the primary limitations to this study was the price and availability of water quality sensors. When sourcing the sensors for this research it became clear that the non-contact sensor variants for the parameters were not only beyond the budget of this research but would in the end make the integrated water quality sensing system not cost effective. As such, the results of this research are based on the use of low- to mid-range water quality sensors (based on price), and better results might be obtained if water quality sensors at higher prices were to be used.

A further significant limitation was the time available to study the performance effects of the sensors over time. Ideally the sensors used in the study would have run, collecting data, for at least a full year to get a complete picture of how the sensors react to changes in the external environment over such a time period. The active study on sensor performance was conducted over 20 days and it is reasonable to expect that improved data integrity would have been achieved with extended test time.

A minor limitation of this study was the need to manually calibrate some of the sensors used in the study, which means that there was room for human error in the results of this study and the sensors do not have a pre-set calibration that could be relied upon to reproduce the results of this research.

9.2 Contributions

This work contributes to the wider source of academic knowledge in multiple ways.

- This research validates the conditions in which an integrated water sensing system could be practically implemented and provides insight into the practical allocation of contact and non-contact sensors for use in long-term submerged water quality sensing.
- This research provides insight into the practical effect external fouling has on sensor measurements and shows that some of the theoretical drawbacks of sensors are not always an issue in practice.
- This research validates some of the previous research done into electrode electrical conductivity sensors by confirming, through a comparison of an electrode sensor and

inductive sensor, that over time the measurement result of an electrode electrical conductivity sensor begins to deviate.

- This research validates previous research into the practical use of a non-contact water temperature sensor which determined that such sensors are accurate and provide a valid alternative to standard contact sensors.
- The results of this research show a potential issue with a low-end TDS sensor. They clearly demonstrated a large amount of deviation in their results. This needs further evaluation to enable their confident use in an integrated measurement system as proposed.

9.3 Suggestions for Future Work

There are multiple avenues available for future research, expanding on this research, to develop a more in-depth understanding of which sensors are best to use for long-term submersion in an integrated sensing system.

- The active testing of the sensors in this study was conducted over a period of 20 days. It is recommended in future research that the testing period be extended to enable greater analysis of the time sensitivity of sensor performance.
- The testing of the sensors in this study was conducted using a single controlled source of surface water. Further analysis could be done to determine if the results of this research are replicated using multiple samples of surface water.
- The research results concur with previous research that electrode conductivity sensor measurements begin to deviate over time. There is ongoing development and testing that seeks to solve this issue; however, it is still an area that compromises the overall study program of water quality. Future research could investigate the development of an affordable electrode conductivity sensor that does not have measurement deviation after extended periods of submersion.
- Another key area for sensor development would be with respect to availability of cheaper but reliable optical sensors. This research has suggested that this technology could be used very successfully as part of an integrated water quality sensor system. Critically, development of this sensor type needs to address the requirement for water submergence without any risk of damage.
- The results of this research show a large deviation between the results of the apparently identical TDS sensors used. Further research needs to be done using multiple sensors

to determine if this is a common issue with the low-end TDS sensors before they can be deployed in a fully integrated system.

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Appendix 1

Arduino Mega Sensor Code used in the integrated sensor device.

```
#define SensorPin A0           //pH1 meter Analog output to Arduino Analog Input 0
#define Offset 0.00           //deviation compensate
#define LED 13
#define samplingInterval 20
#define printInterval 800
#define ArrayLenth  40    //times of collection
int pHArray[ArrayLenth];   //Store the average value of the sensor feedback
int pHArrayIndex=0;
//==========================================
#define SensorPin2 A1           //pH2 meter Analog output to Arduino Analog Input 0
#define Offset 0.00           //deviation compensate
#define LED 13
#define samplingInterval2 20
#define printInterval2 800
#define ArrayLenth2  40    //times of collection
int pH2Array[ArrayLenth2];   //Store the average value of the sensor feedback
int pH2ArrayIndex=0;
//==========================================
#define TdsSensorPin A2
#define VREF 5.0      // analog reference voltage(Volt) of the ADC
#define SCOUNT  30           // sum of sample point
int analogBuffer[SCOUNT];    // store the analog value in the array, read from ADC
int analogBufferTemp[SCOUNT];
int analogBufferIndex = 0,copyIndex = 0;
float averageVoltage = 0,tdsValue = 0,temperature = 25;
//==========================================
#define TdsSensorPin2 A3
#define VREF 5.0      // analog reference voltage(Volt) of the ADC
#define SCOUNT  30           // sum of sample point
int analogBuffer2[SCOUNT];    // store the analog value in the array, read from ADC
```

```
int analogBufferTemp2[SCOUNT];

int analogBufferIndex2 = 0,copyIndex2 = 0;

float averageVoltage2 = 0,tdsValue2 = 0,temperature2 = 25;

//========================================

#include <DFRobot_EC10.h>  //conductivity

#define EC_PIN A4

float voltage,ecValue,temper = 20;

DFRobot_EC10 ec;

//========================================

int ThermistorPin = 5;

int Vo;

float R1 = 10000;

float logR2, R2, T;

float c1 = 1.009249522e-03, c2 = 2.378405444e-04, c3 = 2.019202697e-07;

//========================================

void setup() {

  pinMode(LED,OUTPUT);

  Serial.begin(9600);

  pinMode(TdsSensorPin,INPUT);

  pinMode(TdsSensorPin2,INPUT);

}

//========================================

void loop() {

  pH1_Sensor();

  pH2_Sensor();

  Turbidity_Sensor1();

  Turbidity_Sensor2();

  TDS_Sensor1();

  TDS_Sensor2();

  Thermistor();

  delay(60000);

}
```

```
//=======================================
void pH1_Sensor()
{
  static unsigned long samplingTime = millis();
  static unsigned long printTime = millis();
  static float pHValue,voltage;
  if(millis()-samplingTime > samplingInterval)
  {
      pHArray[pHArrayIndex++]=analogRead(SensorPin);
      if(pHArrayIndex==ArrayLenth)pHArrayIndex=0;
      voltage = avergearray(pHArray, ArrayLenth)*5.0/1024;
      pHValue = 3.5*voltage+Offset;
      samplingTime=millis();
  }
  if(millis() - printTime > printInterval)   //Every 800 milliseconds, print a numerical, convert the state of the LED indicator
  {
    Serial.print("Voltage:");
        Serial.print(voltage,2);
        Serial.print(" ");
        Serial.print("pH:");
    Serial.println(pHValue,2);
   // Serial.print(" ");
        digitalWrite(LED,digitalRead(LED)^1);
        printTime=millis();
  }
}
double avergearray(int* arr, int number){
  int i;
  int max,min;
  double avg;
  long amount=0;
  if(number<=0){
```

```
 Serial.println("Error number for the array to avraging!/n");
 return 0;
}
if(number<5){   //less than 5, calculated directly statistics
 for(i=0;i<number;i++){
  amount+=arr[i];
 }
 avg = amount/number;
 return avg;
}else{
 if(arr[0]<arr[1]){
  min = arr[0];max=arr[1];
 }
 else{
  min=arr[1];max=arr[0];
 }
 for(i=2;i<number;i++){
  if(arr[i]<min){
   amount+=min;        //arr<min
   min=arr[i];
  }else {
   if(arr[i]>max){
    amount+=max;    //arr>max
    max=arr[i];
   }else{
    amount+=arr[i]; //min<=arr<=max
   }
  }//if
 }//for
 avg = (double)amount/(number-2);
}//if
return avg;
```

```
}
//========================================
void pH2_Sensor()
{
  static unsigned long samplingTime = millis();
  static unsigned long printTime = millis();
  static float pHValue,voltage;
  if(millis()-samplingTime > samplingInterval)
  {
      pH2Array[pH2ArrayIndex++]=analogRead(SensorPin2);
      if(pH2ArrayIndex==ArrayLenth)pH2ArrayIndex=0;
      voltage = avergearray(pH2Array, ArrayLenth)*5.0/1024;
      pHValue = 3.5*voltage+Offset;
      samplingTime=millis();
  }
  if(millis() - printTime > printInterval)   //Every 800 milliseconds, print a numerical, convert the state of the LED indicator
  {
    Serial.print("Voltage:");
        Serial.print(voltage,2);
        Serial.print(" ");
        Serial.print("pH:");
    Serial.println(pHValue,2);
   // Serial.print(" ");
        digitalWrite(LED,digitalRead(LED)^1);
        printTime=millis();
  }
}
double avergearray2(int* arr, int number){
  int i;
  int max,min;
  double avg;
  long amount=0;
```

```
if(number<=0){
  Serial.println("Error number for the array to avraging!/n");
  return 0;
}
if(number<5){   //less than 5, calculated directly statistics
  for(i=0;i<number;i++){
    amount+=arr[i];
  }
  avg = amount/number;
  return avg;
}else{
  if(arr[0]<arr[1]){
    min = arr[0];max=arr[1];
  }
  else{
    min=arr[1];max=arr[0];
  }
  for(i=2;i<number;i++){
    if(arr[i]<min){
      amount+=min;        //arr<min
      min=arr[i];
    }else {
      if(arr[i]>max){
        amount+=max;    //arr>max
        max=arr[i];
      }else{
        amount+=arr[i]; //min<=arr<=max
      }
    }//if
  }//for
  avg = (double)amount/(number-2);
}//if
```

```
  return avg;
}
//========================================
void Turbidity_Sensor1()
{
  int sensorValue = analogRead(A6);// read the input on analog pin 0:
  float voltage = sensorValue * (5.0 / 1024.0); // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
    Serial.print("Turbidity:");
        Serial.print(voltage);
        Serial.print(" ");
  delay(500);
}
//========================================
void Turbidity_Sensor2()
{
  int sensorValue = analogRead(A7);// read the input on analog pin 0:
  float voltage = sensorValue * (5.0 / 1024.0); // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
    Serial.print("Turbidity:");
        Serial.print(voltage);
        Serial.print(" ");
  delay(500);
}
//========================================
void TDS_Sensor1()
{
   static unsigned long analogSampleTimepoint = millis();
   if(millis()-analogSampleTimepoint > 40U)     //every 40 milliseconds,read the analog value from the ADC
   {
     analogSampleTimepoint = millis();
     analogBuffer[analogBufferIndex] = analogRead(TdsSensorPin);    //read the analog value and store into the buffer
     analogBufferIndex++;
     if(analogBufferIndex == SCOUNT)
```

```
      analogBufferIndex = 0;
  }
  static unsigned long printTimepoint = millis();
  if(millis()-printTimepoint > 800U)
  {
    printTimepoint = millis();
    for(copyIndex=0;copyIndex<SCOUNT;copyIndex++)
      analogBufferTemp[copyIndex]= analogBuffer[copyIndex];
    averageVoltage = getMedianNum(analogBufferTemp,SCOUNT) * (float)VREF / 1024.0; // read the analog value more stable by the median filtering algorithm, and convert to voltage value
    float compensationCoefficient=1.0+0.02*(temperature-25.0);    //temperature compensation formula: fFinalResult(25^C) = fFinalResult(current)/(1.0+0.02*(fTP-25.0));
    float compensationVolatge=averageVoltage/compensationCoefficient;  //temperature compensation
    tdsValue=(133.42*compensationVolatge*compensationVolatge*compensationVolatge - 255.86*compensationVolatge*compensationVolatge + 857.39*compensationVolatge)*0.5; //convert voltage value to tds value
    //Serial.print("voltage:");
    //Serial.print(averageVoltage,2);
    //Serial.print("V   ");
    Serial.print("TDS:");
    Serial.print(tdsValue,0);
    Serial.print(" ");
    //Serial.println("ppm");
  }
}
int getMedianNum(int bArray[], int iFilterLen)
{
    int bTab[iFilterLen];
    for (byte i = 0; i<iFilterLen; i++)
    bTab[i] = bArray[i];
    int i, j, bTemp;
    for (j = 0; j < iFilterLen - 1; j++)
    {
    for (i = 0; i < iFilterLen - j - 1; i++)
```

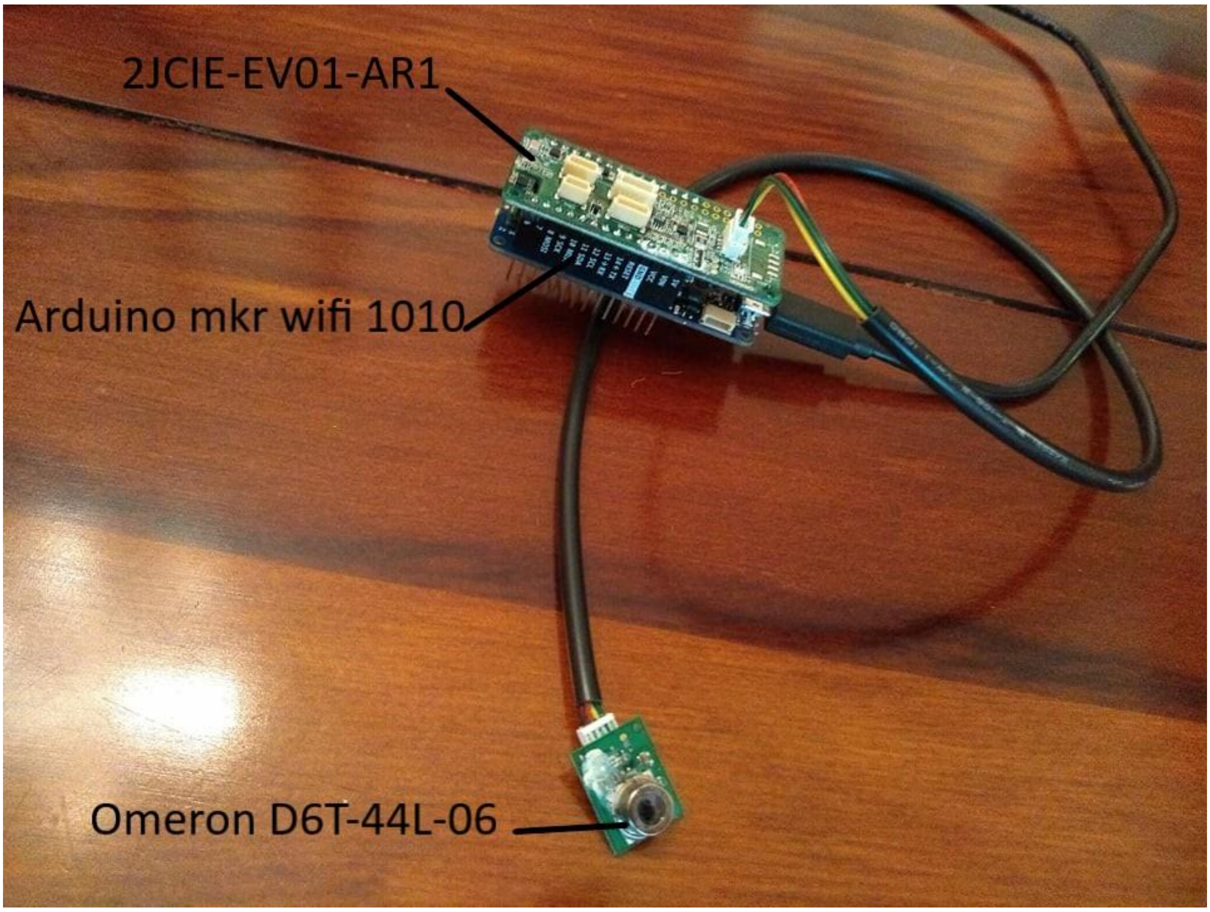
```
       {
     if (bTab[i] > bTab[i + 1])
        {
     bTemp = bTab[i];
        bTab[i] = bTab[i + 1];
     bTab[i + 1] = bTemp;
      }
    }
    }
    if ((iFilterLen & 1) > 0)
   bTemp = bTab[(iFilterLen - 1) / 2];
    else
   bTemp = (bTab[iFilterLen / 2] + bTab[iFilterLen / 2 - 1]) / 2;
    return bTemp;
}
//======================================

void TDS_Sensor2()
{
  static unsigned long analogSampleTimepoint = millis();
  if(millis()-analogSampleTimepoint > 40U)     //every 40 milliseconds,read the analog value from the ADC
  {
   analogSampleTimepoint = millis();
   analogBuffer2[analogBufferIndex2] = analogRead(TdsSensorPin2);    //read the analog value and store into the buffer
   analogBufferIndex2++;
   if(analogBufferIndex2 == SCOUNT)
      analogBufferIndex2 = 0;
  }
  static unsigned long printTimepoint = millis();
  if(millis()-printTimepoint > 800U)
  {
    printTimepoint = millis();
```

```
    for(copyIndex=0;copyIndex<SCOUNT;copyIndex++)
     analogBufferTemp[copyIndex]= analogBuffer[copyIndex];
    averageVoltage = getMedianNum(analogBufferTemp,SCOUNT) * (float)VREF / 1024.0; // read the analog value more stable by the median filtering algorithm, and convert to voltage value
    float compensationCoefficient=1.0+0.02*(temperature-25.0);    //temperature compensation formula: fFinalResult(25^C) = fFinalResult(current)/(1.0+0.02*(fTP-25.0));
    float compensationVolatge=averageVoltage/compensationCoefficient;  //temperature compensation
    tdsValue=(133.42*compensationVolatge*compensationVolatge*compensationVolatge - 255.86*compensationVolatge*compensationVolatge + 857.39*compensationVolatge)*0.5; //convert voltage value to tds value
    //Serial.print("voltage:");
    //Serial.print(averageVoltage,2);
    //Serial.print("V   ");
    Serial.print("TDS:");
    Serial.print(tdsValue,0);
    Serial.print(" ");
    //Serial.println("ppm");
  }
}
int getMedianNum2(int bArray[], int iFilterLen)
{
    int bTab[iFilterLen];
    for (byte i = 0; i<iFilterLen; i++)
    bTab[i] = bArray[i];
    int i, j, bTemp;
    for (j = 0; j < iFilterLen - 1; j++)
    {
    for (i = 0; i < iFilterLen - j - 1; i++)
       {
     if (bTab[i] > bTab[i + 1])
        {
     bTemp = bTab[i];
        bTab[i] = bTab[i + 1];
     bTab[i + 1] = bTemp;
```

```
      }
    }
    }
    if ((iFilterLen & 1) > 0)
  bTemp = bTab[(iFilterLen - 1) / 2];
    else
  bTemp = (bTab[iFilterLen / 2] + bTab[iFilterLen / 2 - 1]) / 2;
    return bTemp;
}
//========================================
void Thermistor() {
 Vo = analogRead(ThermistorPin);
 R2 = R1 * (1023.0 / (float)Vo - 1.0);
 logR2 = log(R2);
 T = (1.0 / (c1 + c2*logR2 + c3*logR2*logR2*logR2));
 T = T - 273.15;
 T = (T * 9.0)/ 5.0 + 32.0;

 Serial.print("Temperature: ");
 Serial.print(T);
 //Serial.println(" F");
 delay(500);
}
//========================================END
```

Appendix 2

Photoelectric Temperature Sensor Code and set-up



Arduino Code

```
/* includes */
#include <Wire.h>

/* defines */
#define D6T_ADDR 0x0A  // for I2C 7bit address
#define D6T_CMD 0x4C  // for D6T-44L-06/06H, D6T-8L-09/09H, for D6T-1A-01/02

#define N_ROW 8
#define N_PIXEL 8
#define N_READ ((N_PIXEL + 1) * 2 + 1)

#define SAMPLE_TIME_0010MS  10
```

```
#define SAMPLE_TIME_0012MS  12

#define SAMPLE_TIME_0016MS  16

#define SAMPLE_TIME_0025MS  25

#define SAMPLE_TIME_0050MS  50

#define SAMPLE_TIME_0070MS  70

#define SAMPLE_TIME_0140MS  140

#define SAMPLE_TIME_0250MS  250

#define SAMPLE_TIME_0500MS  500

#define SAMPLE_TIME_1000MS  1000

#define SAMPLE_TIME_2000MS  2000

#define SAMPLE_TIME_4000MS  4000

#define SAMPLE_TIME_8000MS  8000


#define PARA_0010MS_1 ((uint8_t)0x90)

#define PARA_0010MS_2 ((uint8_t)0x33)

#define PARA_0010MS_3 ((uint8_t)0x87)

#define PARA_0012MS_1 ((uint8_t)0x90)

#define PARA_0012MS_2 ((uint8_t)0x34)

#define PARA_0012MS_3 ((uint8_t)0x92)

#define PARA_0016MS_1 ((uint8_t)0x90)

#define PARA_0016MS_2 ((uint8_t)0x35)

#define PARA_0016MS_3 ((uint8_t)0x95)

#define PARA_0025MS_1 ((uint8_t)0x90)

#define PARA_0025MS_2 ((uint8_t)0x36)

#define PARA_0025MS_3 ((uint8_t)0x9C)

#define PARA_0050MS_1 ((uint8_t)0x90)

#define PARA_0050MS_2 ((uint8_t)0x37)

#define PARA_0050MS_3 ((uint8_t)0x9B)

#define PARA_0070MS_1 ((uint8_t)0x90)

#define PARA_0070MS_2 ((uint8_t)0x38)

#define PARA_0070MS_3 ((uint8_t)0xB6)

#define PARA_0140MS_1 ((uint8_t)0x90)
```

```
#define PARA_0140MS_2 ((uint8_t)0x39)
#define PARA_0140MS_3 ((uint8_t)0xB1)
#define PARA_0250MS_1 ((uint8_t)0x90)
#define PARA_0250MS_2 ((uint8_t)0x3A)
#define PARA_0250MS_3 ((uint8_t)0xB8)
#define PARA_0500MS_1 ((uint8_t)0x90)
#define PARA_0500MS_2 ((uint8_t)0x3B)
#define PARA_0500MS_3 ((uint8_t)0xBF)
#define PARA_1000MS_1 ((uint8_t)0x90)
#define PARA_1000MS_2 ((uint8_t)0x3C)
#define PARA_1000MS_3 ((uint8_t)0xAA)
#define PARA_2000MS_1 ((uint8_t)0x90)
#define PARA_2000MS_2 ((uint8_t)0x3D)
#define PARA_2000MS_3 ((uint8_t)0xAD)
#define PARA_4000MS_1 ((uint8_t)0x90)
#define PARA_4000MS_2 ((uint8_t)0x3E)
#define PARA_4000MS_3 ((uint8_t)0xA4)
#define PARA_8000MS_1 ((uint8_t)0x90)
#define PARA_8000MS_2 ((uint8_t)0x3F)
#define PARA_8000MS_3 ((uint8_t)0xA3)


/***** Setting Parameter *****/
#define comparingNumInc 6  // x samplingTime ms  (range: 1 to 39)   (example) 6 x 250 ms -> 1.5 sec
#define comparingNumDec 6  // x samplingTime ms  (range: 1 to 39)   (example) 6 x 250 ms -> 1.5 sec
#define threshHoldInc 10 //  /10 degC   (example) 10 -> 1.0 degC (temperature change > 1.0 degC -> Enable)
#define threshHoldDec 10 //  /10 degC   (example) 10 -> 1.0 degC (temperature change > 1.0 degC -> Enable)
bool  enablePix[8] = {true, true, true, true, true, true, true, true};
/****************************/


/***** Setting Parameter 2 *****/
#define samplingTime SAMPLE_TIME_0250MS //ms (Can select only, 10ms, 12ms, 16ms, 25ms, 50ms, 70ms, 140ms, 250ms, 500ms, 1000ms, 2000ms, 4000ms, 8000ms)
```

```
/****************************/

uint8_t rbuf[N_READ];
int16_t pix_data[8] = {0};
int16_t seqData[8][40] = {0};
bool  occuPix[8] = {0};
bool  occuPixFlag = false;
uint8_t  resultOccupancy = 0;
uint16_t  totalCount = 0;

/** JUDGE_occupancy: judge occupancy*/
bool judge_seatOccupancy(void) {
  int i = 0;
  int j = 0;
  for (i = 0; i < 8; i++){
    for (j = 0; j < 39; j++){
      seqData[i][39 - j] = seqData[i][38 - j];
    }
    seqData[i][0] = pix_data[i];
  }
  if (totalCount <= comparingNumInc){
    totalCount++;
  }
  if (totalCount > comparingNumInc){
    for (i = 0; i < 8; i++){
      if (enablePix[i] == true){
        if (occuPix[i] == false){
           if ((int16_t)(seqData[i][0] - seqData[i][comparingNumInc]) >= (int16_t)threshHoldInc){
            occuPix[i] = true;
          }
        }
        else{
```

```
      if ((int16_t)(seqData[i][comparingNumDec] - seqData[i][0]) >= (int16_t)threshHoldDec){
      occuPix[i] = false;
          }
        }
      }
    }
    if (resultOccupancy == 0) {
      for (i = 0; i < 8; i++){
        if(occuPix[i] == true){
          resultOccupancy = 1;
          break;
        }
      }
    }
    else{  //resultOccupancy == true
      occuPixFlag = false;
      for (i = 0; i < 8; i++){
        if (occuPix[i] == true){
          occuPixFlag = true;
          break;
        }
        else{
        }
      }
      if (occuPixFlag == false){
        resultOccupancy = 0;
      }
    }
  }
  return true;
}
```

```
uint8_t calc_crc(uint8_t data) {

    int index;

    uint8_t temp;

    for (index = 0; index < 8; index++) {

        temp = data;

        data <<= 1;

        if (temp & 0x80) {data ^= 0x07;}

    }

    return data;

}


/** <!-- D6T_checkPEC {{{ 1--> D6T PEC(Packet Error Check) calculation.

 * calculate the data sequence,

 * from an I2C Read client address (8bit) to thermal data end.

 */

bool D6T_checkPEC(uint8_t buf[], int n) {

    int i;

    uint8_t crc = calc_crc((D6T_ADDR << 1) | 1);  // I2C Read address (8bit)

    for (i = 0; i < n; i++) {

        crc = calc_crc(buf[i] ^ crc);

    }

    bool ret = crc != buf[n];

    if (ret) {

        Serial.print("PEC check failed:");

        Serial.print(crc, HEX);

        Serial.print("(cal) vs ");

        Serial.print(buf[n], HEX);

        Serial.println("(get)");

    }

    return ret;

}
```

```
/** <!-- conv8us_s16_le {{{1 --> convert a 16bit data from the byte stream.

 */

int16_t conv8us_s16_le(uint8_t* buf, int n) {

    int ret;

    ret = buf[n];

    ret += buf[n + 1] << 8;

    return (int16_t)ret;   // and convert negative.

}




/** <!-- setup {{{1 -->

 * 1. initialize a Serial port for output.

 * 2. initialize an I2C peripheral.

 */

void setup() {



  uint8_t para[3] = {0};

  switch(samplingTime){

    case SAMPLE_TIME_0010MS:

      para[0] = PARA_0010MS_1;

      para[1] = PARA_0010MS_2;

      para[2] = PARA_0010MS_3;

      break;

    case SAMPLE_TIME_0012MS:

      para[0] = PARA_0012MS_1;

      para[1] = PARA_0012MS_2;

      para[2] = PARA_0012MS_3;

      break;

    case SAMPLE_TIME_0016MS:

      para[0] = PARA_0016MS_1;

      para[1] = PARA_0016MS_2;
```

```
  para[2] = PARA_0016MS_3;
  break;
case SAMPLE_TIME_0025MS:
  para[0] = PARA_0025MS_1;
  para[1] = PARA_0025MS_2;
  para[2] = PARA_0025MS_3;
  break;
case SAMPLE_TIME_0050MS:
  para[0] = PARA_0050MS_1;
  para[1] = PARA_0050MS_2;
  para[2] = PARA_0050MS_3;
  break;
case SAMPLE_TIME_0070MS:
  para[0] = PARA_0070MS_1;
  para[1] = PARA_0070MS_2;
  para[2] = PARA_0070MS_3;
  break;
case SAMPLE_TIME_0140MS:
  para[0] = PARA_0140MS_1;
  para[1] = PARA_0140MS_2;
  para[2] = PARA_0140MS_3;
  break;
case SAMPLE_TIME_0250MS:
  para[0] = PARA_0250MS_1;
  para[1] = PARA_0250MS_2;
  para[2] = PARA_0250MS_3;
  break;
case SAMPLE_TIME_0500MS:
  para[0] = PARA_0500MS_1;
  para[1] = PARA_0500MS_2;
  para[2] = PARA_0500MS_3;
  break;
```

```
    case SAMPLE_TIME_1000MS:
      para[0] = PARA_1000MS_1;
      para[1] = PARA_1000MS_2;
      para[2] = PARA_1000MS_3;
      break;
    case SAMPLE_TIME_2000MS:
      para[0] = PARA_2000MS_1;
      para[1] = PARA_2000MS_2;
      para[2] = PARA_2000MS_3;
      break;
    case SAMPLE_TIME_4000MS:
      para[0] = PARA_4000MS_1;
      para[1] = PARA_4000MS_2;
      para[2] = PARA_4000MS_3;
      break;
    case SAMPLE_TIME_8000MS:
      para[0] = PARA_8000MS_1;
      para[1] = PARA_8000MS_2;
      para[2] = PARA_8000MS_3;
      break;
    default:
      para[0] = PARA_0250MS_1;
      para[1] = PARA_0250MS_2;
      para[2] = PARA_0250MS_3;
      break;
  }

    Serial.begin(9600);  // Serial baudrate = 115200bps
    Wire.begin();  // i2c master

    Wire.beginTransmission(4);  // I2C client address
    Wire.write(0x02);                  // D6T register
```

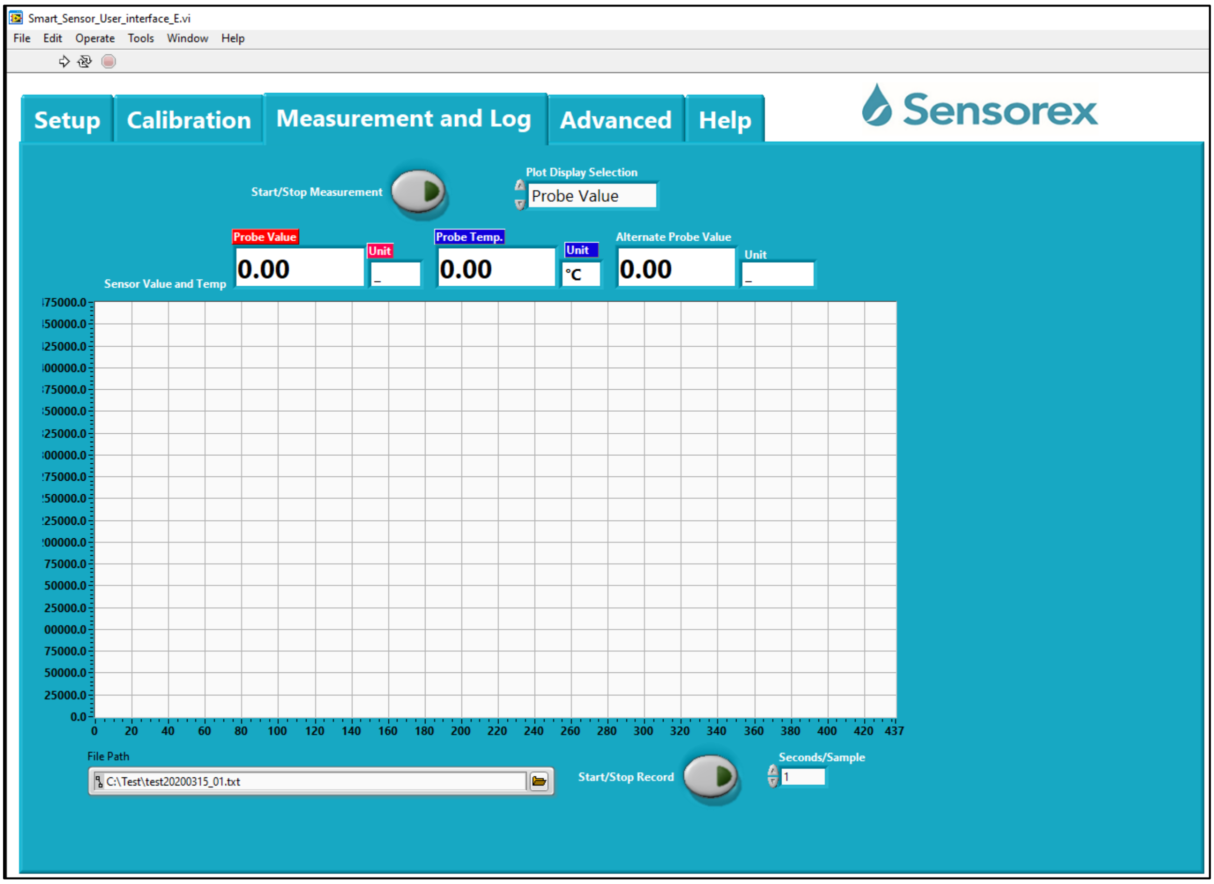
```
    Wire.write(0x00);                // D6T register
    Wire.write(0x01);                // D6T register
    Wire.write(0xEE);                // D6T register
    Wire.endTransmission();          // I2C repeated start for read
    Wire.beginTransmission(4);  // I2C client address
    Wire.write(0x05);                // D6T register
    Wire.write(para[0]);             // D6T register
    Wire.write(para[1]);             // D6T register
    Wire.write(para[2]);             // D6T register
    Wire.endTransmission();          // I2C repeated start for read
    Wire.beginTransmission(4);  // I2C client address
    Wire.write(0x03);                // D6T register
    Wire.write(0x00);                // D6T register
    Wire.write(0x03);                // D6T register
    Wire.write(0x8B);                // D6T register
    Wire.endTransmission();          // I2C repeated start for read
    Wire.beginTransmission(4);  // I2C client address
    Wire.write(0x03);                // D6T register
    Wire.write(0x00);                // D6T register
    Wire.write(0x07);                // D6T register
    Wire.write(0x97);                // D6T register
    Wire.endTransmission();          // I2C repeated start for read
    Wire.beginTransmission(4);  // I2C client address, D6T_ADDR
    Wire.write(0x02);                // D6T register
    Wire.write(0x00);                // D6T register
    Wire.write(0x00);                // D6T register
    Wire.write(0xE9);                // D6T register
    Wire.endTransmission();          // I2C repeated start for read
}


/** <!-- loop - Thermal sensor {{{1 -->
```

```
 * 1. read sensor.
 * 2. output results, format is: [degC]
 */
void loop() {

  int i, j;

  memset(rbuf, 0, N_READ);
  // Wire buffers are enough to read D6T-16L data (33bytes) with
  // MKR-WiFi1010 and Feather ESP32,
  // these have 256 and 128 buffers in their libraries.
  Wire.beginTransmission(4);  // I2C client address
  Wire.write(D6T_CMD);              // D6T register
  Wire.endTransmission();           // I2C repeated start for read
  Wire.requestFrom(D6T_ADDR, N_READ);
  i = 0;
  while (Wire.available()) {
    rbuf[i++] = Wire.read();
  }

  if (D6T_checkPEC(rbuf, N_READ - 1)) {
    return;
  }

  // 1st data is PTAT measurement (: Proportional To Absolute Temperature)
  int16_t itemp = conv8us_s16_le(rbuf, 0);
  Serial.print("PTAT:");
  Serial.print(itemp / 10.0, 1);
  Serial.print(", Temperature:");

  // loop temperature pixels of each thrmopiles measurements
  for (i = 0, j = 2; i < N_PIXEL; i++, j += 2) {
```

```
        itemp = conv8us_s16_le(rbuf, j);
        pix_data[i] = itemp;
        Serial.print(itemp / 10.0, 1);  // print PTAT & Temperature
        if ((i % N_ROW) == N_ROW - 1) {
            Serial.print(" [degC]");  // wrap text at ROW end.
        } else {
            Serial.print(", ");   // print delimiter
        }
    }
    judge_seatOccupancy(); //add
    Serial.print(", Occupancy:");
    Serial.println(resultOccupancy, 1);
    delay(samplingTime);
}
```

Appendix 3

Inductive conductivity sensor set-up



Plot Display Selection: Probe Value

Probe Value: 0.00 Unit: _

Probe Temp.: 0.00 Unit: °C

Alternate Probe Value: 0.00 Unit: _

File Path: C:\Test\test20200315_01.txt

Seconds/Sample: 1