École polytechnique de Louvain

Stakeholder-based Specifications for Portable Water Quality Sensing

Metro Cebu, Philippines

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Abstract

Despite the UN Sustainable Development Goal to ensure universal and equitable access to safe and affordable drinking water for everyone by 2030, water quality remains a significant global challenge. The Philippines is an example of a vulnerable country regarding water resources as it experiences heavy water stress. Regular monitoring is critical to mitigating the risks associated with consuming unsafe water. Portable sensors offer significant benefits, enhancing rapid intervention and access to essential diagnostics. They empower diverse stakeholders to take part in water quality monitoring by making it accessible under non-laboratory conditions. However, traditional water quality monitoring systems are often inadequate for in-situ measurements due to lengthy result times, high costs, and require specialised expertise. Commercial portable sensors are limited to a certain number of analytes, are too expensive, lack user-friendliness, and require professional training. This limits monitoring in resource-limited areas. Therefore, current research focuses on developing compact, user-friendly, cost-effective point-of-use devices that allow rapid on-site detection. Despite technical progress, there is a significant gap in the availability of low-cost portable sensors that meet users' needs. One reason for the lack of commercialisation of proof-of-concept sensors, despite their potential, is the absence of research adapted to end-user requirements and integrating cost considerations and consumer needs during the early design stages of the prototypes.

This master's thesis addresses these shortcomings by exploring a method for identifying the requirements of portable water quality sensors that align with the needs of stakeholders in Metro Cebu, Philippines. By mapping local water expertise and identifying relevant stakeholders, the study aims to understand the regional challenges in water quality measurement and control. It will determine the specifications and design priorities for sensors through on-site testing and interviews with stakeholders, such as water suppliers and local governments. Additionally, by assessing the effectiveness of existing devices, this work evaluates the potential for adaptations and innovations in portable sensor technology to meet identified needs. Insights gathered from interactions identify precision, affordability, and user-friendliness as critical requirements for portable sensor design. Commercially available portable sensors do not respond to those three needs simultaneously. Further research is necessary in point-of-use sensor development. The focus should not only be on solving technological challenges, but stakeholders and end-users must be engaged early in the design process by using similar methods to identify requirements. Prototypes must be validated in local field conditions to ensure that new designs effectively address real-world needs and enhance user engagement and satisfaction, which is crucial. This work is part of a broader research initiative on biosensors and is conducted in collaboration with the Water Resource Center of the University of San Carlos.

Acronyms & Abbreviations

BOD Biological Oxygen Demand

BRW WQMA Butuanon River Watershed Water Quality Management Area

CCENRO Cebu City Environment and Natural Resources Office

CENRO City Environment and Natural Resources Office

CFU Culture-Forming Unit

COD Chemical Oxygen Demand

CS Citizen Science

DAO DENR Administrative Order

DENR Department of Environment and Natural Resources

DO Dissolved Oxygen

DOH Department of Health

E. coli Escherichia coli

EC Electrical Conductivity

EIS Electrochemical Impedance Spectroscopy

EMB Environmental Management Bureau

GES General Effluent Standards

IoT Internet of Things

ISE Ion-selective electrode

ISFET Ion-sensitive field-effect transistor

JICA Japan International Cooperation Agency

JMP WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene

LFA Lateral Flow Assay

LGU Local Government Unit

LOC Lab-on-a-chip

LWD Local Water District

LWUA Local Water Utilities Administration

MCENRO Mandaue City Environment and Natural Resources Office

MCWD Metro Cebu Water District

MPN Most Probable Number

NEDA National Economic and Development Authority

NTU Nephelometric Turbidity Units

NWRB National Water Resources Board

ORP Oxidation-Reduction Potential

PCR Polymerase chain reaction

PFAS Perfluoroalkyl and Polyfluoroalkyl Substances

PNSDW Philippine National Standards for Drinking Water

POC Point-of-care

PWRI Pilipinas Water Resources Inc.

SWI Saltwater Intrusion

TCO True Colour Unit

TDS Total Dissolved Solids

TSS Total Suspended Solids

UN United Nations

UNICEF United Nations Children's Fund

USC University of San Carlos, Cebu

WASH Water, Sanitation and Hygiene

WHO World Health Organization

WQG Water Quality Guidelines

WQMA Water Quality Management Area

WRC Water Resource Center

WRMO Water Resources Management Office

WRR Water Resource Region

WSP Water Service Provider

Contents

Introduction

Access to drinking water is a fundamental human right, essential to health, recognised under UN Sustainable Development Goal 6, with specific targets for water, sanitation and hygiene. In 2022, 2.2 billion people still lacked safely managed drinking water [1]. Water quality is a worldwide problem because water resources are limited and subject to life-threatening contamination. The climate crisis exacerbates water-related issues. Regular water quality monitoring is essential to limit the risks of drinking water from unsafe sources. However, traditional monitoring methods are inadequate because the time taken to obtain results is long, they are often very costly and rely on complex processes that require specialist expertise [2].

Portable sensors are ideal candidates to offer immediate results, on-site testing, cost-effectiveness, accessibility, broad spatial coverage, and user-friendly solutions to improve water management practices. They enhance access to essential diagnostics. They allow measurements outside laboratory settings and empower diverse stakeholders to participate in water quality monitoring. However, the current state of the portable sensors market does not meet the basic monitoring needs required to ensure safe drinking water. This is due to socio-economical and technical shortcomings or even the non-existence of portable sensors for specific analytes. It restricts water monitoring options in resource, expertise or infrastructure limited areas. Two central problems are at the root of this. First, the traditional water quality monitoring systems are often inadequate for in-situ measurements because they are difficult, if not impossible, to miniaturise into affordable portable devices. The shortcomings of traditional water quality measurement methods and sensors highlight the need for continued research and innovation in sensor technology, especially in compact, user-friendly, cost-effective point-of-use devices that allow rapid on-site detection. Because of this problem, a lot of research is being carried out, focusing on developing point-of-use sensors. Second, despite progress in lateral flow assays, microfluidics, nanomaterials, substrates and miniaturising transduction methods, technical and non-technical challenges remain, causing a significant gap in the availability of commercial low-cost portable sensors that meet users' needs. One reason for the lack of commercialisation of proof-of-concept sensors, despite their potential, is the absence of research adapted to end user requirements and cost considerations during the early design stages of the prototypes. Addressing traditional approaches' limitations and aligning them more closely with user needs can improve water quality monitoring.

The purpose of this master's thesis is to address these shortcomings by exploring a method to identify the requirements of portable water quality sensors aligned with the needs of stakeholders in Metro Cebu, Philippines. Matching sensor functionalities with local requirements allows for avoiding the risk of dissociation between the needs of end users and the final product. The study aims to map local water expertise, understand the unique local context, and discern relevant stakeholders. Design and specification priorities for portable sensors are drawn through stakeholder interviews. On-site testing of existing portable sensors allows experience of the reality of fieldwork. When done by potential end users, it provides feedback on usability and is further used to discern needs. This research seeks to evaluate the effectiveness of existing low-cost devices and explore potential innovations in portable sensor technology.

This thesis is part of a collective research project on biosensors initiated by Professor Jean-Pierre Raskin's team (ICTeam, UCLouvain) in collaboration with the teams of Professor Annika Gillis (ELI, UCLouvain) and Professor Sophie Hermans (IMCN, UCLouvain). For the past six years, the *Biosensors* team has been developing biosensors to quantify the concentration of bacteria such as enterococci or salmonella [3, 4]. This master's thesis fits within Margo Hauwaert's PhD thesis. This research is conducted in collaboration with the Water Resource Center Foundation Inc. of the University of San Carlos in Metro Cebu. Through its collaboration in the Philippines, the *Biosensors* team aims to take a responsible engineering approach by aligning local stakeholders' needs as closely as possible with the functionalities of the biosensors developed. This thesis will help identify the conditions for an interpretable and valuable result for the end user and how to make a device robust and user-friendly under non-lab conditions. In addition, manipulating existing sensors in a context such as Metro Cebu will help identify requirements for achieving user-friendliness of sensors (simple handling, calibration and maintenance, as well as explanations that can be interpreted regardless of the end users' level of education).

The first chapter gathers the objectives of this master's thesis, followed by a state-of-the-art review on water quality and monitoring technologies, detailing relevant parameters, norms, importance, and the different methods that exist to measure analytes. This includes a focus on the existing portable water quality sensors and their shortcomings, as well as monitoring strategies like citizen science. Previous studies involving the user needs for environmental monitoring equipment design are reviewed. Afterwards, the context of this study is explained based on a literature review and the help of local partners, providing an overview of water quality policies and regulations in the Philippines and a detailed overview of the water sector in Metro Cebu. The equipment and experimental validation methods are then presented, a comparison with historical data and laboratory equipment is performed, and the impact of local conditions on sensor performance is assessed. The method and results of potential users' feedback on the sensor manipulations and stakeholders' interviews are addressed in the following chapter, identifying the design priorities and which needs are already met by the selected sensors. Finally, this master's thesis concludes with a summary and future perspectives.

Chapter 1

Objectives

This master thesis fits within the scope of a research project developing biosensors and aims to take a broad look at portable sensors to identify design-related recommendations specific to relevant use cases for water quality sensors.

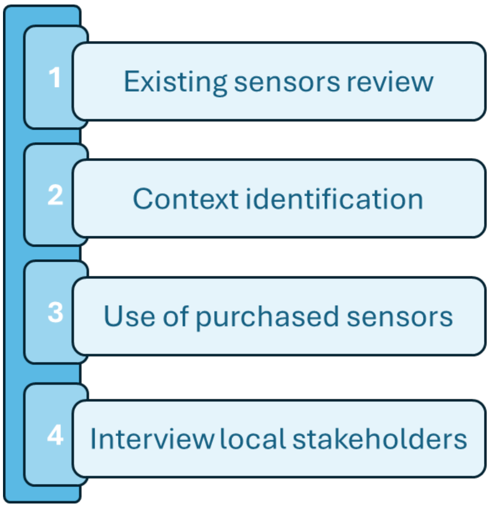
The goal of this master thesis is to determine specifications for water quality monitoring sensors based on the user needs, more specifically, the needs of local stakeholders involved in water quality monitoring. The purpose is to avoid a misalignment between these needs and the ones perceived by sensor developers. The main objectives of this thesis are described as follows:

1. **Local water expertise mapping & relevant stakeholders identification**: Description of the water sector in the Philippines and more precisely in Metro Cebu by detailing the water production, distribution and use context, regional issues and water quality measurement challenges, as well as mapping of local expertise in water quality monitoring and control. Determination of the interactions between the various players and the water quality analysis requirements for the situation under review.

2. **Specifications and design priorities of water quality sensors**: Determination of design priorities by testing already existing sensors on site and interviewing local stakeholders (water suppliers, research centres, local governments, citizens, water quality laboratories and monitoring equipment vendors). Comparison of the different devices in real-life situations regarding analytes, technology, context of use, technical characteristics (such as precision, reliability and measurement method), and critical socio-economic aspects (such as training required, accessibility, and cost). Observation of sensor utilisation by potential end users to receive feedback. Identification of relevant analytes and detection ranges, as well as the monitoring needs of the stakeholders over the entire detection protocol, encompassing sampling, transport, sensor manipulation, calibration and maintenance data reading, and data interpretation. Deduction of sensor characteristics required to meet the needs.

3. **Adaptations and complementary innovations for water quality sensors**: Assessment of which identified needs can already be met by existing portable sensors and for which needs innovation could improve the current portable sensor offer. The outcome is the different adaptations or complementary innovations required to achieve effective, low-cost monitoring on a large scale and the definition of the various multidisciplinary research areas to be involved to accelerate the development of this type of sensor.

The following steps were followed to carry out the described objectives:



1. Detailed review of existing methods for testing water quality, leading to a preliminary choice of different sensors. The purchased sensors were tested and validated. The data gathered from partners and previous studies allowed for the identification of shortcomings of existing technologies and devices.

2. Context identification through literature and discussions with local partners: local water expertise mapping & relevant stakeholders identification in the water sector

3. Use of purchased sensors in the local context and with local stakeholders to experience the reality of fieldwork in the specific context and to receive their feedback. The impact of location-dependent conditions and related challenges was assessed.

4. Interviews with local stakeholders to identify needs for water quality monitoring and shortcomings of existing technologies.

Part of the stages took place in Metro Cebu, the Philippines, in partnership with the Water Resource Center Foundation, Inc. (WRC).

Chapter 2

Monitoring Technologies and Strategies for Water Quality Assessment

1 Water quality generalities

This chapter aims to introduce the hydrological concepts used throughout the rest of the document, as well as global water quality trends and define key water quality parameters critical for assessing and managing water resources effectively. Moreover, water quality monitoring methods, technologies and innovations will be described.

1.1 Earth's freshwater & water cycle

Our planet is made of 71 % of water. However, only 2.5% of the water volume is freshwater (with less than 1000 ppm of dissolved salts [5]), and less than 1% is available freshwater, i.e. water of rivers, lakes, reservoirs and aquifers that can be extracted [6]. Freshwater, necessary for sustaining all biological systems on Earth, is essential for human health but is also needed for agriculture, industries, etc. It is thus a limited and precious resource.

The convergence of climate change, pollution and population growth increases the stress on global freshwater resources. Climate change impacts water temperature, alters precipitation patterns and increases the frequency of extreme weather events, leading to water scarcity due to prolonged droughts and water supply contamination due to increased flooding [7]. Pollution, from industrial discharge to agricultural runoff or fossil fuel use contaminates water sources, making them unsuitable for consumption. Moreover, water needs are increasing faster than population growth, primarily due to industrial water consumption and, most significantly, agricultural irrigation [1]. There is an urgent need for sustainable water management practices, for which water monitoring plays a crucial role.

1.1.1 Water cycle & Water balance

The *hydrologic cycle* or *water cycle* describes how all water on Earth, whether in the oceans, ice caps, atmosphere, surface water bodies, or underground aquifers, circulates through these various components repeatedly [8]. The replenishment of freshwater resources is highly reliant on other water cycle components and is impacted by human activity [9]. Water that was used or consumed, often containing a lot of pollutants, re-enters the groundwater and surface water systems and flows through the environment.

The contamination clean-up time varies depending on the type of water body, and contamination is sometimes irreversible [10]. A comprehensive understanding of local water cycles and consumption is essential for developing effective strategies to manage floods and droughts, reduce infrastructure risks and costs, and improve water management policies [9].

The *water balance* or *water budget* describes the flow of water into and out of a system in a specific area and period of time. A positive water balance corresponds to the case where losses are smaller than the intake, meaning there is less evapotranspiration flow than precipitation, making surface runoff and infiltration of water into the soil (recharge) possible [11]. The water balance plays a major role in determining the quantity of water available for use in a region and allows the measurement of water stress and prediction of water shortages. Evaluating the impacts of climate variability and human activity on water reserves can be done by analysing the changes in the water balance of a specific area over a certain period of time [12]. An effective monitoring system of water quality and quantity is key to better water management.

An *aquifer* is composed of permeable rock, including a saturated zone capable of conducting significant groundwater flow and allowing the capture of substantial water quantities. It may also contain an unsaturated zone. An aquifer is considered homogeneous if it possesses interstitial permeability, as seen in sands and gravels, where the percolation rate or seepage velocity is slow. Alternatively, it is heterogeneous if it features fissure permeability, such as in granite or karstic *limestone*, the percolation rate is then much faster [13]. Aquifers can be confined, meaning they are situated beneath the land surface and are fully saturated with water. Because of its encapsulation between layers of impermeable material, the aquifer is filled with pressurised water [14]. When a well taps into confined aquifers, the inherent pressure within the aquifer may be sufficient to force the water up to the surface, depending on the rock's permeability (*artesian well*) [15]. In contrast, an unconfined aquifer, also called a water table aquifer, is partially or fully filled, closer to the Earth's surface, and thus exposed to atmospheric pressure, allowing the water level to fluctuate. Because this aquifer is closer to the surface, it is more susceptible to meteorologic conditions and any surface contamination [14].

The *water table* is the subsurface boundary where the soil layer meets the area saturated with groundwater (known as the saturated zone of an aquifer) [16]. Groundwater is water located under the Earth's surface, below the water table, where it completely saturates the spaces between sediments and the cracks within rock formations (see Figure 2.1) [8].

1.1.2 Saltwater Intrusion

Saltwater intrusion (SWI) refers to seawater moving into freshwater aquifers, typically occurring at the interface where freshwater and saltwater meet. In low-lying coastal aquifers, saltwater intrusion is a natural occurrence due to differences in pressure and density between the two water types. With saltwater being denser than freshwater, it can move inland below the freshwater. Under normal conditions, the extent to which saltwater can penetrate inland is limited by the pressure exerted by the freshwater column due to its higher elevation. SWI can be significantly aggravated by several factors like sea level rise and extreme weather events (hurricanes and storms), which can disrupt the balance at the freshwater-saltwater interface. Moreover, human activities, particularly groundwater pumping, play a critical role in exacerbating saltwater intrusion. When groundwater is extracted, it reduces the volume of freshwater available, decreasing the pressure that

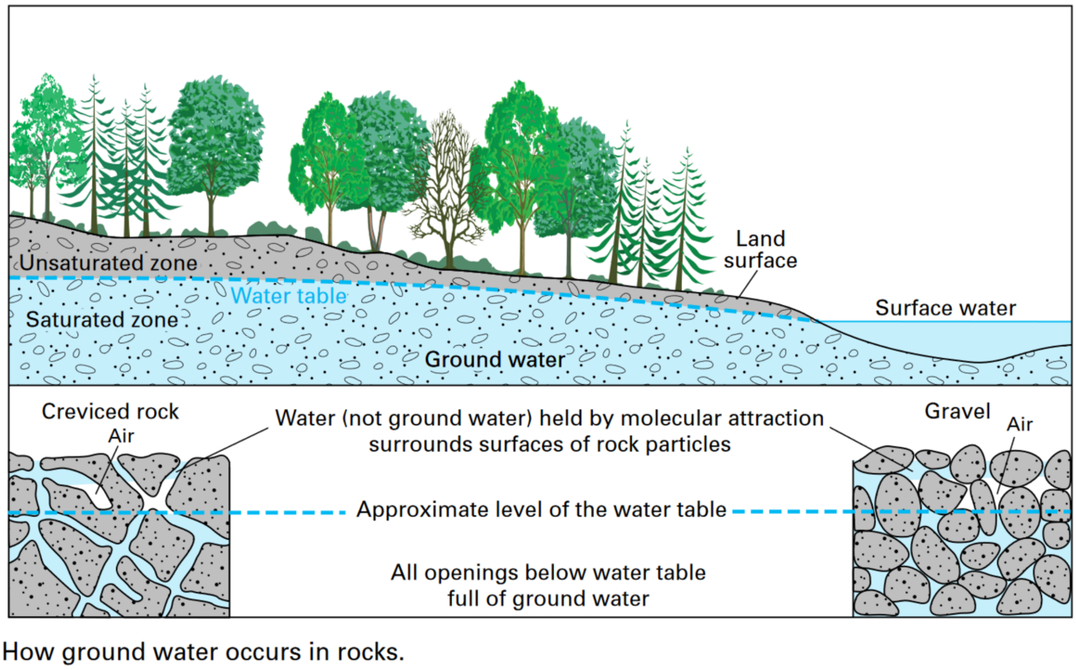


Figure 2.1: Water table & Groundwater [15]

holds back the saltwater, thus allowing it to move further inland. When withdrawing freshwater near the interface between the two bodies of groundwater, the saltwater will move upwards through the freshwater and towards the point of the withdrawal, creating *up-coning* [17] (see Figure 2.2). The movement of water within aquifers is dependent on the permeability of the aquifer material. Aquifers with high permeability allow easier water flow, contributing to faster and more extensive saltwater intrusion under conditions where the freshwater barrier is weakened [18].

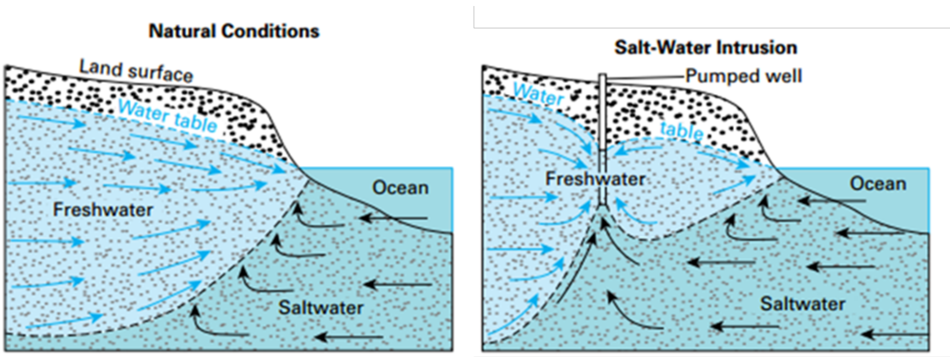


Figure 2.2: SWI process due to pumping [19]

Consuming saline drinking water can be detrimental to human health, especially during the critical stages of the life cycle, such as infancy and pregnancy [20]. As saltwater has a high osmotic pressure, it can lead to severe physiological impacts, affecting osmosis regulation, causing dehydration, raising blood pressure and straining kidney function. There are areas where SWI prevents the use of water catchments for drinking water supply or even irrigation. The methods to measure salinity are described in Section 1.3.

1.1.3 Water pollution

Water pollution is the contamination of water originating from a multitude of sources, the most common one being man-made products and activities, like chemicals such as heavy metals, antibiotics, fertilisers and pesticides, pathogens, nutrients, plastic, industrial waste discharge, individual dumping, septic systems' waste, landfill, etc. Water bodies can be contaminated from point sources, contaminants from an easily identified source such as industrial or domestic waste, or non-point sources, such as runoff that drains the waste from agriculture and contaminated soils [21]. *Groundwater pollution* occurs when contaminants infiltrate the aquifer's water, making it harmful for human consumption or the environment. Because of the interconnection of groundwater and surface water, they can show similar contaminants.

1.2 Water quality in the world

The issue of water security and sustainability has become increasingly pressing for many governments, driven by rapid population growth, urbanisation, industrial activities and climate change that threaten the consistent supply of clean water. According to the World Health Organisation (WHO), over 2 billion people live in water-stressed countries, 296 million use water from unsafe wells and springs, and 115 million collect untreated water [22]. The UN 2021 report shows that 3 billion people use water bodies without quality monitoring [23].

1.2.1 Importance of Safe Drinking Water

Access to drinking water is a fundamental human right, essential to health, recognised UN under Sustainable Development Goal 6, with specific targets for water, sanitation and hygiene (WASH). The WHO Guidelines for drinking water quality define *safe drinking water* as not having any harmful effects on health, even when consumed over an entire lifetime. This includes considering the vulnerabilities and health needs that people may have at various ages, such as infants or children. Safe drinking water is required for all usual domestic purposes, such as drinking, preparing food, and maintaining personal hygiene [24].

The WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) categorises access to drinking water according to the JMP service ladder [25] into surface water, unimproved, limited, basic and safely managed access. For example, *basic access* is defined as water "sourced from an improved source, provided that collection time is not more than 30 minutes for a round trip including queuing". However, the Joint Monitoring Programme classification has some shortcomings as it only focuses on two components of water insecurity: source and distance, while stability across time and acceptability, for example, are relevant too. Therefore, researchers proposed a standardised method to assess and compare water insecurity experiences, the Household Water InSecurity Experiences (HWISE) Scale. It is a tool used to measure the degree of water insecurity experienced by households based on 12 components to understand the impact on the daily lives of household members. In this context, *household water insecurity* is defined as "a condition when affordability, reliability, adequacy, and/or safety is significantly reduced or unattainable so as to threaten or jeopardise well-being, which includes physical and mental health and the capacity to undertake necessary productive, social, and cultural activities" [26].

Water-related diseases, caused by pathogenic micro-organisms, like viruses and bacteria present in water, can be transmitted through ingestion of drinking water, inhalation of water droplets or dermal contact. They can be classified based on the mode of transmission: waterborne (ingestion), water-washed (poor personal hygiene), water-based (intermediate aquatic host) and water-related insect vector (insect vectors associated with water) [27]. Common waterborne diseases are cholera, diarrhoea, dysentery, hepatitis A, typhoid and polio. It is estimated that around 1 million people die each year from diarrhea due to unsafe drinking water, poor sanitation, and inadequate hand hygiene. Infants, young children, debilitated individuals, and the elderly are at greater risk, especially in unsanitary conditions [22]. Water- and sanitation-related diseases are among the leading causes of death for children under the age of five [28]. Clean water and effective sanitation are essential to preventing these diseases. Besides the microbial aspect, water can also contain chemical contaminants that, with prolonged exposure through drinking water, can lead to adverse health effects in humans. Given the health risks of poorly treated water, the monitoring for water quality is necessary to ensure the detection and prevention of health risks.

1.3 Water quality parameters

Water contamination can be of three types: bacterial, chemical or physical. Significant water quality parameters are summarised in Tables 2.1, 2.2 and 2.3 with their corresponding WHO Guideline value for drinking water. Water quality requirements differ depending on the intended use of water [29]; here, we focus on drinking water recommendations. The constant revision of drinking water quality standards is essential to accommodate the inclusion of pollutants of emerging concern, such as plastics, pharmaceuticals, and PFAS, ensuring that regulatory measures effectively safeguard public health. It is important to note that WHO regulations only include upper limits for toxicological, aesthetic or other reasons, like avoiding piping system deterioration, and that no attention is paid to the need for minerals in drinking water for good health or preventing the burden of disease [30]. A lot of parameters do not have a guideline value (g.v.) because their levels found in drinking water are not considered of health concern (indicated by "/" for the guideline value in the following tables). Aesthetic considerations are related to the acceptability of water (see Section 1.3.4). Global physicochemical parameters are water quality indicators representing overall water characteristics and often encompass multiple underlying chemical species (turbidity, temperature, conductivity, alkalinity, hardness, pH, dissolved oxygen, etc.).

1.3.1 Physical parameters

Physical Parameters	**WHO Guideline value**	**Notes**
Turbidity	/	<1 NTU (aesthetic, no health-based g.v.)
Temperature	/	Cool water (aesthetic, no health-based g.v.)
Colour	/	< 15 TCO (aesthetic, no health-based g.v.)
Taste and odour	/	taste and odour thresholds for specific parameters are specified (aesthetic, no health-based g.v.)
Solids	/	TDS < 600 ppm (aesthetic, no health-based g.v.)
Electrical conductivity	X	Not considered in WHO, EU directives: 2500 $\mu S/cm$ (20°C)

Table 2.1: Physical parameters of water quality and their corresponding WHO Guideline value [24, 29]

Turbidity refers to the cloudiness of water, which is a direct measure of the amount of suspended particles present. It is a measure of the ability of light to pass through water measured in Nephelometric Turbidity Units (NTU) with a nephelometric turbidimeter [29], an optical sensor measuring the amount of light scattered by particles in the sample. It can also be measured visually with a Secchi Disk or a Transparency Tube.

Temperature influences several properties and processes of water, including the odour, viscosity, chemical reaction rates, and solubility of substances [29]. Temperature affects multiple parameters such as Biological Oxygen Demand (BOD), Dissolved Oxygen (DO), pH and Electrical Conductivity (EC) as well as the efficiency of water treatment processes like sedimentation and chlorination [31]. Warmer water carries less dissolved oxygen and has a higher conductivity; the impact of temperature on the pH of an arbitrary sample is not predictable. To standardise data related to those parameters so that it can be compared meaningfully, reference temperatures and/or temperature compensation are used as well as calibration solutions with known impacts of temperature. Water is generally most pleasing to people when it is between 10°C and 15°C [29].

Colour, taste and odour are generally more of an aesthetic concern rather than a health issue and are related to the acceptability of water (see Section 1.3.4). Colour is measured in True Colour Units (TCO), while odour or taste is expressed in terms of a threshold number. The WHO Guidelines specify that "the appearance, taste and odour of drinking water should be acceptable to the consumer" [24].

Solids in water are categorised into dissolved and suspended types (*Total solid (TS) = Total dissolved solid (TDS) + Total suspended solid (TSS)*). These are typically quantified by filtering and evaporating the water sample to leave behind residues that are weighed [29].

Electrical Conductivity (EC) measures the ability of a solution to conduct an electrical current, which correlates with the ion concentration in the water (S.I. units: siemens per meter [S/m]). If the temperature rises, the conductivity increases. Temperature changes not only the solution level of the ions but also their mobility. EC is gauged using two or four electrodes EC meters and induction sensors (see Section 2.1.1 for a more detailed description of EC meters). The usual drinking water values are 50 - 500 $\mu S/cm$ (pure water has a conductivity of 0.055 $\mu S/cm$, industrial wastewater of 5 mS/cm.

One of the main methods to measure salinity involves calculating the Total Dissolved Solids as most dissolved solids in water will be salt ions. However, evaporating a water sample and weighing the residual materials is an impractical technique for field or monitoring station applications due to its complexity. The more widely used method involves measuring the water's electrical conductivity with EC meters, which correlates directly with TDS and salinity levels (dissolved salts contain charged ions that conduct electricity):

$$TDS\ [\text{mg/L}] \cong EC\ [\mu\text{S/cm}] \times (0.5 - 0.7)$$

where the EC/TDS conversion factor depends on the type of water and is typically 0.5. It is higher for strong ionic solutions such as fertilisers [32]. EC can thus be an estimate of salinity S [ppm] $\cong 0.5 \times EC\ \mu S/cm$]. In marine water and saline environments, the relationship between salinity and conductivity is based on the Practical Salinity Scale. The relationship between salinity and EC varies with water temperature [20].

1.3.2 Chemical parameters

Chemical parameters can be classified as organic or inorganic and as molecules, ions and global chemical parameters. They can be naturally occurring in water (pH, hardness, chloride, iron, manganese, etc.), coming from industrial sources and human dwellings (benzene, mercury, cyanide, etc.), from agricultural activities (pesticides, nitrate, etc.), from water treatment or from materials in contact with drinking-water (lead, copper, disinfectants like chlorine, etc.) [24]. Various measuring methods exist for chemical parameters, including titration method, colorimetric methods, ion-specific electrodes, refractometers and chromatography. Metals can also be measured with techniques such as atomic absorption spectrometry and inductively coupled plasma. Those methods are further described in Section 2 and in Appendix A.

Chemical Parameters	**WHO Guideline value**	**Notes**
Global chemical parameters		
pH	/	
Acidity	X	Not considered in WHO Guidelines
Alkalinity	X	Not considered in WHO Guidelines
Hardness	/	
Dissolved oxygen	/	
Biochemical oxygen demand (BOD)	X	Not considered in WHO Guidelines
Chemical oxygen demand (COD)	X	Not considered in WHO Guidelines
Ions & Molecules		
Chlorine residual	5 mg/L for free chlorine	
Chloride	/	250 mg/L (taste, no health-based g.v.)
Fluoride	1.5 mg/L	
Iron	/	0.3 mg/L (taste, no health-based g.v.)
Manganese	0.08 mg/L	
Copper	2 mg/L	
Zinc	/	3 mg/L (aesthetic, no health-based g.v.)
Sulfate	/	250 mg/L (taste, no health-based g.v.)
Nitrogen Other toxic inorganic substances (e.g. Lead)	Nitrate: 50 mg/L Nitrite: 3 mg/L 0.01 mg/L	g.v. for nitrate/nitrite ion
Other toxic organic substances (e.g. Aldicarb)	0.01 mg/L	Aldicarb is a pesticide
Radioactive substances	Guidance levels in Bq/L	based on individual dose criterion of 0.1 mSv/year

Table 2.2: Chemical parameters of water quality and their corresponding WHO Guideline value [24, 29]

pH, or potential of hydrogen, is a critical parameter defined as the negative logarithm of the activity of hydrogen ions present in the solution: $pH = -Log\ a[H_+]^1$. It is a dimensionless number, ranging from 0 to 14, indicating the acidic or basic nature of a solution, with 7 as the neutral value and the pH of pure water at 25°C. Basic or alkaline solutions (lower concentrations of hydrogen (H_+) ions) have higher pH values than the neutral value, the opposite is valid for acidic solutions that have a pH lower than 7. Water pH affects

[1] Even though pH is a measure of H^+ ions it is a broad indicator of water's acidic or basic nature and thus considered as a general parameter.

biological and chemical reactions in the water and can significantly influence water quality and treatment. pH can be measured using indicators, colorimeters or electrochemical measuring systems (described further in Section 2.1.1). A broad array of other techniques has been developed to determine pH levels, such as Field Effect Transistor-based electrical detection (Ion-selective field effect transistor).

The **Oxidation-Reduction Potential** (ORP) measures the tendency of a substance to gain or lose electrons, indicating its ability to act as an oxidising or reducing agent (positive ORP means the solution is oxidative). **Alkalinity** in water refers to its capacity to neutralise acids and maintain stability in pH levels, resisting shifts toward acidity. It is often sourced from limestone bedrock deposits and is expressed mg/L as C_aCO_3.

Chloride ions (Cl^-) are not harmful to human health but can cause an unpleasant taste (salty taste for sodium chloride).

Chlorine (Cl_2) is added to water for treatment and disinfection. **Total chlorine** includes all forms of chlorine present in the water, which comprises both the free chlorine and the combined chlorine. **Chlorine residual**, or free chlorine, measures the concentration of chlorine left in the water after the disinfection process. It's crucial to ensure that treated water remains safe from microbial contamination as it travels through the distribution system. At the point of delivery, the minimum residual concentration of free chlorine should be 0.2 mg/L [24].

Nitrogen compounds include organic nitrogen, ammonia, nitrite, and nitrate. The primary causes of pollution are from agricultural runoff (fertilisers), sewage, septic installations and industrial discharges. **Nitrate** is present naturally in groundwater (usually lower than 10 ppm) due to decomposition. High levels of nitrate are particularly concerning as they can cause eutrophication in bodies of water by leading to excessive growth of algae and aquatic plants. In drinking water, excessive nitrate levels can lead to methemoglobinemia or "blue baby syndrome" in infants[2].

Water **hardness** is determined by the concentration of multivalent cations in the water, primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}). Hard water can lead to scaling in pipes and inefficiency in soap usage, while soft water may be corrosive. It is measured in German Degrees (°dH) where 1°dH is equivalent to approximately 10 mg/L of CaO, or around 7.1 mg/L of Ca. Units such as mmol/L (1 mmol/L equals 5.6 °dH) or mg/L as $CaCO_3$ are also used. **Carbonate hardness** is the portion of total hardness that is associated with bicarbonates (HCO_3^-) and carbonates (CO_3^{2-}). It is often equivalent to alkalinity. The non-carbonate hardness is associated with Ca^{2+} and Mg^{2+} ions bound to other anions than (bi)carbonates.

Dissolved oxygen is a critical indicator of water quality in streams, rivers, and lakes, with higher concentrations signifying better quality. The amount of DO in water fluctuates with pressure, temperature, and salinity. To measure DO, different methods can be employed such as the Winkler titration method, colorimetric, electrochemical and optical methods (see Section 2.1.1 for more details on the electrochemical method).

[2]Bottle-fed very young infants may be at risk when nitrate (NO_3) concentrations are high in water because nitrates can be reduced to nitrites (NO_2) in their stomachs. Those nitrites can interact with haemoglobin, changing it into a form that is unable to carry oxygen effectively throughout the body.

Manganese and **iron** naturally occur and do not cause health problems in low concentrations. However, in larger quantities, manganese can cause adverse neurological effects. Both elements cause a noticeable bitter taste to drinking water, even at very low concentrations, and increase the turbidity of the water, rendering it unacceptable to most people. **Copper** can be toxic if in too high concentrations and causes undesirable tastes.

Fluoride is naturally occurring in some areas. While beneficial in preventing tooth decay at low concentrations, excessive exposure can lead to dental or skeletal fluorosis.

Biological oxygen demand (BOD) measures the amount of oxygen required by bacteria to decompose organic material present in a water sample. The greater the BOD, the greater the degree of organic pollution in water. The oxygen consumed by microorganisms and bacteria oxygen consumed is the DO in the water. The measure of BOD often takes several days.

The **chemical oxygen demand (COD)** measures the total quantity of oxygen required to chemically oxidise both biodegradable and non-biodegradable substances in water. Since it accounts for all organic compounds, COD levels are usually higher than BOD levels. COD levels can be measured more rapidly than BOD.

A vast number of other chemical parameters found in water may be dangerous to public health, even in trace amounts: toxic inorganic substances (metallic or non-metallic), toxic organic substances (usually man-made pollutants like pesticides or detergents) and radioactive substances [29].

1.3.3 Biological parameters

The presence or absence of living organisms is a significant indicator of water quality. By surveying the fish and insect populations, one can often evaluate the health of natural waters. Certain organisms (flagship species) are also used as bioindicators to detect specific pollutants due to their known sensitivity to those contaminants [29].

<table>
<tr><th>Biological Parameters</th><th>WHO Guideline value</th></tr>
<tr><td>Bacteria</td><td>E. coli: 0 CFU/100mL</td></tr>
<tr><td>Algae</td><td rowspan="3">Recommendations to avoid contamination and for risk management are specified</td></tr>
<tr><td>Viruses</td></tr>
<tr><td>Protozoa</td></tr>
</table>

Table 2.3: Biological parameters of water quality and their corresponding WHO Guideline value [24, 29]

Bacteria are single-celled organisms that can reproduce rapidly under optimal conditions of food, temperature, and pH. They exist in various forms, such as aerobic, anaerobic or facultative, depending if they require oxygen for their metabolism. Most species of bacteria develop fastest with temperatures around 35°C [29]. Bacteria pose risks by causing waterborne diseases like typhoid, dysentery, cholera and Legionnaires' disease. Total coliforms from which Escherichia coli (E. coli) and thermotolerant coliform bacteria, are essential indicators organisms of water pollution. They exist in human intestines and can thus be found in body wastes. Their presence in water indicates the recent contamination of water by sewage. Detecting faecal contamination in water is crucial because it can indicate the presence of pathogenic bacteria, viruses, and protozoa originating from human or animal waste. E. coli is considered the most suitable indicator of faecal contamination and has a guideline specified by the WHO that is of no Culture-Forming Units (CFU) of indicator bacteria detected in a 100 mL sample for drinking water. E. coli also presents some pathogenic strains. Another indicator of faecal pollution are intestinal enterococci that have the advantage of surviving longer in water environments than E. coli (or thermotolerant coliforms) and being more resistant to salinity, drying and chlorination but can also originate from other sources [24].

Algae are microscopic autotrophic plants contributing to wastewater treatment but sometimes causing issues with taste and odour in water supplies. **Viruses** are the smallest biological entities capable of reproduction. They rely on hosts to survive and are known for causing waterborne diseases like hepatitis A or poliomyelitis. **Protozoa** are single-celled microscopic animals, including Giardia and Cryptosporidium, that consume organic particles, can cause gastrointestinal diseases and challenge disinfection processes [29].

The **membrane filtration method** is a technique used to detect and count the presence of bacteria in water. Water samples are passed through a membrane filter with pores small enough to retain bacteria. The filter is then placed on a nutrient medium and incubated, allowing any bacteria present to form colonies. Another technique is the multiple-tube fermentation method or Most Probable Number (MPN) method which is a culture procedure that provides a statistical estimation of the concentration of viable E. coli in water by observing the growth in multiple liquid media tubes under varying dilutions and is based on the principle of extinction dilution. Many other techniques exist like the Heterotrophic Plate Count (HPC) measuring colony formation on culture media of heterotrophic bacteria, the Enzyme-Linked Immunosorbent Assay (ELISA) method using antibodies specific to E. coli to detect its presence, the Polymerase Chain Reaction (PCR) method detecting E. coli DNA sequences. Presence/Absence tests exist and are further described in Section 2.1.2.

1.3.4 Acceptability aspects of water

Microbial, chemical, and physical components in water can influence its appearance, odour or flavour. The perception of drinking water flavour encompasses taste, feeling (mouthfeel and nosefeel), and retronasal odour (see Figure 2.3) [33], and consumers often base their assessment of water's quality and acceptability on these factors as these are the aspects they can perceive with their own senses. These three acceptability aspects influence the perception of safety, and thus the overall water consumption behaviours of consumers. Therefore, it is of utmost importance to ensure safe but also acceptable drinking water. If the water has an acceptability parameter that does not suit consumers, they may lose confidence in the quality of the water and turn to other, potentially less safe, sources. Even if the water is safe to drink, these parameters are essential to ensure that consumers can be confident that it is indeed safe to drink [24].

Acceptability of water is mostly a matter of own perception because studies show that public perception of drinking water quality does not always align with the actual quality of the water [34]. One reason for this is that certain substances can affect the flavour, odour or appearance of water at concentrations much lower than those that pose health risks [24]. *Aesthetic parameters* like magnesium, for example, negatively influence the acceptability of water below the health-based maximum concentration limit [34].

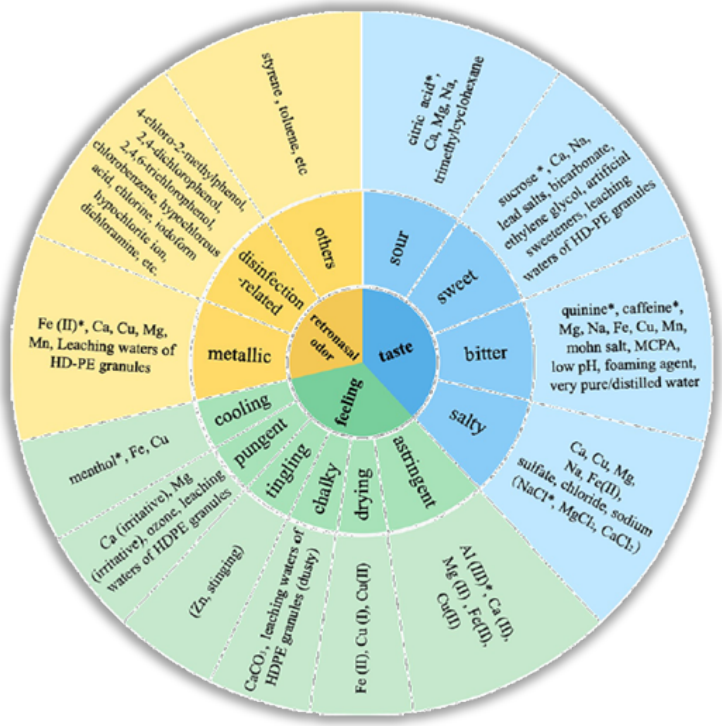


Figure 2.3: Drinking water flavour wheel [33]

Consumers are not the only ones using the acceptability parameters as a benchmark to assess water quality. Some water distribution companies, such as the Belgian water company Vivaqua, pay employees trained to notice changes in water acceptability parameters in order to detect potential contamination. These people, posted at different locations of Vivaqua's water sources, take daily samples and check the odour, flavour and appearance of the water, warning if anything is amiss. This monitoring method comes in addition to the numerous tests carried out on their distribution network, and the parameters that are continuously monitored.

2 Water quality sensors

Monitoring water quality is essential for the prevention of health risks as well as effective management, making the establishment of a water quality monitoring system a top priority for any country committed to addressing water quality issues. While water quality data is crucial for regulators, its value significantly increases when it is accessible to the public [20].

The need for water quality monitoring is leading to the development of numerous innovative water quality monitoring devices testing the physio-chemical characteristics of water, described in Section 2.2. Modern technology can greatly enhance efforts to overcome challenges related to water quality and quantity and make pollution prevention more effective, cost-efficient and achievable. However, some challenges remain, further described in Section 3.4.

Sensors classification can be based on the type of parameter analysed (biological, chemical or physical), the number of parameters (single or multi-parameter) analysed, the way measured data is displayed (wireless sensors that transmit data to the cloud or to another device, data loggers, digital display sensors or colorimetric display sensors) or the type of sensors (digital sensors (pocket meters and professional sensors), paper-based sensors and tests kits). Most sensors for water quality monitoring employ receptors that selectively interact with specific target analytes (analyte-specific membranes, bioreceptors, etc.). These receptors are integrated with transducers, signal processors, and user interfaces to create a complete system (see Figure 2.4) [35]. One of the types of sensor classification is founded on the technology used to measure parameter concentrations, where sensors can be classified based on the type of transducer (optical, electrochemical or mechanical) and further categorised based on the type of detection system used.

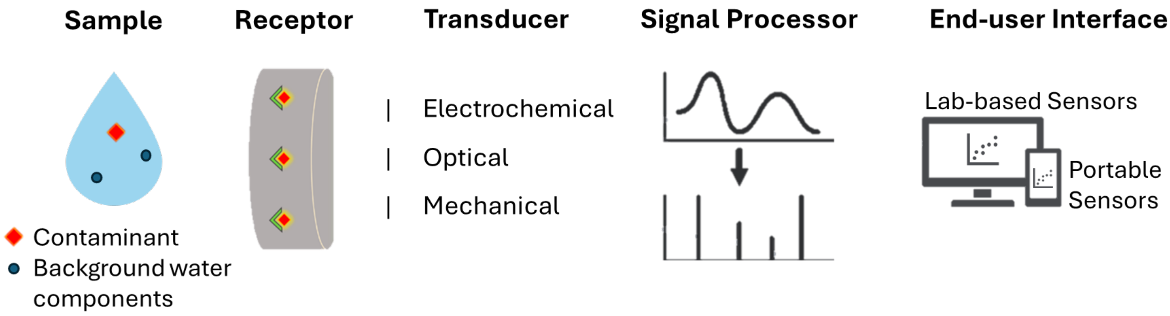


Figure 2.4: Conceptual design and principal components of an integrated digital sensor device (modified from [35])

2.1 Transduction methods

This section describes the most common technologies for measuring water quality parameters based on the type of transducer and its principle of operation. It also gives concrete examples of sensors using the detection technologies described for specific parameters.

2.1.1 Electrochemical devices

Electrochemical sensors measure electrical properties, such as current, voltage, and impedance, produced by reduction or oxidation reactions involving target analytes. They transduce electrochemical information into an analytical signal. These sensors can be further categorised into several types:

1. **Voltammetric** sensors detect analytes by measuring current changes as a function of applied time-dependent potential.

2. **Amperometric** sensors measure current generated by the redox reactions of an electroactive species at a working electrode. This is typically achieved by maintaining a fixed potential at the working electrode, with respect to a reference electrode, and monitoring the current. A third electrode, the counter electrode can be added, completing the electrical circuit in the cell and allowing to maintain a constant potential, regardless of the current. The measured steady-state current is directly related to the concentration of the electroactive species or its consumption or production rate [36].

3. **Potentiometric** sensors measure the electrical potential difference between working and reference electrodes, with no substantial current flowing between them. The

potential of the reference electrode remains constant during the test, but the working electrode's potential fluctuates with analyte concentration. **Ion-selective electrode (ISEs)** are a form of electrochemical sensor that detects ion concentrations in water by employing a selective membrane designed for specific ions, such as heavy metals. The potential difference across this ion-selective membrane corresponds to the concentration of the target ion in the solution and may be estimated using the Nernst equation [36, 37, 38]. **Gated field-effect devices (ChemFETs)** are based on traditional field-effect transistor architecture, which includes a source, drain, gate, and a semiconducting channel. In ChemFETs, the gate is modified to respond to specific chemical interactions. An example is **Ion-sensitive field-effect transistors (ISFET)**, a type of field-effect transistor that detects changes in ion concentration. The analyte-selectivity is implemented through an ion-selective membrane applied directly to the gate of the transistor. The gate of the transistor is thus sensitive to ion activity in the solution, leading to changes in the source-drain current, which is then transduced. Field-effect transistors have been demonstrated for monitoring physicochemical water quality, including ions and pH. It is suitable for on-site testing due to its ease of low cost and quick response [38, 39].

4. **Impedance-based** sensors, also called Electrochemical Impedance Spectroscopy (EIS)-based sensors, measure impedance changes by supplying low sinusoidal voltage to the electrochemical system at different frequencies and measuring observed resultant current. Impedance changes as a function of frequency are obtained and the results are analysed in terms of equivalent circuits [37].

5. **Conductometric** sensors use conductivity measurements in a material or medium to determine analyte concentrations. **Chemiresistive** sensors are made of two electrical contacts connected by an active layer, which is the interface with the sample. Chemiresistors detect the presence of analytes through changes in the electrical conductivity of the active layer [39]. Direct contact with the analyte is required.

Most electrochemical sensors, such as ion-selective electrodes, are prone to high maintenance and frequent calibration. Indeed, the effectiveness of electrochemical sensors is fundamentally limited by the quality of the reference electrode used, representing a critical vulnerability in their long-term functionality [39].

Transduction method	**Detection principle**
Potential	Potentiometry (ion-sensitive electrodes), ChemFET
Generated current	Amperometry, voltammetry
Conductance/resistance	Chemiresistor, bulk conductance
Impedance	Electrochemical impedance spectroscopy

Table 2.4: Classification of electrochemical transduction methods (based on [39])

pH Glass Electrode Traditionally, pH is measured using either colorimetric or potentiometric methods (glass electrodes). However, many other techniques exist, such as ISFETs for example[40]. Standard digital sensors measuring pH use a glass electrode, with a H_+-ion selective porous glass membrane, and a reference electrode which produces a constant and stable voltage (see Figure 2.5). The voltage measured between the two electrodes is proportional to the activity of the H_+ ions contained in the solution, and results can be displayed either in mV or, after conversion with the Nernst equation, in pH units.

The working electrode and the reference electrode can be housed in the same body (referred to as combined electrodes) or mounted separately (separate electrodes). The slope of the Nernst equation relating measured potential with pH values changes with temperature. Consequently, a compensation method is required to achieve higher accuracy. This process can be automated if the temperature is measured simultaneously by the sensor, or it can be done through manual compensation by providing the sensor with the temperature or by keeping the buffer calibration solutions and the solutions at the same temperature. While temperature compensation can adjust for changes in electrode sensitivity due to temperature, it cannot predict how the pH of the sample itself changes with temperature. This is the opposite of conductivity measurements, for which the mathematical relationship between conductivity and temperature is well understood, and measurements can be brought to a reference temperature of 25°C for meaningful comparison. The pH glass electrode needs to be maintained in preservation solutions because the glass membrane of a pH electrode must remain hydrated to function correctly. It helps preserve the reference electrolyte solution. Moreover, reference junction (see Figure 2.5) contamination happens when the junction becomes clogged, which is the most sensitive part of the electrode, directly influencing its lifetime [42].

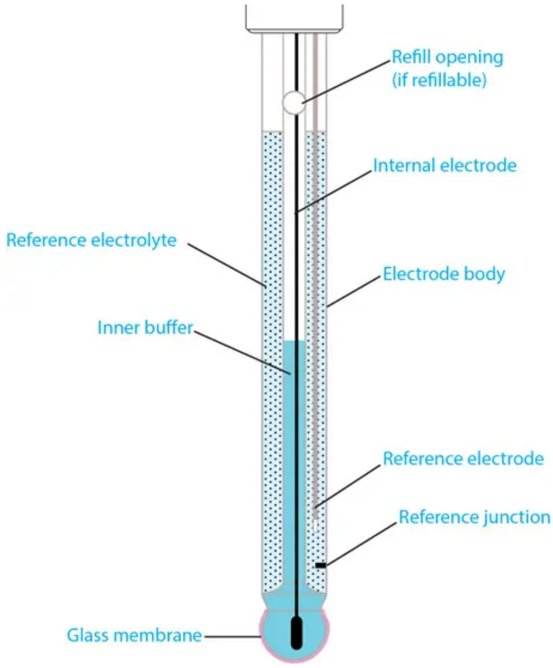


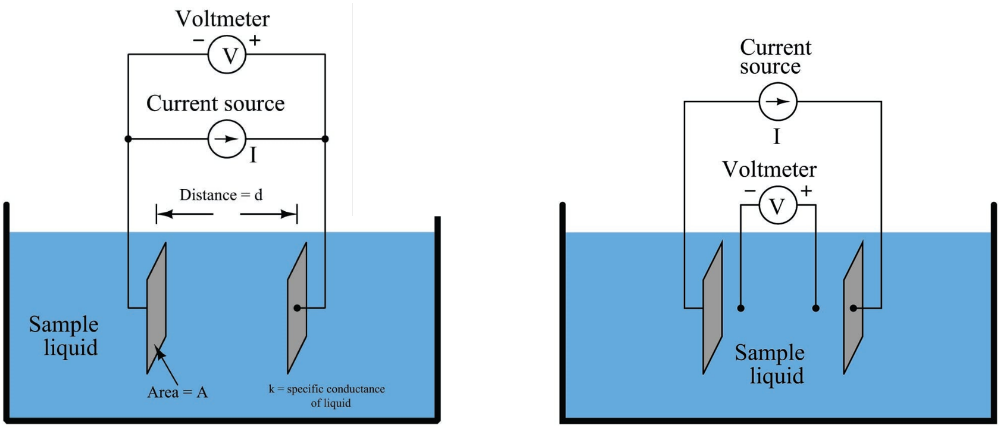
Figure 2.5: Combined pH glass electrode [41]

Electrical Conductivity meter As stated before, conductivity is a measure of the capacity of the water to conduct electricity and is directly related to its ion concentration. It is a non-specific method, as it is unable to distinguish the nature of the ions. Conductivity is obtained through a measure of conductance which can be measured with a EC meter composed of:

- **2-electrode probes** (Figure 2.6a): an alternating current is applied to two electrodes immersed in a sample causing the anions to move toward the positive electrode and cations toward the negative one, making the sample act as an electrical conductor. The resulting potential is measured. This method is used for low conductivity values as errors due to the polarisation of the electrodes might occur with high concentrations (high ion concentration leads to mutual repulsion of ions and, therefore, a reduction in current).
- **4-electrode probes** (Figure 2.6b): measurements over a wider conductivity range are allowed by using two additional external rings to prevent polarisation. The alternating current is applied to these external rings to establish a potential difference between the internal electrodes which is measured.
- **Inductive probes or toroidal sensors**: composed of a transmission and a reception coil. Conductivity is measured based on the induced magnetic field and the resulting

current in the reception coil. They are primarily used in industrial applications (very high conductivity) and are thus not applicable to field measurements.

Unlike pH electrodes, conductivity probes do not wear out or change over time, potentially having a very long lifespan with proper use, though the cell constant (used in the conductivity calculations) can change if the surface is altered by trapped air bubbles, fingerprints, scratches, or salt deposits [42].



(a) EC meter with 2-electrodes (b) EC meter with 4-electrodes

Figure 2.6: Portable EC meter [43]

Dissolved Oxygen Clark electrode The Clark sensor is an amperometric sensor composed of a Clark electrode or polarographic electrode measuring the dissolved oxygen (DO) concentration. It is composed of a platinum or gold cathode and a silver/silver chloride anode connected electrically through an electrolyte. The electrolyte and the sample are separated by a permeable membrane that allows oxygen to diffuse (see Figure 2.7).

A constant voltage is applied to the electrodes, causing oxygen to diffuse through the membrane and reduce at the cathode, generating a current flow. The current is directly proportional to the partial pressure of oxygen outside the membrane, which is converted using the ideal gas law ($PV = nRT$) to saturation [%] or concentration values [mg/L]. The oxygen concentration near the electrode can become depleted, resulting in lower readings than the actual bulk concentration. To ensure accurate readings, a convective flow must continuously replenish the oxygen at the electrode surface, which is typically achieved by stirring the solution. The sensor often also includes a temperature sensor for compensation because the oxygen solubility in water is highly

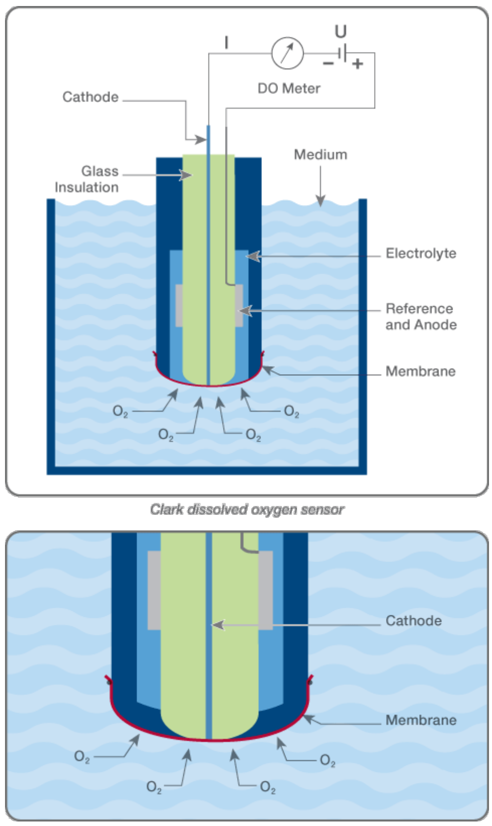


Figure 2.7: DO Clark electrode [44]
Cathode reaction $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Anode reaction: $A_g^+ + Cl^- \rightarrow A_gCl + e^-$

dependent on temperature and the diffusion of oxygen through the membrane of electrochemical changes with temperature due to variations in molecular activity. Increasing salt concentration leads to a decrease in oxygen solubility. The Clark electrode can also be galvanic if composed of a zinc cathode. The Clark electrode has a limited operational lifespan, and regular maintenance is required to replace the membrane and electrolyte solution, which can be labour-intensive. The response time can be relatively slow compared to other modern sensors, particularly if the membrane is thick or if there is significant fouling. This can be a limitation in situations where rapid changes in dissolved oxygen levels need to be detected. The cathode should always be smooth and shiny, but it tends to tarnish, which reduces the sensitivity of the system and can prevent calibration. This can be remedied by gently rubbing the cathode. Another method to measure DO is with an optical probe which is more costly but has the advantage of minimal maintenance requirement because no consumables or parts (such as membranes) need to be replaced. This significantly reduces downtime for maintenance, eliminates costs associated with replacing spare parts, and requires less expertise. Moreover, it does not consume oxygen, does not require flow for its operation and is less impacted by interference due to other gases [42, 44].

2.1.2 Optical devices

1. **Colorimetric** sensors evaluate the presence or concentration of a substance based on the colour of a surface or solution. Qualitative or quantitative measurements can be done either manually by visual inspection (often with tools like comparator charts), semi-automatically using instruments such as colorimeters or photometers, or fully automated with specialised sensor optics. In most cases, it requires chemical reagents. The most simple versions of such sensors are paper strips where the reagents are immobilised on the strip (see further). Visual colour changes of those strips can be interpreted without sophisticated equipment (with the naked eye or a smartphone camera). Colorimetry is the most widely used optical detection method, providing a simple and cost-effective approach. When performed manually, it has the advantage of eliminating the need for specialised equipment. Nevertheless, this technique has poor sensitivity and also suffers from subjectivity issues in the interpretation of colour if done manually. These are common in paper-based assays and lateral flow devices [37, 39].

2. **Absorbance based** sensors measure changes in light absorbance on the binding of target analytes, often using colorimetric reactions to indicate the presence of specific chemicals [37].

3. **Fluorescence, chemiluminescence and phosphorescence** sensors use luminescent labels for detecting target analytes with high sensitivity. They measure the light emitted by the sample following a stimulus [37, 39].

4. **Surface plasmon resonance** can occur when plane-polarised light hits a metal film under total internal reflection conditions (free electrons on a metal surface collectively oscillate when they interact with light). Surface plasmon resonance-based devices detect changes in the refractive index due to the binding of the analyte to the sensor film (also called refractometric sensors) [35, 37].

5. **Surface-enhanced Raman spectroscopy** is a light scattering technique in which a molecule scatters light from a high-intensity laser, with most light scattered at the same wavelength (Rayleigh Scatter), but a small fraction scattered at different

wavelengths depending on the analyte's chemical structure (Raman Scatter). It is a non-contact mode of analysis [35, 37].

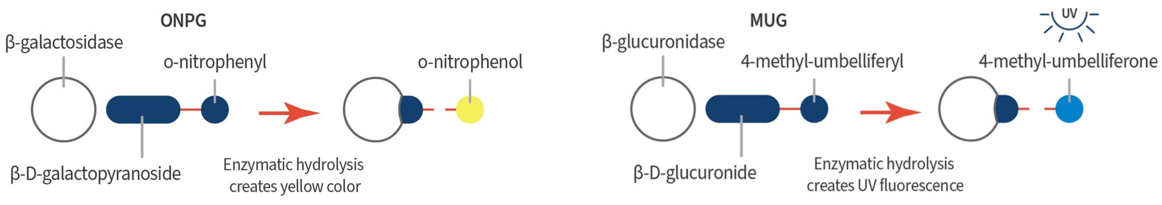
6. **Evanescent field-based fiberoptic** sensors can be used to monitor fluorescence, refractive index changes, absorbance spectroscopy via the evanescent field or detecting spectroscopic shifts [37].

Optical sensors can sometimes be simple to use manually and, in some circumstances, designed for remote monitoring, but they often rely on the addition of reagents and sophisticated optical setup, which limits portability and real-time monitoring [39].

Smartphone reading devices Those devices allow low-cost optical chemical and biological sensors to be integrated with smartphones using cameras and image processing software, offering a user-friendly interface for easy operation [35]. For example, smartphones can be combined with colorimetric methods and can be integrated with optical fibres [45]. However, achieving high accuracy and sensitivity in analysis remains a challenge.

Remote sensing technologies Spaceborne and airborne Sensors employ satellite imaging or aerial photography to monitor large-scale water quality characteristics, including turbidity, algal blooms, suspended sediments and temperature fluctuations. They are based on optical sensors and measure reflected or emitted electromagnetic radiation from water bodies to infer physical, chemical, and biological aspects [35]. While remote sensing is effective for assessing some parameters of water quality, it lacks precision when used alone and should be complemented by traditional sampling methods and field surveys [46].

Bacteria Presence/Absence tests Test bottles can be used to detect bacteria like coliforms in water. They contain a Presence/Absence broth consisting of a nutrient solution that supports the growth of coliform bacteria and contains a pH indicator. During the incubation time, if coliform bacteria are present in the sample, they will multiply and metabolise the nutrients in the broth and, by doing so, will modify the pH of the solution. This will cause the indicator to change colours.



(a) Coliform detection (b) E. coli detection

Figure 2.8: Enzyme substrate Bacteria test [47]

Detection can also be done with enzyme substrate coliform tests where the broth contains a chromogenic indicator, traditionally ortho-nitrophenyl-β-D-galactopyranoside (ONPG), that is hydrolysed by an enzyme, β-galactosidase, produced by total coliform bacteria, resulting in a coloured compound (see Figure 2.8a). It is possible for the broth to also contain a reagent (fluorogenic indicator 4-methylumbelliferyl-β-D-glucuronide (MUG)) producing a fluorogenic product when hydrolysed by enzymes specific to E. coli (β-glucuronidase), as indicated in Figure 2.8b. Since E. coli contains both enzymes, a positive result for E. coli in a water sample will change the sample's colour and cause it to fluoresce

[47]. This straightforward and cost-effective method does not require complex equipment or extensive technical training, making it accessible for on-site testing in various settings, including remote or resource-limited areas. The bacteria test bottle is a single-use testing method and results are not immediate (incubation time). Most tests combine both methods (pH and enzymes).

Paper strip indicators Test strips, sometimes also called dipstick assays or dip-and-read test strips, are easy-to-use indicator tests to assess one or various water quality parameters. Regular test strips are typically made of paper with chemical reagents embedded on them that react with a specific quantity of analytes in the water (colorimetric method). Aperture test strips are composed of a thin colour indicator chemical-impregnated membrane where the solution can pass through thanks to a back-and-forth motion (as shown in Figure 2.9). This enhances the sensitivity of the test strips, enabling them to detect lower concentrations of analytes compared to traditional test strips [48].

The tests are performed by simply dipping the strip into the water sample for a specified period and then comparing the colour change to a reference chart. Results are typically available within a few minutes, even a few seconds, making them ideal for rapid assessments. They provide semi-quantitative results, indicating the magnitude of contamination based on the colour change after dipping the strip in the water sample. They are compact, lightweight and adapted to be used in the field. Moreover, they are generally inexpensive compared to other sensing techniques, making them accessible for regular monitoring. However, as stated before, they have poor sensitivity and also suffer from subjectivity issues in the visual interpretation of colour. They are single-use and need to be stored properly. An example is the **universal pH indicator**, which is composed of several indicators, such as, among others, methyl red and phenolphthalein, that display a range of colour changes across a wide spectrum of pH values, indicating the acidity or alkalinity of a solution. Universal indicators are available as both paper strips (dye-infused paper strips) and liquid solutions.

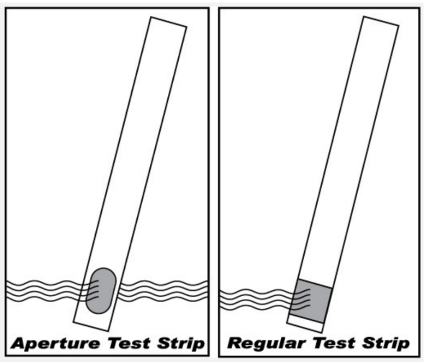


Figure 2.9: Paper-based Indicators [48]

2.1.3 Mechanical devices

There are other systems for detecting water quality parameters, such as those based on changes in mass due to the presence of the analyte (mechanical transduction), which can be detected due to changes in the resonance frequency of an oscillating crystal or beam [39]. **Piezoelectric sensors** detect when a target analyte binds to a piezoelectric surface because it causes a frequency shift in the oscillation, which changes the piezoelectric current. This change in current is directly proportional to the mass of the analyte, enabling the sensor to quantify the analyte based on the frequency variation.

2.2 Promising water monitoring technologies

Electrochemical, optical, and mechanical transduction methods can be used to detect physical, chemical, and biological water quality parameters, in the latter case we speak of biosensors (see Section 2.2.1). Transduction methods and detection principles can be integrated into portable platforms such as miniaturised and multiplexed probes, paper-based assays, lateral flow devices, microfluidic systems (i.e., lab-on-a-chip devices), and sensors can be connected to digital platforms or satellite imagery for remote assessment of water quality [35]. This section describes those technological aspects and the different promising emerging contaminant detection platforms, such as paper-based assays, lateral flow assays, and microfluidic-based devices. These platforms are suitable for in-situ measurements and provide rapid and easy diagnostics.

2.2.1 Biosensors

Electrochemical, optical and mechanical technologies can be used to measure biological parameters when coupled with biological recognition elements such as enzymes, aptamers, or antibodies that selectively bind target analytes, resulting in a measurable response that is transduced into an electrical, optical or mechanical signal [37]. Those sensors can be, among others, enzyme-based sensors, aptasensors or immunosensors depending on the recognition element used [35]. The field of biosensors is currently a focus of extensive research due to ongoing innovations. A review by Kumar et al. summarises recent developments in biosensors and sensing systems based on a variety of transducer technologies for water quality monitoring with a specific focus on rapid pathogen detection [37].

2.2.2 Point-of-use sensors

Point-of-care (POC) devices are sensors providing a rapid localised assessment of contamination by a target analyte [49]. They are often associated with the health sector to provide diagnostics near the patient. In the water sector, "point-of-care", "point-of-use" and "point-of-test" sensors all refer to compact portable sensors that allow on-site water quality monitoring by containing miniaturised detection setups. POC biosensors have the potential to revolutionise health care and disease prevention in both developing and developed countries by providing rapid, accurate, easy to operate and specific detection of microorganisms causing water-related diseases [40]. To guide the development of point-of-care sensors, the WHO recommended they adhere to the ASSURED criteria, which were revised as the REASSURED criteria due to rapid digital technology advancements: Real-time connectivity, Ease of specimen collection, Affordable, Sensitive, Specific, User friendly, Rapid and Robust, Equipment free or Environmental friendliness, and Deliverable to end-users [50] (see Appendix A for detailed specifications). Those criteria are applicable across many point-of-use sensing applications in resource-limited settings [2].

2.2.3 Paper-based assays

Paper substrates are promising for creating low-cost, simple and portable sensors, especially point-of-care biosensors. The use of cellulose-based membranes offers advantages such as a high surface area-to-volume ratio due to their porosity, efficient absorption, and biocompatibility, which makes it easy to immobilise bioreceptors. Additionally, paper-based sensors are inexpensive to manufacture, degradable and accessible, with minimal chemical handling required. Traditionally, these sensors use the inherent capillarity of paper for qualitative or semiquantitative colorimetric detection, providing visual colour changes. Well-known paper-based sensors present on the market are the traditional paper test strips and Lateral Flow Assays (LFAs) [40]. While paper-based sensors have limitations in terms of accuracy and sensitivity, they are attractive candidates for point-of-care applications [40]. Technologies that combine paper-based substrates with nanomaterials, microfluidics (due to their high capillarity), and electrical sensing to provide precise quantitative measurements are being researched to improve sensitivity and quantification [3, 40].

2.2.4 Lateral flow assays

Lateral flow assays (LFAs) are paper-based devices allowing low-cost in-situ tests [51]. LFAs are under intensive development because of the new prospects that come from using of nanotechnologies and nanomaterials [52]. Well-know LFAs are pregnancy or SARS-CoV-2 tests. LFAs are usually composed of four overlapping paper-based pads called sample pad, conjugate pad, membrane and absorbent pad. The sample is initially placed on the sample pad and flows through the different pads due to capillary forces.

Standard or sandwich LFAs use bioreceptors (often antibodies) labelled with gold nanoparticles or other particles present in the conjugate pad that will recognise the target analyte if it is present in the sample. The sample flows through the membrane and reaches the test line and control line. On the test line are fixed capture antibodies, which are specific to the target analyte and will thus be bound to the analyte-bioreceptor compound if the targeted analyte is present in the solution. The control line is composed of control antibodies, which are not specific to the labelled bioreceptors meaning the line should always appear coloured. A single red line indicates a negative result and two coloured lines mean a positive result [51].

Competitive LFAs: In the case of competitive LFAs, the test line is composed of immobilised target analytes. This means the analyte present in the sample and the immobilized analyte on the test line will compete for binding with the labelled bioreceptor (antibody). The presence of the target analyte in the sample prevents the labelled antibody from binding to the immobilised analyte at the test line, reducing or preventing the formation of a visible line. This means that a positive result corresponds to only one line, in contrast to standard assays. Competitive LFAs are particularly useful for small analytes that don't have two binding sites [52].

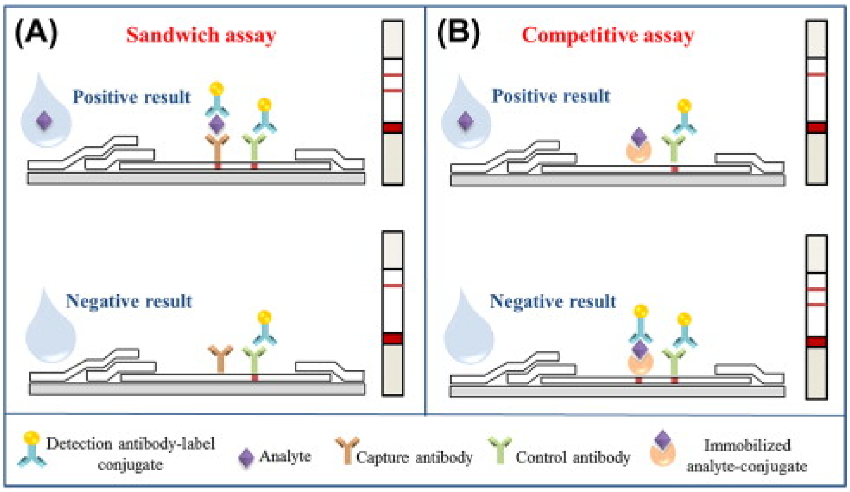


Figure 2.10: General working principle of LFAs: standard assay (left side), competitive assay (right side) [52]

Nanoparticles play a crucial role in LFAs as they are used as labels to provide results. The most common way results are displayed is through colorimetry, which allows results to be read with the naked eye. As the signal produced on the test line is proportional to the amount of target analyte in the sample, analytical quantitative results can also be obtained through various transducing methods, including optical, electrochemical, and magnetic approaches. Fluorescent detection in LFAs is possible using nanoparticles that emit light when excited, but it requires additional equipment, making it less suitable for point-of-care devices [53]. Alternatively, electrochemical and magnetic detection methods can be done with conductive and magnetic nanoparticles, respectively [54, 55].

LFAs have limitations due to the restricted volume of sample needed (higher amounts could deteriorate the strip), and results are mainly qualitative because electronic/electrochemical transduction remains a challenge and as specificity and sensitivity issues can occur [56, 52]. Moreover, sandwich-type LFAs are often limited by the false negatives occurring when analytes are present in very high concentrations; this is called the "high-dose hook effect". In the presence of excess target analyte, the amounts of labelled bioreceptors are insufficient to bind to all the target analytes to form *analyte-labelled bioreceptor* complex. The free target analyte then competes with the *analyte-labelled bioreceptor* complex to react with capture antibodies on the test line [57].

2.2.5 Microfluidics

Microfluidics is a discipline that manipulates small volumes of fluids, applications are microminiaturised devices composed of channels with dimensions of tens to hundreds of micrometers. Microfluidic sensors use principles including laminar flow, capillary forces, and diffusion in those small-scale channels to control liquids and execute complicated analytical tasks in a tiny device [35]. It has advantages such as faster reaction times, better process control, system compactness and parallelisation, minimal sample requirement, on-site application and reduced cost [40, 58]. Microfluidic devices may be made from a variety of materials such as paper, glass or polymers, each with unique qualities based on their intended use or application. Microfluidic devices can be combined with electrochemical and optical methods for detecting various chemical and biological contaminants in water. **Lab-on-a-chip (LOC)** devices are an example of POC sensors and are miniaturised systems that integrate various laboratory functions, including sensing elements, processing components and microfluidic channels, onto a single platform for multiplexed detection of analytes in water samples [35]. Research on microfluidic-based analytical sensors is booming and is at the core of many lab-on-a-chip devices [58]. Charbaji et al. developed a paper-based microfluidic device for detecting nitrate in water [59] with a limit of detection and quantification of 0.53 ppm and 1.18 ppm, respectively. Alonzo et al. propose a microfluidic device performing a rapid and highly sensitive bacteriophage-based assay to detect E. coli [60]. This sector of research and applications holds great promise for the future of sensors but continues to encounter substantial hurdles, such as interference due to the complexity of the water matrix [61], limited test throughput and the need for increased automation [59] or rapidity [60].

2.2.6 IoT Integrated devices for water quality monitoring

The Internet of Things (IoT) refers to a network of interconnected devices and systems that communicate and exchange data over the Internet. Water quality sensors, coupled with transmission capabilities, can collect and share data in real-time, enabling continuous and remote monitoring of water quality. Once the data is stored in the cloud, it opens up possibilities for data analysis, optimisation, and real-time decision-making. While IoT applications for real-time water quality monitoring are projected to minimise operational and logistics costs while increasing the number of sites monitored, a number of challenges must be addressed, including availability, reliability, performance, scalability, interoperability, and security [31]. Sensors transmitting data in real time exist but are often very expensive. A less costly option is to couple low-cost sensors with microcontrollers and transmission devices, like Arduino or Field Programmable Gate Array boards and Zigbee chips, to allow smart monitoring of water [62]. Large-scale sensor deployment, when done by integrating substantial data volumes with sophisticated data analysis methods like machine learning and Geographic Information Systems, can provide crucial insights into the distribution of the contaminants' effects on the environment. Another method to obtain better spatial and temporal coverage is Citizen Science, which is discussed in detail in Section 4.

3 Market-based analysis of existing portable sensors

This section contains a market-based review of existing portable sensors, relating their characteristics such as brand, monitored parameter(s), monitoring technology, detection range, and approximated price range. This market study is not exhaustive but aims to give an overall picture of the technologies available and their specifications. The different sensors are classified in function of their type with colours: colorimetric test bottles, colorimetric paper-based sensors, pocket format sensors and professional single- or multi-parameter portable sensors (see Figure 2.11). Optical and electrochemical sensors are distinguished (light and dark grey, respectively), and sensors costing less than 50 euros have their price highlighted in pink.

Figure 2.11: Sensor types classification

3.1 Portable sensors market for general physicochemical parameters monitoring

General physicochemical parameters of water quality are electrical conductivity, salinity, Total Dissolved Solids, Total Suspended Solids, turbidity, temperature, pH, Oxidation-Reduction Potential, hardness, alkalinity, Dissolved Oxygen, Chemical Oxygen Demand and Biological Oxygen Demand. As a reminder, those parameters represent overall water characteristics and refer to multiple underlying chemical species. As shown in Table 2.12, many portable sensors exist on the market to measure temperature, pH, ORP, hardness, alkalinity, DO, EC/TDS[3] and salinity. Some sensors measuring those parameters are very low-cost (<50, No. 18 - 26), and others, more robust and accurate, are costly (>400 EUR, No. 6 - 8, 11 - 16). Most pocket meters' prices are situated between those two extremes. Some very low-cost pocket meters measuring EC and pH exist because those parameters have well known and commercialised detection methods (2 electrodes and glass electrodes). More expensive sensors have more calibration points, providing very accurate results for

[3]Electrical Conductivity and Total Dissolved Solids are presented together as TDS values are based on EC measures (see Section 1.3.2)

broad measurement ranges, but have a more complex calibration procedure. Sensors with fewer calibration points see their accuracy drop outside the ranges around their calibration points. In all cases illustrated here, EC, DO and pH measurements are done with a 2 or 4 electrodes sensor, a glass electrode sensor and a polarographic electrode sensor, respectively. BOD, COD, TSS and turbidity sensors, on the other hand, are rare and expensive. The method to measure those parameters is often complex, requiring more expensive parts. In general, single- or multi-parameter sensors with storage or transmission capabilities, often refers as "professional sensors", are very expensive and complex to operate (long manuals).

No.	Manufacturer	Parameter	Sensor model	Detection method	CAL	Range	Cost [EUR]
2	Horiba	pH	PH-33	glass electrode	5	0 to 14 pH	130
3		EC/TDS/T°	EC-33	2 electrodes	3	EC: 0 to 199.9 mS/cm	130
4		Salt (NaCl)	Salt-11, Salt-22	2 electrodes (EC conversion)	2	0 to 100 ppt	160
5		ORP	ORP-11	ORP electrode	1	-1000 to 1000 mV / 1 mV	230
6		pH/ORP/EC/TDS/Salinity/Resistivity/T°	Laqua PC220	EC: 4 electrodes, pH: glass electrode	5 (EC), 6 (pH)	EC: 0 - 200.0 mS/cm, ORP: ± 2000 mV	910
7		pH/ORP/DO/Temperature	Laqua PD220	pH: glass electrode, DO: polarographic	2 (DO), 6 (pH)	ORP : ± 2000 mV DO: 0 to 20 mg/L	1,100
8		PH/ORP/DO/EC/TDS/Salinity/Seawater Specific Gravity/Turbidity T°	U-53	EC: 4 electrodes, pH: glass electrode, DO: polarographic	5 (EC), 2 (pH)	EC: 0 to 100 mS/cm, ORP: ± 2000 mV, DO: 0 to 50 mg/L, Turbidity: 0 to 1000 NTU	3,700
9	Hanna Instruments	Salinity	HI98319	2 electrodes (EC conversion)	2	0 to 10 ppt	93
10		PH/EC/TDS	HI98130	EC: 2 electrodes, pH: glass electrode	1 (EC), 2 (pH)	EC: 0 to 20 mS/cm	179
11		EC/TDS/Resistivity/Salinity/T°	HI98192	EC: 4 electrodes	5 (EC)	EC: 0 to 400 mS/cm	1,300
12		pH/EC/DO	HI98199	EC: 4 electrodes, pH: glass electrode	6 (EC), 4 (pH)	EC: 0 to 200 mS/cm; DO: 0 - 50 mg/L	1,700
13		DO, DBO	HI98193	Polarographic	2 (DO)	DO: 0 to 50 mg/L	1,400
14	Solnist	EC/T°/Water level	107 TLC Meter	EC: 4 electrodes	4	EC: 0 to 80 mS/cm	980
15	Eureka	Turbidity/T°/pH/EC (ORP)	Manta+30	NA	NA	EC: 0 to 275 mS/cm	NA
16	Hach	Turbidity	2100Q	Optic (nephelometry)	1	0 to 1000 NTU	1,000
17	Unbranded	DO	JPB-70A	Polarographic (Clark electrode)	2	0 to 20 mg/L	127
18		pH/EC/TDS/Salinity/S.G./ORP	C-600	EC: 2 electrodes, PH: glass electrode	1 (EC), 3 (pH)	EC: 0 to 400.0 mS/cm	25
19	BMUT	TDS/EC/T°	BMUT 3 in 1 tester	2 electrodes	0	EC: 0 to 10 mS/cm	14
20		PH	BMUT pH tester	glass electrode	3	0 to 14 pH	14
21		Total Hardness,	BMUT Total Hardness	Colorimetric paper-based indicator	/	0,25,50,120,250,425	0.36
22		Total Hardness, Total alkalinity, Carbonate Hardness, pH, ...	BMUT 16 in 1	Colorimetric paper-based indicator	/	Hardness: 0,25,50,120,250,425 pH: 6, 6.4, 6.8, 7.2, 7.6, 8.2, 9	0.19
23	Simplex Health	Total Hardness, Total alkalinity, pH, ...	Test strip 5 in 1	Colorimetric paper-based indicator	/	Hardness: 0,25,75,150,300, 1000 pH: 5.5, 6.5, 7, 7.5,8, 8.5, 9.5	1.2
24	Smardy Blue	Total Hardness, Total alkalinity, pH, ...	Smardy 9 in 1	Colorimetric paper-based indicator	/	Hardness: 0,5,10,15,20,25 pH: 5.5, 6.5, 7, 7.5,8, 8.5, 9.5	0.85
25	JBL	Total Hardness, Carbonate Harness, pH, ...	JBL PRO SCAN	Colorimetric paper-based indicator	/	pH: 5.8 - 9.4	1
26	Unbranded	pH	Universal indicator	Colorimetric paper-based indicator	/	1,2, ..., 13, 14	<0.02

Figure 2.12: Market-based overview of general parameter portable sensors
Legend: dark grey = electrochemical method, light grey = optical method, NA = no data available, pink = price < 50 EUR, other colours: see Figure 2.11

3.2 Portable sensors market for ions and molecules monitoring

As shown in the non-exhaustive Table 2.13, several portable sensors for measuring specific ions and molecules exist, though they only cover the most encountered ions. The affordable sensors only exist as paper-based indicators that give semi-quantitative results. The sensors providing quantifiable data are expensive (>50 EUR), and if the sensor is required to calibrate or needs a high detection range, prices are above 400 EUR. Indeed, the less expensive colorimetric sensors (photometers) are not equipped with calibration. Colorimetric methods need reagents to operate (additional costs) and more complex measurements.

No.	Manufacturer	Parameter	Sensor model	Detection method	CAL	Range	Cost per test [EUR]
1	Horiba (Laquatwin)	Sodium (Na^+)	Na-11	Ion-selective electrode	2	2 to 9900 ppm	400
2		Potassium (K^+)	K-11	Ion-selective electrode	2	4 to 9900 ppm	450
3		Nitrate (NO_3^-)	NO3-11	Ion-selective electrode	2	6 to 9900 ppm	430
4		Calcium (Ca^{2+})	Ca-11	Ion-selective electrode	2	4 to 9900 ppm	450
5		Fluoride (F^-)	F-11	Ion-selective electrode	2	0.1 to 990 ppm	400
6	Hanna Instruments	Free and Total Chlorine (Cl_2)	HI97711	Optic (photometer)	1	0.00 to 5.00 ppm	690
7		Total Chlorine	HI711	Optic (photometer)	0	0.00 to 3.50 ppm	117
8		Iron	HI721	Optic (photometer)	0	0.00 to 5.00 ppm	101
9		Fluoride	HI739	Optic (photometer)	0	0.0 to 20.0 ppm	117
10		Fluoride	HI729	Optic (photometer)	0	0.00 to 2.00 ppm	117
11		Nitrite	HI708	Optic (photometer)	0	0 to 150 ppm	101
12		Nitrate	HI781	Optic (photometer)	0	0.00 to 5.00 ppm	101
13		Manganese	HI709	Optic (photometer)	0	0.0 to 20.0 ppm	117
14	Sensafe	Manganese	Manganese Check	Colorimetric paper-based indicator	/	<0.02, 0.05, 0.1, 0.2, 0.5, 1.0, and 2.0 ppm	1.2
15	Simplex Health	Nitrites, Nitrates, ...	Test strip 5 in 1	Colorimetric paper-based indicator	/	Nitrate: 0, 20, 40, 80, 160, 200 ppm	1.2
17	Smardy Blue	Free Chlorine, Iron, Copper, Lead, Nitrates, Nitrites, ...	Smardy 9 in 1	Colorimetric paper-based indicator	/	Nitrate: 0, 10, 25, 50, 100, 250, 500 ppm Free Chlorine: 0, 0.5, 1, 3,5, 10, 20 ppm	0.85
18	JBL	Nitrites, Nitrates, Chlorine,	JBL PRO SCAN (digital result)	Colorimetric paper-based indicator	/	Nitrate: 0, ..., 500 ppm Free Chlorine: 0, ..., 2.5 ppm	1
19	BMUT	Free and Free Chlorine, Iron, Copper, Lead, Nitrates, Nitrites, Fluoride, Bromine, ...	BMUT 16 in 1	Colorimetric paper-based indicator	/	Nitrate: 0, 10, 25, 50, 100, 250, 500 ppm Free Chlorine: 0, 0.5, 1, 3,5, 10 ppm	0.19

Figure 2.13: Market-based overview of ion and molecule portable sensors.
Legend: dark grey = electrochemical method, light grey = optical method, pink = price < 50 EUR, other colours: see Figure 2.11

3.3 Portable sensors market for coliforms and E. coli monitoring

As a reminder, total coliform and, more specifically, E. coli are the main bacterial indicators of water quality. One of the main limitations of the portable sensor market is the absence of quantitative bacteria sensors. The only low-cost options are bacteria test bottles and lateral flow assays (presence/absence results). Besides being qualitative, the time needed for the tests to provide results is very long. Indeed, incubation is required for several hours to several days except for testers with lower detection limits testing several species of bacteria. Test No. 5 takes 15 min before results but is not specific to coliforms and the detection limit is 10^5 times too high for relevant bacteria results in drinking water (0 CFU/100 mL). Moreover, incubation temperatures outside laboratory settings are challenging to control, leading to uncertainties regarding the incubation time needed before relevant results.

For comparison, a qualitative test kit for coliforms containing an incubator, and thus coping with the latter shortcoming, is listed (No. 7). However, this incubator needs a connection to an electrical socket for the power supply (not portable), causing the price of the tests to increase. More expensive (>1,000 EUR) (semi-)quantitative bacteria test kits exist. They were not listed here as they present the same limitation because they are composed of equipment that is not portable (because the power supply is not adapted) and need a laboratory setting as well as trained users.

No.	Manufacturer	Parameter	Detection method	Range	Accuracy	Time	Price per test [EUR]
1	AquaVial	Total coliforms & E. coli	Colorimetric (pH)	P/A	1CFU/mL	24 to 72 h	9.48
2	Medasa	Total coliforms & E. coli	Colorimetric (pH)	P/A	1CFU/10mL	24 to 48 h	7.49
3	SimplexHealth	Total coliforms & E. coli	Colorimetric (pH+Enzyme)	P/A	1 CFU/100mL	24 to 48 h	15.43
4	La Motte	Total coliforms & E. coli	Colorimetric (pH+Enzyme)	P/A	not specified	24 to 48 h	4.98
5	SenSafe (Quick)	Coliform and non-coliform bacteria	Colorimetric (LFA)	P/A	1000 CFU/mL	15 min	9.97
6	Merck (Singlepath)	E. coli O157	Colorimetric (LFA)	P/A	5 CFU/100mL	18 to 24 h	9.12
7	C4 hydro	Colifroms & E. coli	Colorimetric	P/A	<0.1CFU/100mL	24h	104.5

Figure 2.14: Market-based overview of low-cost bacterial portable sensors
Legend: P/A: presence/absence (qualitative), pink = light grey = optical method, price < 50 EUR, other colours: see Figure 2.11[4]

Many studies also performed similar reviews of emerging devices and techniques that are at the research and development stage [38, 63]

3.4 Shortcomings of existing water quality sensors

. Most water contaminants detection processes described in Section 2.1 or mentioned in Section 1.3 are time-consuming, laborious and require sample pretreatment, reagents, electrical sockets for power supply, trained operators, as well as heavy, bulky and very expensive devices. The expensive instruments are often very fragile and need high maintenance. As a result, most methods, procedures and the resulting sensors are adapted for laboratory settings and thus unfit for in-situ measurements [31, 40]. Additionally, this leads to a lot of laboratory-based technologies not being accessible or affordable in resource-limited areas lacking basic infrastructure and/or professionals. Examples of conventional techniques to detect contaminants that need to be performed in laboratory conditions by highly skilled operators are most bacteria detection methods (plate counts, membrane filtration method, polymerase chain reaction, etc.), atomic absorption spectroscopy, mass spectroscopy and others (described in Section 1.3.3 and Appendix A). These traditional procedures are accurate and sensitive, but they cannot be miniaturised in affordable portable sensors. However, rapid on-site monitoring is necessary to allow for quick decision-making, minimise transport bias (there is a risk of data alteration due to sample transport), and reduce the need for frequent, expensive laboratory testing.

As a result, compact, user-friendly, and cost-effective point-of-use devices with high specificity and sensitivity that allow for on-site detection are catching the attention of researchers [40]. Point-of-use sensors are advised to follow the REASSURED criteria (see Section 2.2.2 and Appendix A). A lot of research and notable progress has been made on promising water monitoring technologies (lateral flow assays, nanomaterials and microfluidic principles, see Section 2.2) improving receptor interfaces and miniaturising transduction methods. However, as technical and socio-economical challenges remain, those progresses are rarely transposed into commercially available sensors.

A study evaluating challenges faced by sensor developers when trying to make proof-of-concept sensors into practical and usable technologies shows that most of them struggle

[4] *pH* and *Enzyme* refer to the bacteria detection method (see Section 2.1.2

with remaining technical challenges related to cost, complexity, limited sensitivity and selectivity, the impacts of the water matrix, lack of robustness in real-world environments, lack of portability, difficult manufacturing and complicated integration of sensor components to achieve precise, accurate, and user-friendly operation. Non-technological challenges consist, among others, of lack of funding, lack of partnerships with potential end users, lack of understanding of the market needs and lack of design according to feedback from stakeholders. Moreover, there is an increasing number of water-related studies, but a lot of research is driven by scientific curiosity instead of replying to stakeholders or user needs [35]. The research on point-of-use sensors shapes the future outlook of water monitoring but several steps need to be taken before the developed technologies become available.

As a result of the difficulty of miniaturisation of traditional measurement methods as well as the lack of commercialisation of promising innovations, very few to no commercial sensors comply with REASSURED criteria, even partly. The market-based overview shows that some few parameters, such as pH and conductivity, can be easily detected using robust, accurate, and portable methods. These methods can be low-cost when lower accuracy is sufficient. However, accurate and rapid portable sensors for other parameters such as turbidity and BOD are either non-existent or very expensive. Additionally, it was established that, for ion and molecule monitoring, semi-quantitative measures (test strips) were the only available very low-cost sensors (below 50 EUR), quantitative colorimetric sensors around 100 euros are available but have limited ranges and no calibration is possible while methods with better sensitivity (electrochemical) and accuracy are more expensive. Moreover, there is a lack of portable biosensing technologies providing close-to-real-time affordable quantitative detection of biological parameters and water-borne pathogens [37]. Commercially available portable sensors most often include high-cost logistics and professional equipment such as professional multiparametric sensors [31]. Existing low-cost sensors do not always provide the accuracy, precision, and reliability required for specific applications (e.g., low-cost tests that provide qualitative or semi-quantitative results). Overall, this leads to affordable and cost-effective on-site testing to remain restricted in resource-limited environments.

It is important to note that REASSURED criteria do not capture context-specific requirements and a systematic methodology to determine those design requirements is lacking [2]. Additionally, as no test is perfect and all detection methods have advantages and shortcomings, trade-offs between cost, accuracy, accessibility and other criteria are often needed [39, 50]. This leads to an additional reason, besides guaranteeing sensor uptake, to know the end-user's priorities for sensor characteristics. To identify those and avoid disconnection of sensors from end-users needs, interaction with end users is needed in early design stages [2, 35, 64]. This is explained further in Section 5.

4 Citizen science methodology for water quality & environment monitoring

Citizen Science (CS) is a form of scientific research that actively involves the public in various stages of the scientific process, from formulating research questions and collecting data to interpreting results and sharing findings [65]. The citizens engage volountary in scientific research, mostly collaborating with professional scientists. By promoting the general public's participation in science, CS makes research accessible to citizens, benefiting both science and society.

Citizen science projects are significantly gaining popularity, with research activities flourishing in geoscience, ecology, atmospheric science, and physics. These projects are particularly thriving in environmental science encompassing, though not exhaustively, air quality, water resources monitoring and water quality, weather patterns, as well as tracking climate change and ecosystems, including detailed inventories of fauna and flora, monitoring of wildlife and assessing biodiversity.

The growth of citizen science projects is partly due to the rapid advancement and decreasing costs of sensors and user-friendly computer and telephone applications [66]. Smartphones and the internet allow easier and broader gathering of data and more convenient public notification about these projects [67, 68].

CS enables extensive coverage of large areas for testing that would be unmanageable for a single researcher, facilitating the collection of a considerable volume of data across significant regions. CS widens the scope and scale of data collection (spatially, temporally and in terms of quantity). It complements traditional scientific data collection methods and knowledge generation [69].

Additionally, CS reduces the cost of data gathering [70] and these programs offer significant added value by ensuring that scientific findings are accessible beyond the scientific community, thereby democratising science and ensuring that knowledge does not remain confined to scientists alone. The societal relevance of science is improved, which can lead to a greater impact on the research outcomes [71]. For example, studies indicate that CS initiatives related to water issues raise participants' awareness of water concerns but also foster a better appreciation for the environment.

However, the impacts on participating communities and citizens in CS projects are often overlooked. While benefits for participants are frequently mentioned, they are rarely explained or thoroughly investigated, leaving them as potential rather than confirmed benefits. Negative impacts are rarely considered, despite their possible commonality and importance in the implementation of citizen science. As citizen science continues to grow in the water sciences, it is crucial to consider both the actual positive and negative effects on participants and communities to ensure an effective approach [67].

Full acceptance of the data generated through CS is hindered by accuracy and quality concerns. While there might be apprehensions about non-experts misinterpreting the data they collect or the data generating unwarranted worries among participants, e.g. misinterpreting water quality results because of lack of knowledge on water quality parameters and their guidelines, these concerns should not overshadow the significant contributions and opportunities that citizen science offers [66]. Training, in particular, contributes to enhancing the accuracy and validity of data as well as coping with the potential lack of knowledge of citizens [69].

CS presents a number of challenges, one is to be able to maintain the long-term commitment of volunteers. Indeed, the CS study's success is based on the choice of citizen scientists: the citizens must be motivated and interested in the project. If motivation is lacking, participants will not follow the protocol or even not deliver results at all. Moreover, diversity among the volunteers and social inclusively is needed (which is highly dependent on the recruitment strategies [71]) for representative results. Therefore, a preliminary survey for citizens' recruitment is essential[5]. This emphasises the need for localisation- and context-specific CS projects that cater to the unique characteristics and requirements of the participants and the communities they serve [66]. The success of monitoring programs based on Citizen Scientists relies on the establishment of a stable partnership between volunteers, specialists, and corporate sponsors. Good collaboration, clear communication and ongoing support to maintain engagement and data quality are essential [72]. Moreover, it is important to have a diverse group of citizen scientists (correct recruitment strategies) and train them thoroughly.

4.1 Existing citizen science projects for water quality monitoring

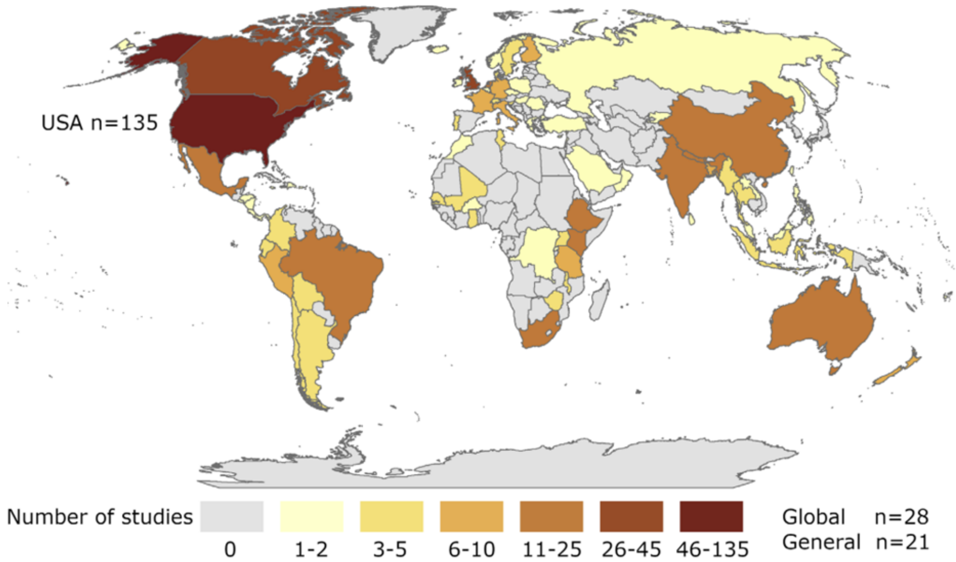


Figure 2.15: Locations and number (n) of published citizen science water projects [68][6]

Many CS projects and research around water quality have been conducted worldwide over the past years, as shown in Figure 2.15. CS is growing rapidly in the field of water sciences and is increasingly recognised as a major method for data collection and environmental monitoring on a global scale as well as for engaging the public in meaningful scientific studies [73]. It can address challenges in traditional water management approaches [74].

As stated before, CS in the water sector is developing rapidly, partly due to the fast development and increasing accessibility of sensors. Indeed, the development of durable, affordable, and easy-to-use sensors enables greater general public participation in scientific research along with Information and Communication Technologies facilitating the flow of data and knowledge [75]. The technology supporting citizen science is advancing rapidly but still needs more scientific development (see Section 3.4).

As a result, citizen participation in water quality monitoring is often confined to gathering data such as water samples, visually gaugeable parameters (water level, colour, etc.), general water quality parameters measurable with affordable sensors (see Section 3), or other indicators like macro-invertebrates, due to the specialised knowledge and equipment

[5]Stated by Sabi Kidirou Gbedourorou, UCLouvain, 2024

[6]This study focused on freshwater (rivers, lakes, groundwater, tap water), marine and coastal studies were not incorporated.

required for more advanced analyses as well as their cost. This corresponds to crowd-sourced data which uses citizens as "sensors" to make basic measurements. In the case of crowdsourcing projects, especially those involving sensors, the training phase is crucial as well as ongoing support during the entire project. The test procedure must be explained in detail and theoretical activities and practical training activities demonstrating the sensor manipulations enable participants to gain knowledge and ensure correct equipment use [72].

Studies assessing the accuracy of data collected by citizen scientists sometimes show mixed results [75]. However, most studies demonstrate that community-based hydrometeorological and water quality monitoring programmes can provide reliable high-quality measurements comparable to formal observations [76, 77, 70, 72]. Data collected by citizens passed quality control standards and have been statistically validated against formal sources [76]. An example is a study evaluating the effectiveness of low-cost, ready-to-use test strips for monitoring nitrate water quality through CS in the Medjerda watershed, which showed that, while standard methods are more reliable, test strips used by citizens can provide convenient and accurate nitrate measurements. With proper training, citizens can effectively use the test strips and monitor water quality [72]. It is demonstrated that, with suitable support, non-scientists can significantly contribute to scientific research on drinking water [66, 78].

Studies exploring the role and value of involving citizens in drinking water research by looking at a specific CS project show that transparency on water quality data clearly functioned as a strong confidence-inducing signal for citizens [66]. In general, CS projects increase general public understanding and trust in science [71].

5 User-based assessment methods for determination of design priorities of environment monitoring sensors

As stated before, there is a need for sensors that align with the actual requirements of users, especially in resource-limited environments. However, sensors are often developed without direct user interaction, potentially leading to a mismatch between the sensors and the users' needs. Sensor development is generally done in 4 stages: design, laboratory testing, laboratory validation, and field testing. Interaction with end-users does not usually occur before the later stages of development, such as sensor field testing, noting that these are not systematically held either, despite their importance. Indeed, validation of the sensors is often performed in controlled laboratory environments, while they might not be as effective in real-world environmental conditions. It is necessary to incorporate user feedback early in the sensor development process to create effective and user-friendly water quality sensors. Designing a sensor tailored to end-users can be done by involving stakeholders and end-users to understand their needs: the desired performance metrics, cost considerations, and user-interfaces of the sensors [2, 35].

Despite this, academic research typically concentrates on specific technical challenges faced by proof-of-concept sensors for transitioning to usable technologies, like the performance of transducers. However, a comprehensive approach to sensor design is needed, integrating all sensor components, such as end-user interfaces. The principles of user-centred design emphasise the importance of understanding the user's needs, involving users throughout the development process, and iterative design. The users' profiles, tasks and environment should be understood to make products more satisfying and easier to use as well as to reduce errors [79]. This concept is mostly used in software design but these principles can be applied to the development of water quality monitoring technologies to ensure they are user-friendly and meet expectations. Such iterative design process with user involvement can lead to a potential increase in time and budget but will increase technology uptake.

5.1 Previous research on user-based sensor design

A study on water quality monitoring systems describes the guidelines for the design of Hydrologic Information Systems for measuring, processing, storing, and disseminating watershed data, including quality and quantity of surface water and groundwater. The first step in developing Hydrologic Information Systems involves understanding how the data will be used and identifying the potential users of this data. To ensure the Hydrologic Information System meets the needs of its users, it's crucial to consult with them at the beginning of the development process. The study emphasises the need for an institutional review, to understand the mandates, roles and aims of the agencies involved, as well as the importance of data needs identification to correctly address the water resource issue and provide data that water stakeholders will effectively use. The study encourages collaboration among water-related agencies to avoid duplicating monitoring efforts and insists on the need to prioritise objectives given that budgetary and resource limitations might restrict the number of locations [9]. Other studies overlooking roadblocks to the innovation of water quality sensors emphasise the need for stakeholder involvement in early stages of development [35], and indicate that few actually perform user needs assessments.

A study, led by Bono et al., aims to identify design priorities for microbial point-of-use water sensors through fieldwork in rural India composed of several interviews with end users, i.e. rural residents. The work aims to demonstrate a systematic approach for determining context-specific design priorities for sensing applications intended for use in resource-limited settings. Meetings with governmental and non-governmental organisations provided insights into water quality management of the region. Moreover, Knowledge, Attitude, and Practice interviews were conducted to understand local perceptions and practices regarding water quality. Group design workshops where participants identified key design attributes of sensors were performed. Finally, choice-based conjoint analysis interviews were done to quantify user preferences among the identified design attributes (reusability, type of output, time to results, ingredient addition, and cost per test). To understand participants' comfort and attitudes toward point-of-use water testing, they were shown a demonstration of a commercial sensor. Participants then tested the water themselves and shared their thoughts on the ease of use [2].

This study highlights the importance of engaging multiple stakeholders which provides a comprehensive understanding of the context and needs. Collaborating with local organisations is primordial to facilitate fieldwork and ensures research benefits the local community. Moreover, demonstrating existing technologies helps gauge user responses and preferences. The design priorities that were found are integrated reporting of contaminant concentration and recommended actions, reusable sensors, same-day results as well as combined ingredients for simplicity. Users showed a strong preference for sensors that provide actionable information and are easy to use and maintain [2].

The study acknowledges several limitations, such as the relatively small sample size, which may not fully represent the diversity of the rural population. It is important to keep in mind that the focus of the study was on a specific region and country, which may not capture the varying water quality challenges and user needs across other resource-limited regions. Moreover, participants were recruited through NGO partners and may have been those already engaged in community activities or with existing awareness of water quality issues, possibly introducing selection bias [2].

Another report produced by the Comprehensive Initiative on Technology Evaluation from the Massachusetts Institute of Technology, whose purpose is to develop methods for product evaluation in global development countries, evaluated water test kits in India. The study compared existing single- and multi-parameter water test kits by assessing their technical performances in laboratory settings as well as through surveys and observation of users manipulating the sensors. For single-parameter test kits, ease of use, availability, affordability and demand were evaluated by participants for two tests from different brands. For multi-parameter test kits, a desk review was performed, and test kits were selected to be evaluated along six criteria: technical performance, ease of use, availability, affordability, demand generation and environmental impact. Expert opinion of the importance of each of the six criteria was converted to scores. The opinion of the individual interviewed decision-makers was weighted using their level of authority. Consensus among the stakeholders was obtained for ease-of-use, affordability and technical performance [64].

To summarise, including stakeholders and end-users in the early stages of the development of sensors is of utmost importance to avoid a misalignment between the user needs and the ones perceived by sensor developers. When developing sensors, the aim is often to respond to an issue linked to water monitoring in a specific context. In order to understand what are the causes, collaboration with local organisations is necessary. Working with local partners will allow to use their established community partnership, therefore facilitating fieldwork and ensuring research benefits the end-users. Involving users continuously and performing iterative testing with prototypes will lead to the best results [2]. During the fieldwork validation stage of a sensor's development, technical performance in field tests conducted by real users should be evaluated. Ease of use cannot be evaluated without working in the field with potential users [64].

Chapter 3

Water Sector of the Philippines and Metro Cebu: Context & Expertise

This chapter provides an overview of the water situation in Metro Cebu, Philippines and identifies relevant local stakeholders. First, the general state of water resources across the Philippines is detailed before the national institutional framework of the water sector is depicted. Key government agencies and relevant policies influencing water governance are identified. The hurdles to integrated water resource management in the country are specified. Thereafter, the chapter examines the roles played by Metro Cebu's relevant stakeholders, as well as water resources quantity and quality. Additionally, it shows how the local population's choice of water sources and their trust in water provision impact the water sector. The chapter concludes with a discussion of the local water expertise in Metro Cebu, providing insights into the challenges for effective water resource management and monitoring in the region.

1 Water resources and quality in the Philippines

The Philippines, constituted of 7,641 islands representing an area of more than 300,000 square kilometres, is divided into three island groups: Luzon, Visayas, and Mindanao. The country has a growing population, estimated at 119 million, ranking 13^{th} in the list of countries by population [80], as well as a growing economy where water supports major industries like agriculture, tourism, and semiconductors [81]. In 2017, the irrigation sector represented about 76% of the water usage based on awarded water use permits, making it the primary consumer of water in the Philippines [82]. The sectors of the economy that use water intensively hold 42% of the country's jobs [83]. In 2024, the country's Gross Domestic Product is expected to grow between 6 to 7% [84]. However, the income gap between urban and rural populations is high [83].

The country faces a significant water scarcity problem, driven by increasing water demand and decreasing water supply leading to around 10% of the population having no access to a basic water supply[1]. Many households and individuals, particularly in rural communities, are neglected regarding access to improved water sources [28, 85]. Only 48% of the population uses safely managed drinking water services [86]. Several factors, including population growth, urbanisation, inefficient water management, and the impacts of climate change exacerbate this scarcity. A study by the World Resources Institute forecasts that

[1] As this classification is based on the JMP service ladder (see Section 1.2.1), it might overlook some water insecurity dimensions like adequacy, reliability, accessibility, and safety [26].

by 2040, the Philippines will face a *high* level of water shortage. The country is ranked 57^{th} out of 167 countries most likely to experience significant water stress [87].

Many emerging contaminants pollute water resources due to poor wastewater management, and lack of investment in a circular water economy [37]. The incidence of food and waterborne diseases rises with increasing poverty and peaks during the rainy season [88]. In 2022, 31% of all illnesses are attributed to polluted waters [89, 90]. The leading causes of diarrhea are contaminated food and water, making it one of the top 10 causes of morbidity and mortality in the country.

The Philippines has a climate characterised by high temperatures, significant humidity, and abundant rainfall [91]. The country's climate is strongly influenced by El Niño Southern Oscillation events whose frequency and intensity are impacted by climate change. The phases of the climate pattern lead to extreme climate events/variability (longer and more intense droughts and flooding), which negatively affect major water reservoirs in the country [92]. Indeed, water supply availability is highly susceptible to variations in river flows and to the rate at which groundwater resources are replenished [82].

2 Philippine water governance and water policy

The Philippines is a unitary presidential constitutional republic. The President serves as both the head of state and the head of government. The government is divided into three interconnected branches: legislative, executive and judicial [94]. Additionally, the country features a decentralised governance structure, where local governments have the ability to self-govern. Each of the 17 administrative regions of the country is divided into Local Government Units (LGUs) at the provincial (82), city (146), municipal (1,488), and barangay (42,046) levels, each led by a local executive: a governor, a mayor or a barangay captain, respectively [95]. Barangays are thus the smallest administrative division and are equivalent, in metropolitan areas, to suburbs. Some highly populated cities are independent cities which are not subject to provincial supervision. Figure 3.1 depicts the Philippine local governance structure in one of the administrative regions.

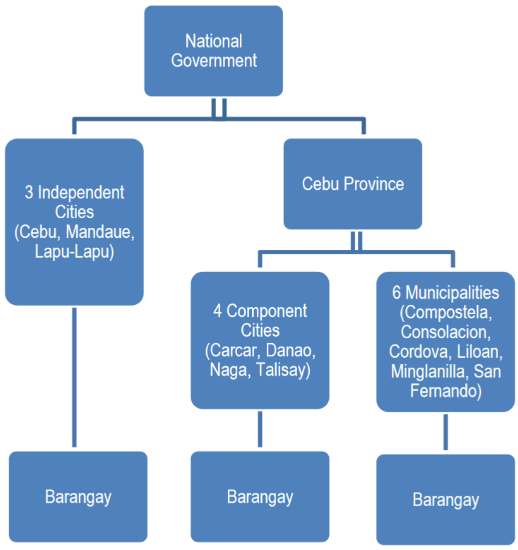


Figure 3.1: Philippine Governance: example of Central Visayas region [93] (national LGU structure also detailed in Figure B.4 in Appendix B)

The country is classified into 12 Water Resource Regions (WRRs) based on natural, river basin and hydrological boundaries. The WRRs' and the 17 administrative regions' boundaries do not match (see Table in Figure 3.2 and Figure B.2 in Appendix B), meaning that multiple LGUs often share common water resources. This leads to fragmented policies, driven by local interests rather than the needs of the entire water basin [96]. The distribution of water resources is eneven, especially considering population densities, leading to shortages in heavily populated areas due to complicated water allocation. For instance, the Central Visayas region (VII) consists of 7.4% of the national population but contains merely 2% of the country's water resources. Central Visayas region (VII), Calabrazon

Water Resource Region	Approximate Administrative Region	MCM/ year	Share (percent)
WRR 1 Ilocos	Region 1 + CAR (partial)	4,498	3.1
WRR 2 Cagayan Valley	Region 2 + CAR (partial)	11,335	7.8
WRR 3 Central Luzon	Region 3	9,611	6.6
WRR 4 Southern Tagalog	Region 4A + 4B + NCR	7,780	5.3
WRR 5 Bicol	Region 5	4,145	2.8
WRR 6 Western Visayas	Region 6	15,344	10.5
WRR 7 Central Visayas	Region 7	2,939	2.0
WRR 8 Eastern Visayas	Region 8	11,907	8.2
WRR 9 Southwestern Mindanao	Region 9	13,182	9.0
WRR 10 Northern Mindanao	Region 10 + 13	31,116	21.3
WRR 11 Southeastern Mindanao	Region 11	13,675	9.4
WRR 12 Southern Mindanao	Region 12 + ARMM	20,458	14.0
TOTAL		145,990	100

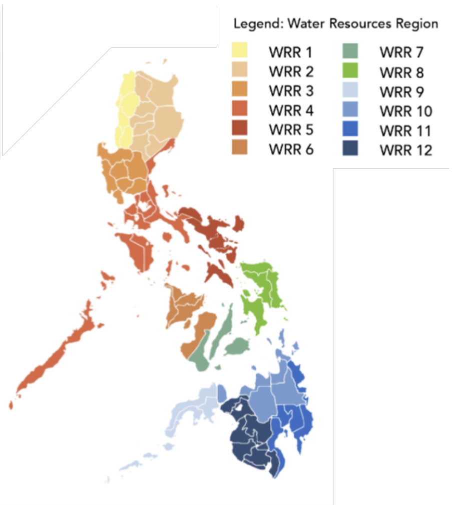


Figure 3.2: Water Resources Regions and Water Resources Potential [81]

region (IV) and National Capital Region (NCR) already face absolute scarcity because the water supply is below 500 m^3 per person [81]. A Japan International Cooperation Agency (JICA) study conducted a water balance assessment for all the WRRs and identified Central Visayas (VII), along with Bicol (V) and Southeast Mindanao (XI), as priority WRR as they are projected to experience significant water balance challenges in the future [97]. Overall, the country's water resources are deteriorating, and it is crucial to effectively measure and manage water [82].

2.1 Key government agencies and their water-related functions

Water management in the Philippines is a highly multilayered, complex and fragmented system involving a diverse array of more than 30 different organisations. These range from national to local levels, and all have their own power based on their mandate, resources, and legitimacy recognition by the public. Coordination among these agencies is generally lacking; they often have overlapping and conflicting mandates [98]. Such a setup undermines the adoption of an Integrated Water Resource Management, which promotes a unified and coordinated approach to managing water resources holistically across different sectors [81]. The fragmented framework for water supply hinders service delivery and resource protection. Despite having a national policy and many laws governing water resources, the implementation of water resource management varies greatly at the local level and many laws are not properly enforced [98, 99].

2.1.1 National legislative level

The **National Economic and Development Authority (NEDA)** develops policies and targets for the water supply and sanitation sector [100]. Most of the other key government agencies involved in the water sector, except the Department of Tourism, do policy planning [98].

2.1.2 National executive level

The state, which owns property rights to all water, awards individual or municipal/collective rights through water permits. The **National Water Resources Board (NWRB)** is the agency responsible for issuing those permits. Its main mandate is the comprehensive management of the nation's water resources and the resource regulation of most Water Service Providers (WSPs) (authorising them to operate and regulating water exploitation) [81, 101]. Another regulating agency is the **Local Water Utilities Administration (LWUA)**, which oversees and supports the development of water distribution networks beyond Metropolitan Manila (economical, technical and operational regulation). The regulatory framework for water in the Philippines is primarily overseen by those two main government-owned and controlled bodies. Table B.2 in Appendix B further describes their regulatory involvement.

Countless other agencies have regulatory mandates related to the water sector. One of them is the **Department of Environment and Natural Resources (DENR)**, which is the primary government agency in the Philippines responsible for supervising the management of the country's natural resources and environment [102]. The National Water Resources Board is an attached agency and is under the DENR's supervision.

Under the DENR also lies the **Environmental Management Bureau (EMB)**, which plays a crucial role in ensuring environmental protection through the enforcement of environmental laws, including those related to water quality. It is responsible for monitoring water bodies' quality as well as water effluents and sets appropriate environmental quality standards. It has regional offices responsible for water monitoring in their designated area but does not cover all regions [99, 103]. One of EMB's key roles is the classification of the 1,019 identified water bodies in the country according to their intended beneficial use (see Table 3.2 in Section 2.2) [104].

Another role of the EMB is the establishment and management of **Water Quality Management Area (WQMA)** (see *Philippine Clean Water Act of 2004* in Section 2.2), which are designated regions with specific water bodies targeted for protection and improvement due to their significance to ecosystems and human populations. The objective of the WQMA is to protect, through stakeholders' collaboration, the water body by keeping their water quality within the Water Quality Guidelines (WQG) in conformity with the water body's classification or even by improving the quality to meet a higher classification [105].

The **Department of Health (DOH)** is responsible for setting, revising and enforcing drinking water quality standards. It is also responsible for giving accreditation of laboratories for drinking water analysis and issuing Initial and Operational Permits for the Development and Operation of Drinking Water Supply Systems. While most national water institutions have regional counterparts governed by national laws, they do not have a grasp on water quality in all regions and local areas.

2.1.3 Local level

Local Government Units provide water and sanitation services to many households, either directly or indirectly through community-based organisations such as cooperatives, Barangay Water and Sanitation Associations, and Rural Water Supply Associations. LGUs are supported by government-owned and controlled corporations, the **Local Water Districts (LWDs)**, which are responsible for the installation and operation of water supply and distribution systems [81]. Many other Water Service Providers exist and there is a trend towards increased private sector participation. Many large and small-scale private operators supply water [98]. Local water entities often show a limited understanding of the applicable laws [98].

Figure 3.3 depicts a non-exhaustive layout of the different agencies involved in the water sector. It shows their often overlapping and conflicting mandates. Each agency generally has independent strategies and programs resulting in a duplication of efforts or clashing projects and activities [81]. Besides the Departments of Tourism and Finance, most key agencies do data monitoring [98]. Their description and functions are further detailed in Tables B.1, B.3 and Figure B.5 in Appendix B.

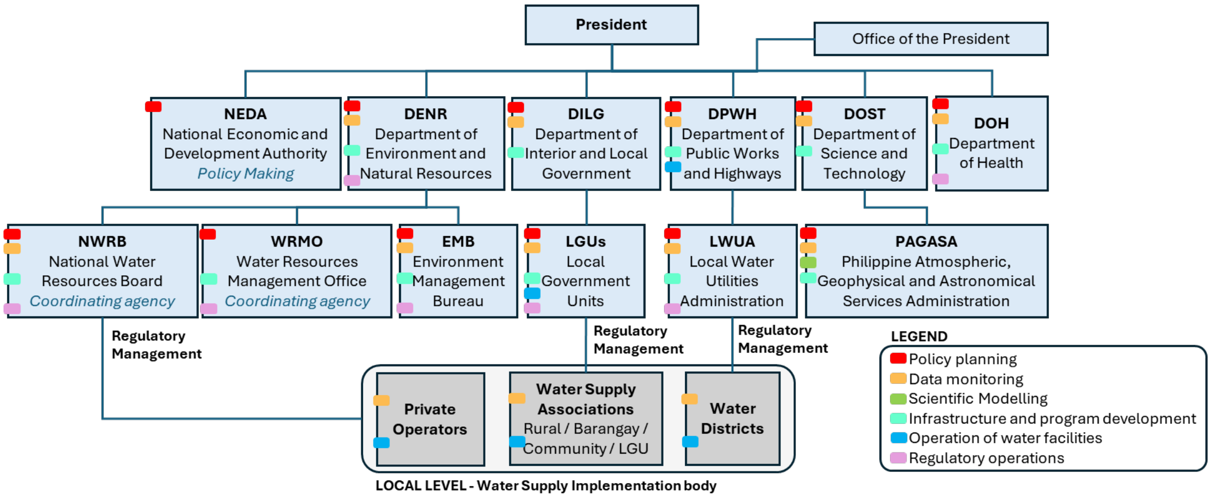


Figure 3.3: Non-exhaustive structure and organisation of major water-related organisations (Blue = national agencies; Grey = Water Service Providers - local level). Source: based on the JICA study (as of 2022) [97, 98]

To date, no law has been passed to create an independent regulatory body responsible for both resource and economic regulation of water. This leads to the following issues in the water sector, hindering an Integrated Water Resource Management [81, 98, 99, 106]:

- **Non-systematic approach** to water resource management. Weak and fragmented institutional set-up and scattered expertise.
- **Unclear definition and delimitation of roles and responsibilities** leading to overlapping and conflicting mandates/priorities. Frequent changes in responsibilities and jurisdictional confusion.
- **Insufficient coordination** between agencies for water policy, planning and strategies: duplication of efforts and conflicting agendas. Failure to take interdependencies into account leads to overlooked broader efficient solutions.
- **Inconsistencies in standards and enforcement of water policy**. The implementation of many laws is still in the development stage. Lack of compliance inspection leads to unauthorised groundwater extraction.
- **Lack of a basic shared centralised water data collection system** leads to an inefficient information flow and lack of data-driven decisions. Monitoring relies on the availability of laboratory facilities, with limited monitoring in more remote areas and of some water quality analytes.
- **No regular updating of water availability data**. Inefficient use of water and illegal extraction worsen water availability uncertainty.

- **Insufficient financial support and resources** (human resources, time and equipment) for sector programs, projects and water monitoring.
- **Inefficient use and wastage of resources**: degradation of water-related infrastructure and water resources due to inefficient management and planning (e.g., Saltwater Intrusion).
- **Lack of public awareness** of the crucial role of water resource management.

To cope with the management issues, the creation of the Water Resources Management Office (WRMO) was approved in February 2023 as the central agency, under the Department of Environment and Natural Resources, to coordinate water-related activities [81, 107]. Despite its role, the WRMO's ad hoc, non-permanent status and lack of policy independence cause it to be influenced by DENR's mandate and prevent it from resolving overlaps and conflicts within the water sector [81].

Creating an independent Department of Water Resources is thus one of the country's priorities, enabling more effective Integrated Water Resource Management and a water sector reform. The agency will be the main entity tasked with planning, policy development, management, allocation, exploitation, development, and protection of water resources in the Philippines. A Water Regulatory Commission will also be established. It will be an independent and quasi-judicial body under the Department of Water Resources and will solely be responsible for issuing operating licenses, regulating water and sanitation tariffs, and ensuring that service providers meet performance standards [81, 97]. The legislative process to establish the Department of Water Resources and the Water Regulatory Commission has started; the Act creating these agencies has been filed on the 7^{th} of August 2024 in the Senate of the Philippines [108].

2.2 Relevant policies

While the Philippines has many laws and policies designed to manage water resources, the above-mentioned problems prevent those regulations from being fully effective and implemented. Below are relevant water policies and administrative orders:

- **Water Supply Service Level** provided by the National Economic and Development Authority Board Resolution No. 12 (Series of 1995): water supply service level is classified as follows [82, 97]:
  - **Level I System (pointsource)**: a protected well or a developed spring with an outlet but without a distribution system (meaning users go to the source to fetch water), generally adaptable for rural areas where the houses are thinly scattered and also found in dense urban areas. A Level I facility normally serves an average of 15 households.
  - **Level II System (communal faucet system or stand posts)**: a piped system whose components include a source, a reservoir, a piped distribution network, and communal faucets. Users still go to the supply point (communal faucet) to fetch water. This simple piped system is generally present in rural and urban fringe areas where houses are densely clustered. Usually, one faucet serves 4 to 6 households.
  - **Level III System (waterworks system)**: an individual house connection system including a source, a reservoir, a piped distribution network, and

individual household taps. It is generally present in densely populated urban areas where the population can afford individual connections.

Level II and Level III are considered safe sources [82]. The levels of service in percentages per region in 2015 are shown in Figure 3.4.

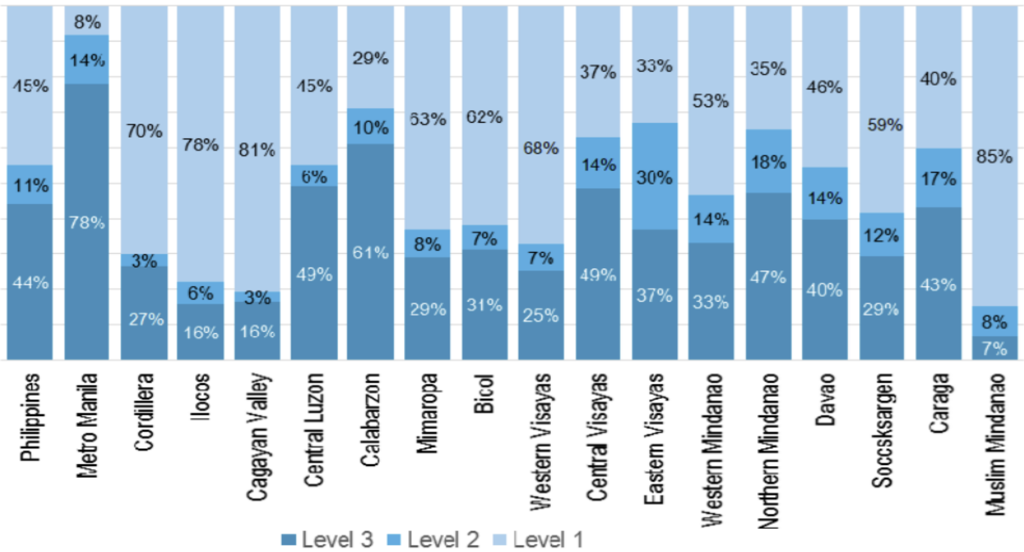


Figure 3.4: Levels of Service in Percentages by Region [82]

- **Philippine National Standards for Drinking Water (PNSDW)**: were developed in 1963 based on the 1958 WHO International Standard for Drinking Water and the 1962 United States Public Health Service Standards. The document was revised several times, with the last version completed in 2017. The PNSDW-2017 applies to all drinking Water Service Providers[2] [109]. It also specifies standards for water analysis methods.

  The drinking water quality parameters are classified as mandatory, primary and secondary. Mandatory parameters are the legally enforceable parameters required to be monitored by all drinking-water service providers (see Table 3.1). Primary parameters are site-specific analytes in water that directly affect health. Lastly, secondary parameters render water unacceptable for drinking, affecting the aesthetic quality of water (taste, odour, and colour). Those do not directly impact health but are essential for consumer acceptance. The minimum frequency requirements for sample examination depend on the type of drinking water parameters and are categorised based on the water supply level (Level I, II or III which varies with the source and mode of supply) and the population served [109].

- **Philippine Clean Water Act of 2004** (Republic Act No. 9275): aims to protect the country's water bodies from pollution (from industries and commercial establishments, agriculture and community/household activities) [90]. As per Section 5 of this act, the DENR in coordination with NWRB was tasked to designate certain areas as

[2]Government and private developers and operators, bulk water suppliers, water refilling station operators, and water vending machine operators; ice manufacturers; all food establishments, residential, commercial, industrial and institutional buildings that use/supply/serve drinking water; water testing laboratories; health and sanitation authorities; the general public and all others who are involved in determining the safety of public's drinking water.

No.	Parameter	Maximum Allowable Level (MAL)	Sampling Location
1	Thermotolerant Coliform (*E. coli*)	$>$ 1 MPM/100ml (Most Probable Number)[3]	Treatment Plant Outlet/Source and Consumers' Taps
2	Arsenic (As)	0.01 mg/L	Treatment Plant Outlet/Source
3	Cadmium (Cd)	0.003 mg/L	Consumers' Taps
4	Lead (Pb)	0.01 mg/L	Consumers' Taps
5	Nitrate (NO_3)	50 mg/L	Treatment Plant Outlet/Source
6	Colour (Apparent)	10 CU	Treatment Plant Outlet/Source and Consumers' Taps
7	Turbidity	5 NTU	Consumers' Taps
8	pH	6.5 - 8.5	Treatment Plant Outlet/Source and Consumers' Taps
9	Total Dissolved Solids	600 mg/L	Treatment Plant Outlet/Source
10	Disinfectant Residual	Chlorine Residual (free chlorine): between 0.3 and 1.5 mg/L	Treatment Plant Outlet/Source and Consumers' Taps

Table 3.1: Mandatory Drinking Water Quality Parameters [109]

Water Quality Management Area using appropriate physiographic units such as watershed, river basins or Water Resource Regions [110].

- **Water Quality Guidelines and General Effluent Standards** or **DENR Administrative Order (DAO) 2016-08**: This Order provides guidelines for the classification of water bodies (usage of freshwater, see Table 3.2, and marine waters) based on their intended beneficial usage and for the designation of WQMA. The Water Quality Guidelines (WQG) and the General Effluent Standards (GES) are norms and regulations established to preserve the quality of all water bodies [111]. The Department of Environment and Natural Resources reviews and updates standards every five years (DAO 2021-19 is the most recent revision) [112]. The monitoring of those water bodies complies with Ambient and Effluent Quality Monitoring Manuals based on American standard methods [99].

Classification (Freshwater)	Intended Beneficial Use	Number of water bodies
CLASS AA	Public Water Supply Class I – Intended primarily for waters having watersheds, which are uninhabited and/or otherwise declared as protected areas, and which require only approved disinfection to meet the latest PNSDW	7
CLASS A	Public Water Supply Class II – Intended as sources of water supply requiring conventional treatment (coagulation, sedimentation, filtration and disinfection) to meet the latest PNSDW	279
CLASS B	Recreational Water Class I – Intended for primary contact recreation (bathing, swimming, etc.)	272
CLASS C	1. Fishery Water for the propagation and growth of fish and other aquatic resources 2. Recreational Water Class II – For boating, fishing or similar activities 3. For agriculture, irrigation and livestock watering	420
CLASS D	Navigable waters	38
	Number of Inland Surface Water Body Classifications	1,016

Table 3.2: Water Body Classification and Usage of Freshwater [97, 111, 112]

Many laws and standards for water quality are based on the standards of other countries, incorporating imported expertise. Research groups have been set up to develop certain standards specific to the Philippine environment.

The water sector is also supported by Non-Governmental Organizations like UNICEF, Greenpeace, etc., along with international donors (JICA, USAID, the World Bank, etc.) who contribute as key stakeholders by providing technical expertise and support for projects aimed at improving sanitation and water management.

3 Water sector in Metro Cebu

Central Visayas (Region VII) is located in the central part of the Visayas island group. It is composed of four provinces: Bohol, Cebu, Negros Oriental, and Siquijor, and three independent Highly Urbanised Cities (not under provincial supervision), namely, Cebu City, Lapu-Lapu City and Mandaue City. Cebu Island has a surface about 4,943.72 square kilometres, its capital, Cebu City, is acknowledged as the regional centre [113].

Among all the administrative regions with the least water resources potential, Central Visayas ranks third [82]. It only overlaps with WRR VII. It is among the most developed and densely populated regions of the country. Regional economic development leads to further growth in population and changes in land use, which puts pressure on public services. The region presents a water supply service with 49% at Level III, 14% at Level II, and 37% at Level I.

Cebu Province's climate has dry and wet seasons. Temperatures can reach as high as 37°C. Beginning in July, the rainy season brings heavy downpours [81]. Like much of the Philippines, Cebu is extremely vulnerable to climate change, experiencing an increasing occurrence of droughts, floods, tropical cyclones, and the impacts of sea level rise.

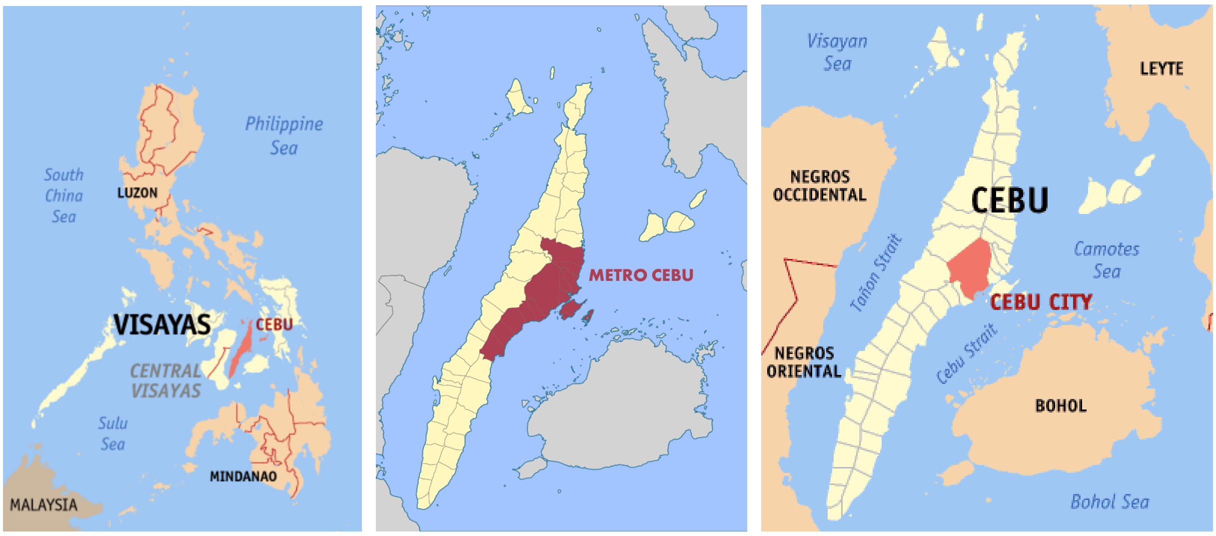


Figure 3.5: Cebu Island, Metro Cebu & Cebu City

3.1 Metropolitan Cebu (Metro Cebu)

Metropolitan Cebu (or Metro Cebu) is one of the largest metropolitan areas after Metro Manila and is situated on Cebu Island. It is composed of 10 LGUs: the cities of Cebu, Mandaue, Lapu-Lapu, Talisay and Naga; and municipalities of Compostela, Liloan, Consolacion, Cordova and Minglanilla (see Figure 3.6).

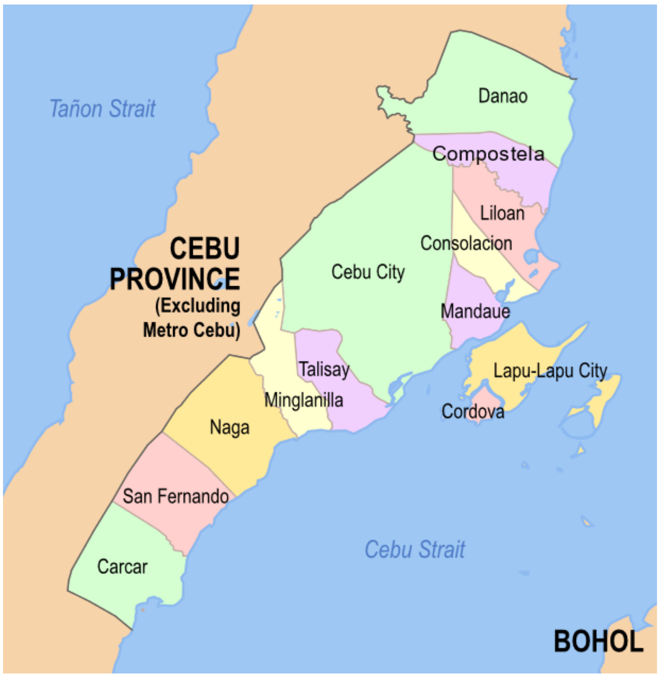


Figure 3.6: Map of Metro Cebu

According to a JICA study of 2023, the total water demand of Metro Cebu is 238 million m^3. Municipal water demand constitutes approximately 78.2%, while industrial water demand accounts for about 21.8%. However, the total annual production capacity only reaches 99.6 million m^3, which meets about 41.8% of the total water demand. The primary production sources are wells (63.4% of the total production capacity), bulk purchase (21.9%), rivers (12.4%) and desalination (2.2%). The study also performed a water balance analysis of Central Visayas (Region VII), showing that, while the annual surface water balance across all cities remains positive, it turns negative during some months of the dry season. Additionally, the groundwater balance forecast for 2050 under current weather conditions predicts negative balances for all cities, with Metro Cebu, among others, experiencing particularly adverse effects [97].

Cebu City, the capital of Cebu province, has a population of 1,025,000 in 2023 [113]. It is one of the most urbanised areas of the Philippines, second to Manila, the country's capital. It comprises of 80 barangays and is a centre for commerce, trade and education [82].

Mandaue City comprises 27 barangays and has a total population of 364,116 as of 2020. It is home to many industries, mainly food and beverages, metalcraft and woodwork, and several waterways: Mahiga and Butuanon rivers and many other smaller creeks. In 2021, waterborne diseases were the eighth cause of morbidity in Mandaue City [114].

3.1.1 Situation in situ

The data collection phase of this master's thesis was performed in Cebu from the start of April to mid-May 2024. That year's dry season was marked by intense dry spells and extreme temperatures due to *El Niño*. By mid-May, most regions of the Philippines were undergoing droughts, meaning they had several consecutive months of way below-normal rainfall conditions [115]. The region also experienced severe heat indexes to the extent that schools had to close for several days [116].

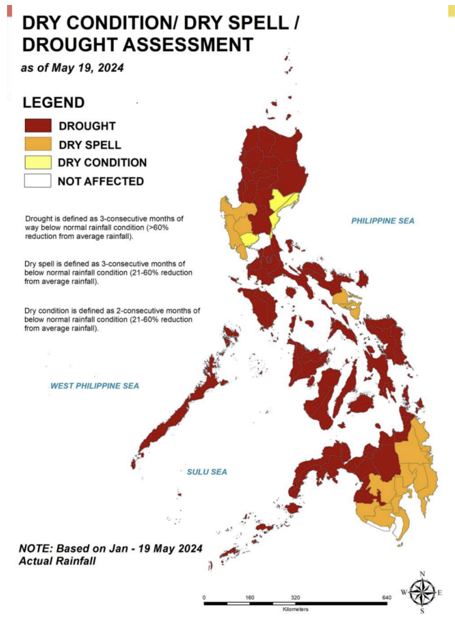


Figure 3.7: PAGASA's May 2024 drought assessment [115]

In Cebu City, more specifically, the major declared a water crisis on the first of April 2024 [117]. Twenty-eight barangays were put under state of calamity, allowing the local government to impose price controls and acquire funds and loans for calamity response. Due to the high temperatures, water sources were depleted and dams operated at less than half their capacity. On the 18^{th} of April, the water deficit of the government-owned Local Water District (Metro Cebu Water District) supplying most of Metro Cebu had reached 50,000 m^3 per day, affecting many barangays by water shortages [118]. In early May, this number reached 65,000 m^3 per day (deficit of 21.5%). To cope with the absence of water, the company dispatched water trucks to extremely affected barangays in Cebu City, Mandaue City, and Talisay City. Sometimes only coming by twice a week, or at very odd hours. By mid-May, water shortage had been reported in 33 areas in Cebu province and the entire Province was declared under state of calamity [119]. At that time, the water crisis in Metro Cebu was further worsened by escalating conflicts between the Local Water Utilities Administration and the Local Water District causing more confusion and havoc in the operations of the water district. [120].

3.2 Stakeholders in Metro Cebu

In Metro Cebu's water sector, there are many players with different responsibilities and levels of authority. They range from national and regional level to local level. At the national level, the key government agencies enumerated in Section 2.1 play a crucial role in the country's water sector, impacting Metro Cebu. On the regional level are counterpart offices of government agencies (DENR VII, EMB VII, DOH VII, etc.). On the level of Metro Cebu lies the LWD: Metro Cebu Water District (MCWD). At the local level, several actors play relevant roles in the water sector: LGUs like cities and barangays, Water Service Providers, universities, industries and other public and private institutions and, finally, citizens, the water end-consumers, including a section of the population that is highly vulnerable to the quality and quantity of river water: the informal settlers living along riverbanks.

The remarks on the nationally disorganised water sector can also be applied to Metro Cebu, where municipal fragmentation, lack of incentives for cooperation, lack of staff and resources, as well as limited information sharing are observed issues [93]. Figure 3.8 visually represents the network of stakeholders involved in water management in Mandaue and

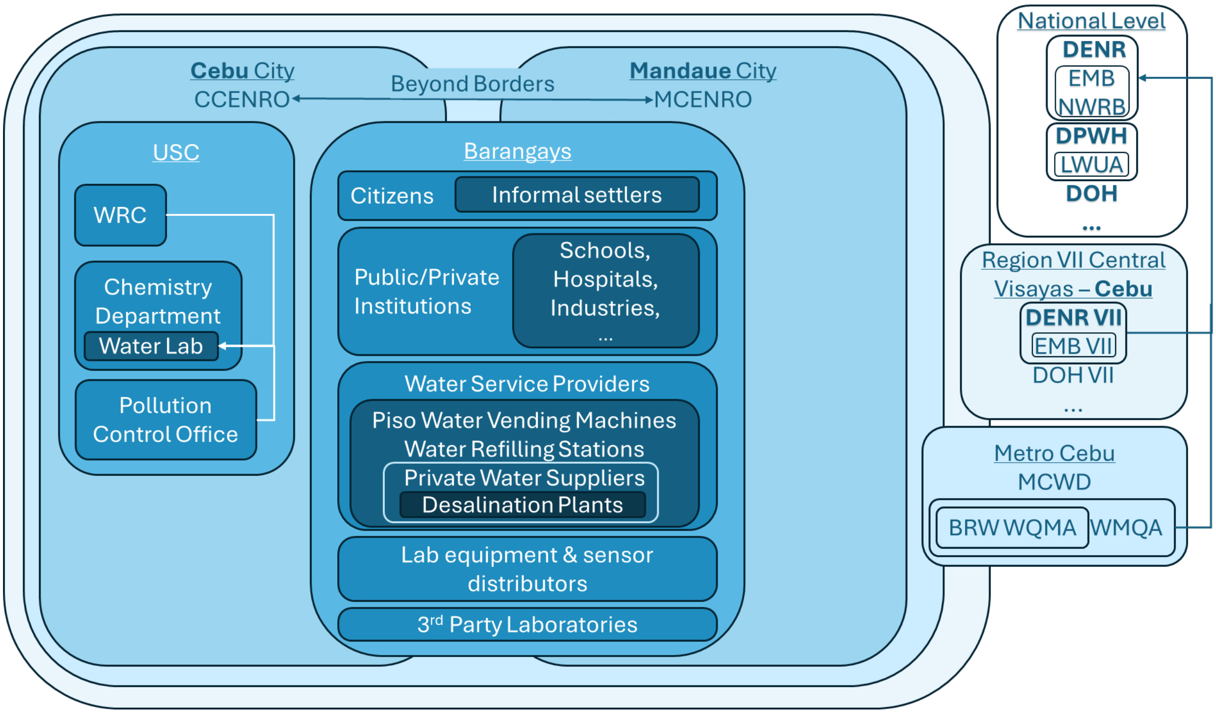


Figure 3.8: Mandaue and Cebu Cities: local stakeholders

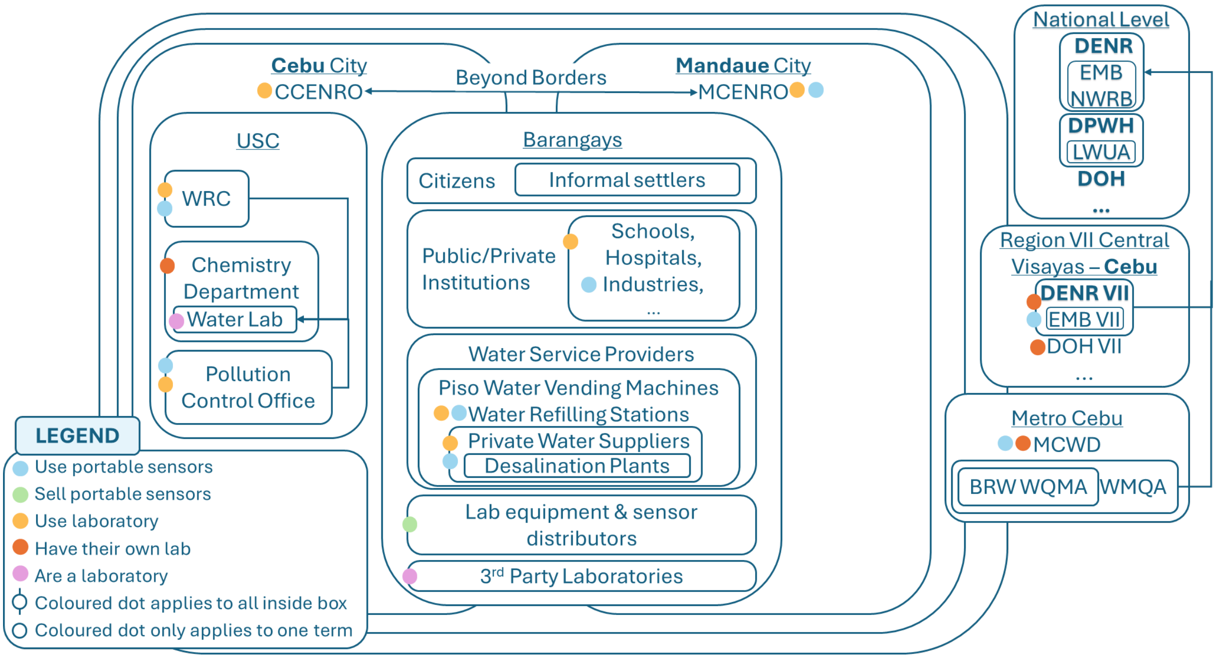


Figure 3.9: Monitoring strategies of the stakeholders

Cebu Cities and their level of authority. Many of those actors are involved in water quality monitoring. Figure 3.9 depicts which actors have their own water quality monitoring equipment composed of portable sensors, which are monitoring equipment sellers, and which call upon their institution's laboratory or a third-party laboratory to perform water quality analysis. As portable bacteriological water quality tests are not commercialised yet (see Section 3.4 in Chapter 2), entities needing to perform bacteriological analysis are constrained to perform laboratory analysis.

3.2.1 Environmental Management Bureau - Region VII Central Visayas (EMB VII)

EMB VII is the region counterpart of the national EMB, regulated by the regional Department of Environment and Natural Resources (DENR VII). It is thus responsible for monitoring the water bodies in Central Visayas (Region VII), issuing effluent permits to industries and organising compliance inspections. Such permits are based on the classification of the water body (often rivers) in which the industry rejects its wastewater. The classification of a water body determines the level of contaminants authorised (see Section 2.2). The effluents permit varies for each industry, and the parameters to be monitored by the industries are coherent with their type of activity.

Regarding surface water quality monitoring, 10 rivers and 6 coastal waters of Metro Cebu are monitored for at least the primary parameters defined in the Water Quality Guidelines (see Section 2.2). Depending on the amount of pollution, classification of the river and its importance, the frequency of monitoring varies and the number of parameters tested vary. The DENR/EMB VII has its own water quality laboratory.

3.2.2 Department of Health - Region VII (DOH VII)

The regional counterpart of the Department of Health is responsible for drinking water standards enforcement and water laboratory compliance. It has its own Water Testing Laboratory located in Cebu City.

Other national government services with water-related mandates have regional branch offices providing the services of the national government and overseeing LGUs in the region. Those are not considered further for this study.

3.2.3 Metro Cebu Water District (MCWD)

Metro Cebu Water District (MCWD) was established in 1974 as a government corporation which is responsible for supplying the water of most of Metro Cebu. MCWD provides tap water from Talisay to Compostella[4]. The water utility is responsible for providing water to its clients, the maintenance of the piping system, the treatment of the distributed water and its quality control, as well as the desludging of septic tanks in partnership with LGUs.

The water production of the Metro Cebu Water District fails to meet the demand of the local population. Data shows that service coverage is less than 40% in both Cebu City and Mandaue City (number of connections) [106, 121]. The coverage drops significantly in poorer areas, where residents often depend on communal water associations (local waterworks systems), communal faucet systems, water vendors, and artesian wells or deep wells equipped with hand or electric motor-driven pumps [114, 121]. The citizens use water from the MCWD for all uses: for drinking purposes, domestic use, watering plants, etc.

One of the reasons for the lack of supply is MCWD's high percentage of Non-Revenue Water, i.e. water that is lost in their distribution network due to theft, evaporation, faulty metering, poor data gathering, and mostly leakage. In 2008, physical losses accounted for 27.9% of non-revenue water while unbilled authorised consumption, unauthorised consumption, customer meter inaccuracy and data handling errors represented 1% (total

[4]MCWD provides the cities of Cebu, Mandaue, Talisay and Lapu-Lapu and the municipalities of Consolacion, Liloan, Compostela and Cordova.

of 29 % of non-revenue water) [106]. This results in an annual loss in revenue by an average of at least 117.759 million PHP. The Commission on Audit reported that in 2021, it represented 29.04% of their total water production, which is higher than the maximum acceptable 20% set LWUA (Board Resolution No. 444, series 2009). This number recently reached 36%, according to LWUA [122].

The main water source is groundwater, extracted via supply pumps, and only 5% comes from surface water. Due to the increasing saltwater intrusion and groundwater pollution, MCWD turned towards desalination. They also purchase water from private waterworks companies with bulk water contracts. Their tariffs (15.2 PHP/m^3 in 2022) do not reflect the scarcity of the resource.

The water is mainly treated through chlorination. The supplied water must respect the local water quality standards, the Philippine National Standards for Drinking Water. Every month, the water is tested at fixed sampling points for bacteria. For chemical-physical parameters, it is only tested once a year. As most sources are groundwater wells, the tests are mainly performed with the water flowing out of the pumps. When results show contamination above maximum levels, specific actions are undertaken (e.g., denitrification in case of nitrate contamination). Some groundwater extraction wells had to be closed since contamination levels were too high.

The MCWD has a water quality laboratory responsible for sample analysis located in Talamban, Cebu City and uses portable sensors for the monitoring of specific water quality parameters (turbidimeter, TDS, pH, etc.). Those portable sensors are not sufficient as they are not legally accredited as methods of analysis, but they are used as a preliminary tool to perform regular control and detect abnormal values.

MCWD plans to implement real-time monitoring for some of its critical water sources using data sent by on-site devices. However, equipping all wells with this technology is prohibitively expensive. MCWD shows interest in using more portable sensors to monitor nitrate levels, for example. When purchasing new equipment, a bidding system is employed as it is a government-owned company [5].

3.2.4 Cebu City Environment and Natural Resources Office (CCENRO)

The City Environment and Natural Resources Office (CENRO) is part of a City's LGU implementing measures to prevent and control land, air and water pollution. In Cebu City, this includes improving the water quality of the rivers that cross the city. CCENRO has its own river rehabilitation plan. Their efforts are concentrated on riverbed protection, solid waste management, mitigation of water pollution, easement regulations and water conservation. They perform water quality analysis on rivers and creeks in Cebu City by bringing samples to a third-party water quality laboratory. They are also in charge of mitigating the effects of flooding [6].

3.2.5 Mandaue City Environment and Natural Resources Office (MCENRO)

The CENRO of Mandaue City has a similar function as the CCENRO and is in charge of rehabilitating the unique two rivers that cross the city (Butuanon and Mahiga Rivers).

[5] Interview with the Head of MCWD's water quality laboratory, April 2024

[6] Interview with CCENRO staff members, April 2024

Their 5-year rehabilitation plan, which started in 2022, focuses on five River Rehabilitation Focus Areas: social preparation, physical planning, informal settlement, slope protection and flood control and finally, water quality. Members of MCENRO perform water sampling and analysis with a portable multi-parameter sensor [7].

In 2021, they started a *Five Year Integrated Pollution Emission Management Plan* in place to adopt centralised pollution monitoring through the cooperation of local stakeholders, especially barangays. The office performs inspections based on the wastewater discharge permits issued to industries and companies by the EMB VII. MCENRO developed a platform, *Eco-Watch*, where citizens can complain about environmental aspects. It allows citizens to notify environmental situations in specific communities like illegal garbage dumping sites.

Beyond Borders Initiative: As the Butuanon River and Mahiga River are shared between the Cebu and Mandaue cities, a Memorandum of Agreement was signed to formalise the partnership between the two cities' LGUs and collaboratively rehabilitate the rivers. The objective is to overcome challenges due to the transboundary nature of the rivers.

3.2.6 Barangays

As stated before, barangays are the lowest political administrative unit of the Philippine government, considered as an LGU like provinces and municipalities. A barangay is managed by elected officials with a Barangay Captain at the head. They are the foundation for citizen involvement in community affairs. They have to provide services such as a health and day-care center and are in charge of collecting solid waste from domestic users.

3.2.7 Private Water Suppliers and Water Vendors

There is a growing presence of private actors in the water supply sector. Large private water suppliers operate water piping networks (e.g., private water utilities like Pilipinas Water Resources Inc. (PWRI)). PWRI sells bulk water to the MCWD and other high-demand institutions such as malls and industries. They are often preferred by those clients due to the more reliable water supply compared to MCWD. A lot of water is also supplied by small-scale private water providers that do not rely on piping systems to distribute water. These include water refilling stations and water vending machine owners. The different types of water sources are described in Section 3.4.

For these private suppliers to be considered safe for public consumption, they must obtain a Certificate of Potability from the local health office, such as the City Health Department in Cebu City. This certificate is issued only if the results from water sampling and testing, conducted by a Department of Health-accredited water analysis laboratory, comply with the Philippine National Standards for Drinking Water. Some of those private water service suppliers use their own monitoring devices to monitor the water quality and the effectiveness of their treatment process.

3.2.8 University of San Carlos, Cebu (USC)

The University of San Carlos, Cebu (USC) was created in 1948 and has many departments where academic research on water-related topics is performed, including the Department of

[7] Interview of MCENRO staff member, April 2024

Chemistry and the Department of Civil Engineering, which offers a master's specialisation in Water Resources and Environment. **The USC Water Laboratory** is an accredited laboratory performing quality water and soil analysis (for University research or private clients) and is part of the Department of Chemistry. Each campus has a Pollution Control Officer responsible for the overview of the wastewater treatment of the campus facilities.

RiverScan Challenge (Climate Cafe) 2024 edition: The first Climate Cafe activity held in Metro Cebu, known as the River Scan Challenge, occurred in 2017[8]. Those yearly events focus on assessing the water quality of rivers and creeks polluted through interviews with local residents and propose solutions to water-related issues. It provides an ongoing collaborative platform for students, government officials, and community stakeholders to develop sustainable solutions together. In 2024, informal settlers living along the Butuanon River were interviewed to asses issues related to water quality. The river and its related stakeholders (informal settlers and WQMA) are described in Section 3.3.3.

3.2.9 Water Resource Center Foundation, Inc. (WRC)

The Water Resource Center (WRC or sometimes also shorten as USC-WRCFI) is the leading consulting centre in Cebu, specialising in hydrology, geo-hydrology, and water resources planning, engineering, and management. The WRC is located on USC's campus in Talamban but is a separate legal entity. Their mission is to provide accurate, reliable, and long-term hydrological data and expertise to support the development, management, and utilisation of water resources by conducting thorough reports and data analysis on the risks and advantages related to water resources [123]. WRC has established effective connections and collaborations with universities and non-academic stakeholders such as Local Government Units, non-governmental organisations, water suppliers and various businesses and industries. They provide their services to a lot of stakeholders in the water sector, even beyond Metro Cebu. Their role is crucial as expertise in water quality and hydrology is scarce in the Philippines and as its renewal faces challenges due to the lack of specialists and technicians.

The WRC's team performs monthly groundwater level monitoring and yearly SWI monitoring studies in Metro Cebu, analysing samples from a total of 135 wells, both public and private. These wells are assessed for chloride concentration, nitrite concentration, pH, and electrical conductivity. A number of these wells have been monitored for almost 50 years. The WRC also performs regular rainfall, evaporation and runoff measurements. The WRC has its own equipment for common global water quality parameters and commissions third-party laboratories for other parameters. The data they collect is crucial for developing a better understanding of Metro Cebu's water balance and the challenges its water resources face.

3.2.10 Water quality laboratories

A certificate for operation and accreditation proof of compliance with standards for drinking water analysis, issued by the DOH, are mandatory for all laboratories where physico-chemical or biochemical analyses are performed. In Metro Cebu, many water quality laboratories exist, like the Water Laboratory at the University of San Carlos and the water quality laboratories of the MCWD and the DENR/EMB VII. As of March 2023,

[8]This initiative is coordinated by the University of San Carlos and the Cebu Leads Foundation, Inc. in the Philippines, in partnership with Rotterdam University of Applied Sciences and Hanze University of Applied Sciences in The Netherlands.

the DOH has accredited 135 laboratories to monitor the quality of drinking water across the Philippines. Among these, 59% are privately owned, while 41% are managed by the government, predominantly located in Metro Manila. Some regions are devoid of any accredited laboratories [100], making water quality monitoring inaccessible.

3.2.11 Industries

Industries of Metro Cebu are mainly involved in food processing, industrial gas manufacturing, seaweed production and metalwork or foundry [82].

Industrial users and commercial economic zones perform on-site or off-site sludge wastewater treatment. Industries' treated wastewater can be discharged in rivers if they have a Wastewater Discharge Permit provided by the EMB VII. The discharged water must comply with the General Effluent Standards and the industry must submit laboratory results of effluents' analyses of significant parameters. Industries are thus supposed to monitor their wastewater regularly by sending samples to third-party laboratories accredited by the DOH. However, as noted before, there is not enough enforcement. Some also own portable sensors to perform additional control of their treatment process. The water quality parameters concerned are determined based on their type of activity and set by EMB, an example being TSS for quarrying and mining activities.

Monitoring equipment The origin of the laboratory equipment and water quality monitoring devices used varies depending on the stakeholder. Many laboratory equipment and water quality sensor sellers have emerged over the years like Yana Chemodities, Inc., Krypton and Fil-Anaserve. They sell their equipment, coming from foreign companies, to government and private water companies, power plants, food industries, universities and water analysis laboratories.

3.3 Water resources and quality in Metro Cebu

The cities of Metro Cebu have a complex water distribution network, with most of its water resources coming from the subsoil, but this is not sufficient to meet the water needs (of households and economic activities), either in terms of quantity or quality (due to saltwater intrusion and contamination). Metro Cebu is part of the critical areas identified by the National Water Resources Board where water is consumed intensively [82]. Many water bodies in the Cebu region have contamination levels well above the thresholds recommended by the WHO [124].

3.3.1 Saltwater Intrusion

As Metro Cebu is a coastal area, Saltwater Intrusion is thus present in the region and noticed since the 1970's [17]. The local aquifers are composed of highly porous and permeable Carcar limestone and quaternary alluvium when closer to the coastline, thus highly vulnerable to SWI [114] (see Section 1.1.2).

Saltwater encroaches on freshwater aquifers due to the lack of freshwater recharge and over-extraction of groundwater by many stakeholders. As explained before, to extract and use groundwater, one needs a permit. However, many are pumping groundwater illegally due to lack of law enforcement. There is no quantification of how much is pumped. Illegal pumping adds to the uncertainty, making the availability of groundwater unknown. The water balance of the area is thus not understood meaning there is little to no knowledge on how much can still be pumped without further worsening SWI. There is a need for more data on underground water and SWI to support evidence-based policy making.

Metro Cebu presents Saltwater Intrusion with a high chloride concentration of above the acceptable level of 250 mg/L set by the Philippine National Standards for Drinking Water (see red line on Figure 3.10), according to a 2022 salinity map that was made by the University of San Carlos Water Resource Center Foundation, Inc. According to the Local Water District (MCWD), SWI has already reached some of its extraction wells and other private wells. The global trend over the years is an advancement of the SWI inland, with higher salinity concentrations further from the coastal line and groundwater quality depleting rapidly (for comparison, a SWI map of 1976 is provided in Appendix B).

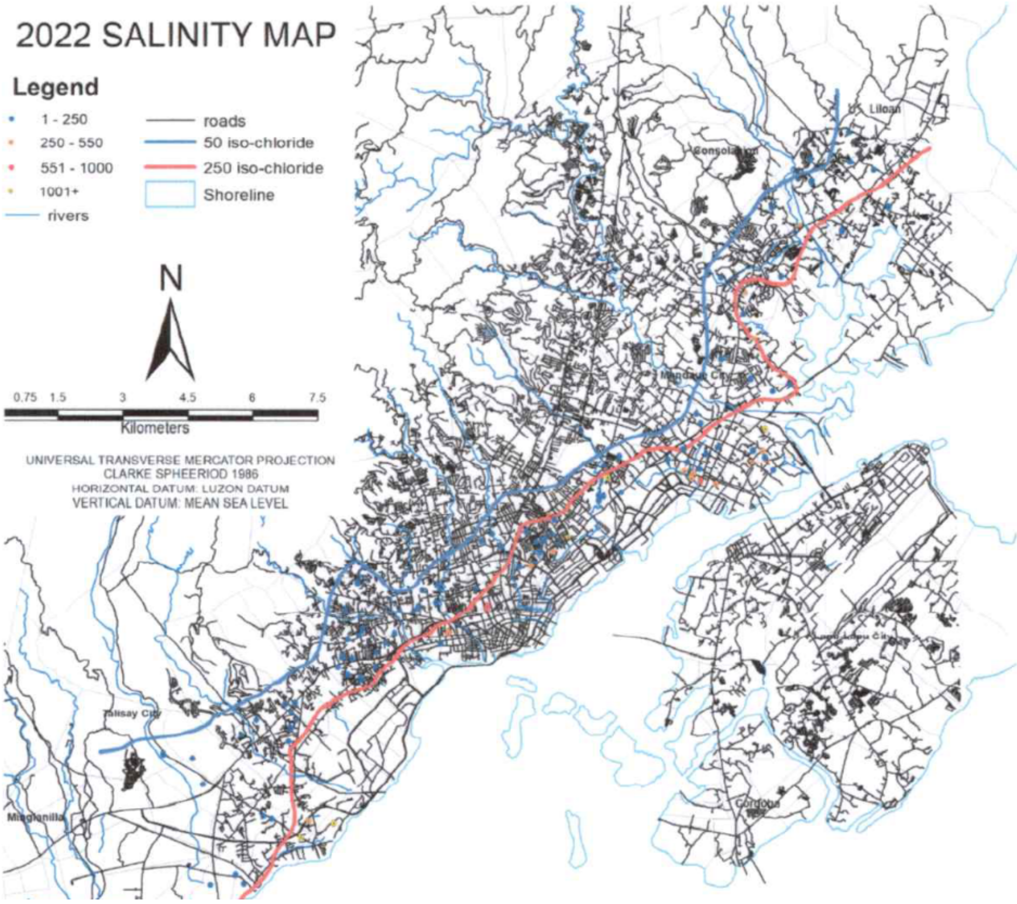


Figure 3.10: SWI 2022 - Source: WRCFI [125]

3.3.2 Groundwater and surface water pollution

Besides Saltwater Intrusion, groundwater and surface water are further contaminated due to high pollution in the area, increasing with rapid urbanisation and industrialisation. The pollution causes are agriculture activities, inadequate waste management, poor sewage and sceptic systems and bad to non-existent industrial wastewater treatment. No centralised sewerage system or treatment facilities are present in Metro Cebu [106] (only 5.6% of households are connected to sewerage systems in the country [100]), but the city relies on drains transporting household's grey water and septic tanks overflow. Infiltration from sceptic systems is frequent. Studies revealed that half of the country's open dumpsites are within a kilometre of a waterway and between 70% to 90% of the illegally dumped waste eventually reaches these waterways. In Metro Cebu, 10% of the population has no toilet facilities with sceptic tanks and dispose of their untreated waste in drains, waterways, adjacent land, etc. [106]. An example of worsening pollution due to rapid urban development is high nitrate levels (often twice or three times higher than the 50 mg/L norm) in groundwater, primarily resulting from agricultural activities and sewage discharge.

3.3.3 River pollution

Rivers in Metro Cebu are known for significant issues with water safety and water quality. During heavy rainfall, the water levels in these rivers rise, creating flooding hazards and putting the large number of residents living along the riverbanks in danger. This is exacerbated by the high rate of urbanisation, causing higher surface runoff during rainfall. In addition to the risk of flooding, there is also considerable pollution in the rivers (often used as waste dumping sites).

According to the Environmental Management Bureau of Region VII, most rivers and creeks located in Metro Cebu do not meet ambient water quality criteria (Biological Oxygen Demand, phosphates, ...). Fecal Coliform levels exceeded the maximum allowable criteria in most of the water bodies, often by several orders of magnitude (see Figure 3.12). Waterbodies with quarrying activities or manual sand and gravel extraction usually exceed allowable criteria for Total Suspended Solids.

Butuanon River The Butuanon River is a 34.5-km river flowing through two major highly urbanised cities in Metropolitan Cebu. The river flows from the mountain barangays of Cebu City, and the midstream and the downstream segments cut through several barangays in Mandaue City, eventually discharging in the Mactan Channel. It is considered one of Cebu's most polluted rivers [126]. The Butuanon watershed was labelled by the Department of Environment and Natural Resources as a Water Quality Management Area in 2014 and the Butuanon River Watershed Water Quality Management Area (BRW WQMA) was created (see Section 2.1 for roles of WQMAs). Butuanon River is an exemplary case as most of the waterways passing through the Metro Cebu experience similar problems.

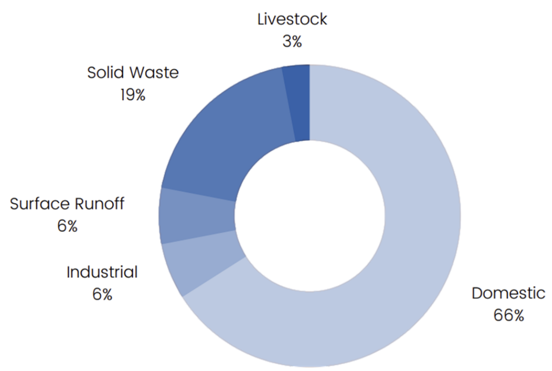


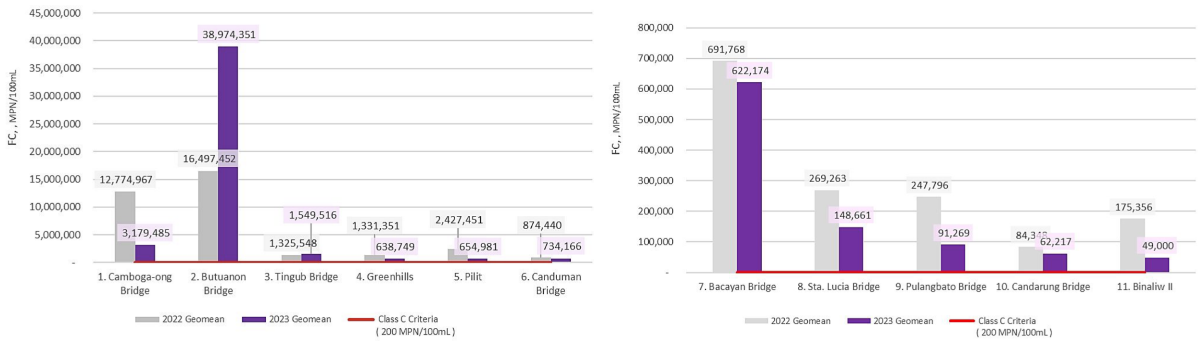
Figure 3.11: Pollution Load Source Distribution in terms of BOD concentrations (adapted from [126]; based on 2020 data of DENR-EMB)

According to the EMB Region VII report, the Butuanon River, once a recreational spot and drinking water and fish source, has been severely polluted by industrial, commercial and residential waste (see Figure 3.11). It was classified in 2000 as a Class D river (unsafe for consumption and recreation) and then as Class C (for fishery or watering) in 2022, as a tentative to reduce pollution[9]. Extensive research, including studies on

[9]As a reminder, the worse the river's classification, the higher the level of authorised effluent pollution (see Section 2.2). The reclassification of the river restricts thus the allowed effluent pollution and will allow stricter monitoring of the water quality by LGUs (Interview with the Mandaue City Environment and Natural Resources Office and EMB VII, more details see Section 3.2.1)

heavy metals in the water, sediments, and fish, as well as EMB's monitoring, confirms the significant pollution [124, 127, 128, 129]. High TSS and temperatures and low DO causing fish species to die. The river was found to be positive for the poliovirus on several occasions in 2021 [124]. Despite rehabilitation efforts, the river's condition remains poor [126].

The condition and pollution of the river are detailed, quantified and illustrated in Appendix B. Wastewater is discharged into the river as it passes through Metro Cebu, adding up and resulting in a river that impacts nearby residents (informal settlers) in terms of odour and colour, and is biologically dead in the lower reaches. Agricultural (upstream), industrial and domestic (middle and downstream) wastewater is often discharged illegally, without the necessary treatment required by the EMB VII to meet GES requirements (lack of enforcement). Informal settlers live in the areas around the river that are supposed to be free of habitation for flood safety reasons and are thus the most impacted by its state and the risks of flooding. The majority do not have septic tanks or proper waste collection systems, and their waste often ends up in the river. Monitoring results clearly show increasing pollution, the more downstream the samples are taken (see Figures B.11a, B.11b, B.8 and B.11d in Appendix B), with DO levels decreasing by nearly a magnitude order between the first upstream and last downstream sampling point, while BOD or fecal coliform levels increase more than 50 times, as shown in Figure 3.12.



(a) Mandaue City Sampling Stations - downstream and midstream

(b) Cebu City Sampling Stations - midstream and downstream

Figure 3.12: Butuanon River - 2022 vs 2023 Water Quality Monitoring Geomean - Fecal Colifrom Count, MPN/100mL. Source: EMB VII, 2024

3.4 Citizen's choice of water sources & the impact of trust

Water sources can be formal, composed of utilities mostly larger and predominantly public, or informal, including all small, independent and scattered entities, often privately owned, that are generally beyond the government's control. The informal water sector and small-scale water providers have developed rapidly over the years and play a growing role in the water supply, mostly in areas where the water supply is low or in regions not reached by formal utilities [130]. Indeed, as previously mentioned, the existing piping system enables approximately only 40% of the population to access its services.

Households' water source choices are marked by mistrust. Access to piped water systems does not guarantee water availability and quality. Water shortages result in intermittent water supply, while inadequate water treatment results in low-quality water. Indeed, Metro Cebu was marked by a severe water crisis in 2024, causing water shortages and some barangays' distribution systems experiencing low pressure to no water (see Section 3.1.1).

This leads citizens to rely on various other water sources, which are only a Level II or III service (see Section 2.2) if they can afford it. Metro Cebu's water supply chain involves a lot of actors and multiple sources as well as methods of delivery.

3.4.1 Drinking Water Sources

The main water supply and distribution in Cebu and Mandaue Cities is provided by tap water (MCWD, local and private waterworks systems), refilling stations, bottled water, water vending machines and household/community-owned hand pumps or electric motor-driven pumps (groundwater supplied through wells). All water sources are supposed to be monitored according to law, however there is not enough compliance. Primary drinking water sources are shown in Figure 3.14.

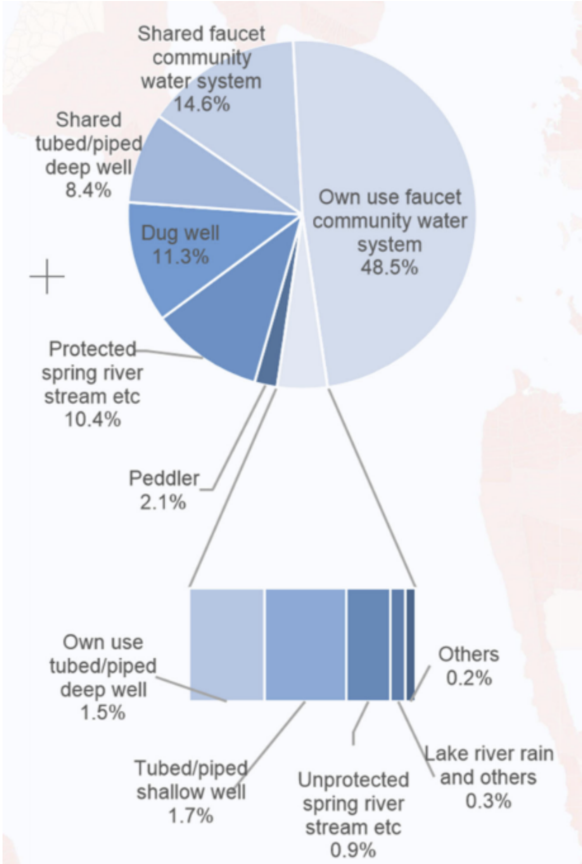


Figure 3.13: Water Sources in Region VII in 2015 [82]

Figure 3.13 shows the distribution of primary water sources for Central Visayas (Region VII), which contains Metro Cebu, in 2015 (only tap water, wells and surface water are studied, no form of bottled water is considered). Drinking water source choices vary by income, with wealthier individuals favouring bottled water and lower-income households opting for tap water. Larger households tend to use tap water more, and urban residents are less likely to use tap water compared to those in rural areas. For household chores and sometimes cooking, wells or tap water are commonly used. Bottled water consumption (whether purchased from stores, water refilling stations or water vending machines) has increased by 75% over the last 6 years[10]. Responsibility for household water management and water-related tasks are often assumed by women [2].

Piped or Tap water Mainly provided by the government-owned public water distribution operator or water utility of Metro Cebu (Metro Cebu Water District), connecting less than 40 % of the population of Metro Cebu. Some barangays, community and municipalities have their own waterworks and large-private water distributors also provide some large consumers (industries, malls and even MCWD). Tap water can be a Level II or III water supply service, depending on whether the tap belongs to the community or to an individual household, respectively.

[10]Based on results from the *Longitudinal Cohort Study on the Filipino Child* presented by Josh Miller at USC's *Seminar on Water and Food Security.* This cohort study is a "15-year study that tracks the lives of a nationally representative sample (5,000) of Filipino children, along with their households and communities, which started in 2016 when they were 10 years old and will continue to follow them every year till 2030" [131].

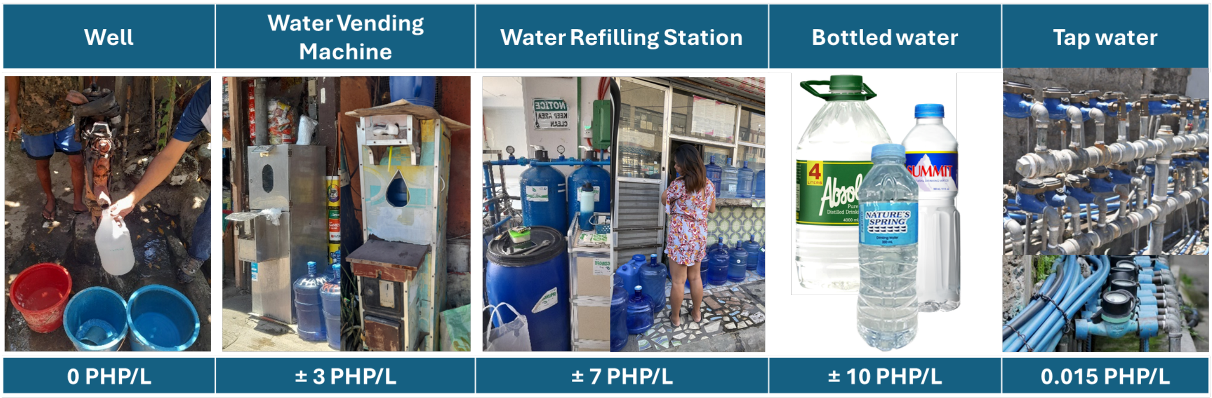


Figure 3.14: Main sources of drinking water for citizens and approximate tariffs[11]

Distribution pipes are often in the open, especially in poorer areas, visible along the streets. The pipes must comply with national norms and when exposed to ultraviolet light (UV), they must be provided with a protective coating. A study led in 2014 assessing the bacteriological quality of bottled and tap water in Cebu City showed that most tap water samples were found to be free of bacteria, indicating that disinfection systems are generally effective. However, instances of E. coli contamination were mainly detected following interruptions in the water supply, suggesting that tap water may occasionally pose a higher risk than bottled water [132]. Contamination through leakages (common as non-revenue water due to leaks is very high), cross-contamination between sidewalk gutters and drinking water pipelines as well as unstable pressure along the distribution system pose high health risks for customers.

Wells Groundwater is accessed through various excavation structures such as hand pumps, electric motor-driven pumps, or artesian wells. These wells can be owned by households or managed by a community and are often used for laundry, cleaning, watering plants, and taking showers. In some communities, a few wells are used for drinking water because they are bacteria-free. This might be due to the high Electrical Conductivity measured ($> 1500\ \mu$S/cm), indicating Saltwater Intrusion, since an elevated concentration of salt inhibits the growth of bacterial species like coliforms [133].

Numerous private wells are undeclared. The extensive use of deep wells has led to excessive and unregulated pumping from the coastal aquifer for industrial and domestic purposes. As mentioned earlier, this use is one of the leading causes of SWI. The exact number of these deep wells and the volume of groundwater extracted remains unknown. Wells are Level I water supply services.

Bottled water Different bottled water companies provide services in Cebu and the Philippines. There is a distinction between mineralised, purified and distilled bottled water depending on water treatment. Bottled water can be bought in supermarkets, in smaller shops like *sari-sari* stores[12], on the street, etc.

The study assessing the bacteriological quality of bottled and tap water in Cebu City showed that the bottled water market is primarily led by manufacturers who have es-

[11]In 2024, 1 PHP is approximately 0.016 EUR.
[12]Small shops along the roads that sell basic necessities such as food, toiletries, and household items in small quantities.

tablished effective water treatment and quality assurance systems that respect national drinking standards. However, certain smaller manufacturers struggle with maintaining bacteriological standards, and there is significant variability in water quality between batches, indicating a need for closer supervision by health authorities [132].

Water Refilling Stations Water refilling stations are shops where water is treated and dispensed into reusable containers, such as five-gallon plastic bottles. The water undergoes additional processing (reverse osmosis, UV treatment, activated carbon filtration, etc.) to obtain demineralised water [16]. They are mostly small businesses but can also be part of larger franchises. These stations have become popular in the Philippines due to citizens' concerns about tap water quality.

The businesses need a sanitary permit. The water has to be regularly tested (monthly bacteriological tests and semi-annual physical and chemical analysis), and maintenance of equipment is supposed to be conducted as stations must comply with local health and safety regulations set by agencies such as the Department of Health. Numerous water refilling stations fail to comply with health and safety regulations [134]. Moreover, the surveillance of such businesses by authorities is often lacking. The owners often rely on external technicians for the maintenance of equipment. Additionally, the equipment used to treat water often originates from abroad, creating a dependency on foreign technologies for water consumption and thus subjecting water prices to the influence of the exchange rate. The standard values of mandatory parameters are thus applicable for refilling stations except for TDS, which must be lower than 10 mg/L (instead <600 mg/L), and pH that needs to be between 5-7 (instead of 6.5-8.5) to validate the efficiency of the treatment process.

Stations are common in residential areas, commercial districts, and public places. They provide a more affordable alternative to bottled water and, as customers often bring their containers to be refilled, it is also more sustainable. Their affordability has led to their widespread presence in the Philippines. As water refilling stations require customers to go to the supply station, they can be assimilated as a Level II water supply service.

Because most of the water refilling stations in Metro Cebu rely on piped water for their supply, they do not address the water crisis in terms of quantity. Indeed, clients are then indirect users of water distribution systems. However, refilling stations allow better accessibility to water, filling the gaps in water supply where the infrastructure does not reach or is insufficient. They also address the problem of lack of confidence in water quality.

Water Vending Machines Also called *piso piso tubig machine*, they are small automatic distribution machines containing a five-gallon bottle and delivering small volumes of water after inserting a coin of 1 PHP. They are present all over the city, mostly part of *sari-sari* stores (small shops). Most of the time, water is consumed as an on-the-spot water source in plastic bags piled up next to the machine. Research assessing the drinking water quality of water dispensers in selected schools of Cebu City found out water from vending machines does not meet safety standards for drinking due to E. coli levels exceeding national (PNSDW) [135]. This results from inadequate maintenance, poor hygiene conditions and high usage frequency [136].

Another source not mentioned here is Mobile Water Tanks that are dispatched during dry spell periods to provide localities where tap water pressure is not sufficient or non-existent or in very remote areas.

3.4.2 Impact of trust on customer's choice of water source

Besides factors like revenue and price of water, proximity and household composition influencing the selection of a water source, the importance of trust in the choice of water supply cannot be overlooked, as it significantly influences consumer decisions and, as a result, their health.

Trust in water service delivery is multifaceted. First, there is trust in performance, which relates to the affordable, consistent availability of water of acceptable quality. This is also linked to the trust in the design of the water system infrastructure to comply with regulations and meet the demand. Then, trust in expertise is related to the belief that professionals managing and operating water systems possess the necessary knowledge and skills to do so effectively. Finally, trust in people, which covers the ethical dimensions such as fairness and transparency and the absence of corruption, supports the overall trust in the water system. When these elements align, they create the correct framework for water service delivery that the public can rely on. A good relationship between water providers and consumers builds trust, making the public confident about the safety and reliability of the provider and choosing it as the main drinking water source. Transparency about water quality and sourcing is essential for building this good relationship.

Citizens, aware of the country's water management shortcomings, experience issues such as poor water access and questionable water quality, which ultimately impact their health and undermine their trust in government-owned agencies and water utilities. In Metro Cebu, public confidence in tap water quality is low. There is widespread distrust among locals regarding the quality and availability of piped water supplied by the water district. One reason is the lack of confidence in the water distribution network; the other is that purified water has become the organoleptic benchmark for drinking water. The trust in water quality is also impacted by previous incidents of waterborne diseases.

Distribution network The primary issue lies in the city's water distribution network. As stated before, the pipes are often exposed, sometimes near sewage in sidewalk gutters and are vulnerable to contamination. When in the open, they absorb heat, particularly during the dry season, causing temperatures of delivered water to rise significantly. Warm water is less likely to comply with acceptability criteria of consumers and is ideal for bacteria proliferation (see Section 1.3 of Chapter 2). Furthermore, the network is plagued by frequent leaks (see non-revenue water of the Metro Cebu Water District) causing water losses and increasing the risk of contamination. During frequent interruptions or water shortages, contamination occurs due to stagnating water and backflows within the system.

There is a need for modernising the tap water distribution system to minimise supply interruptions, leakages and backflow, thus reducing bacteriological risks and raising consumer confidence in tap water. This improvement could also decrease reliance on bottled water, which has a higher environmental impact. However, pursuing the modern waterworks infrastructure benchmark (focusing on piping systems to supply water) can lead to further stigmatisation. Indeed, omitting the more minor, often informal, water suppliers in development plans can lead to keeping marginalising the poorer households that rely on them. According to a World Bank study, there is a pressing need to reconsider the existing focus on traditional piped water systems and explore off-grid solutions as a complementary strategy to meet the UN Sustainable Development Goal 6, which aims for universal access to safely managed water by 2030 [137].

Acceptability of water Consumers decide on the acceptability and value of water mainly based on a judgement of its flavour, odour and appearance [138] (see Section 1.3.4 in Chapter 2). Groundwater in Cebu presents a high hardness, turning the taste of the water sour and salty with a metallic odour (see Section 1.3.4). As a lot of citizens are used to the taste of purified water and even distilled water (sold in bottled water or refilling stations), they are often disturbed by the taste of tap water.

Water devoid of natural minerals through processes like distillation, deionization, or reverse osmosis can have adverse negative health effects [139]. Both calcium and magnesium, for example, have significant roles in human health, being, among others, essential for bones and muscles (heart), respectively. Drinking low-mineral water in the long run will also increase the risk of acidosis (acidified tissues) which may be a precursor to many diseases (cardiovascular diseases, diabetes, osteoporosis and cancer). Many studies show that other macro and micro elements from drinking water are essential [30].

Moreover, drinking water with a low quantity of minerals not only reduces the essential intake of those minerals but can also worsen the body's mineral concentration. Indeed, distilled water is often referred to as "hungry water" as it has a high capacity to absorb and bind with elements to balance its ionic composition, including minerals from the body when ingested, or from metal pipes and containers when stored or transported. This is the origin of the aggressive nature of demineralised water that causes corrosion in pipes and leaches metals and other materials. The body will lose its electrolytes because it can only expel water combined with salts [139]. Studies stress the fundamental importance of remineralising water treated by reverse osmosis, for example, when produced to be drinking water [30].

However, in the Philippines, the dangers of regular low-mineral water are not well known and most citizens drink water with low mineral content. Most citizens consider distilled and demineralised water healthy and those are often promoted for babies and children. As they trust this water's quality, its taste becomes their benchmark for assessing water quality, leading to further distrust of tap water.

As stated before, the citizens' lack of trust in tap water as a drinking water source is the main driver of the development of Water Refilling Stations. The number of actors in the water sector in Metro Cebu keeps increasing, using the water crisis as an opportunity to develop a business. Those refilling stations might thus increase citizens' trust in water quality due to the extensive treatment the water goes through and reduce contamination risks if the treatment process is done correctly. However, the water sold, as well as the one in bottles from distilled water brands, if it is not remineralised, can cause harm to consumers in the long run. This is without mentioning the fact that some refilling stations operate without proper permits or sufficient quality control testing.

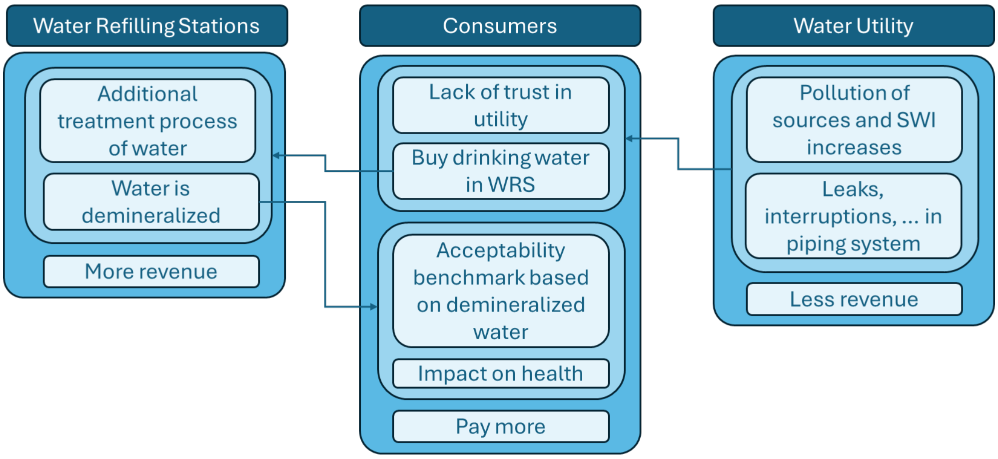


Figure 3.15: Lack of trust from consumers in water utility and its impacts

Because of the lack of trust in the water utility, citizens who can afford it prefer to consume water from other sources like water refilling stations or bottled water, paying more. Water from the water utility is then mainly used for cooking, cleaning, showers, etc. Some water distributing companies in the Philippines, faced with the increasing popularity of refilling stations, invested in opening their own stations treating water from their distribution system. However, this can lead to further distrust in tap water by giving citizens the impression that water utilities consider that their tap water needs additional treatment before consumption[13].

Moreover, as those refilling stations are connected to the tap water, water takes a relatively long and inefficient route, with many redundant processes, before it reaches the consumer. In the worst case, the water is extracted from a source (surface/groundwater) by a private company, fully treated and then remineralised before being sent to the distribution pipes (to protect pipes). The water is then sold to the public distribution company (water utility), mixed with water from other sources and conveyed to a Water Refilling Station, which in turn treats the water before selling it in a five-gallon bottle to a *sari-sari* shop owner, who puts the bottle in his Water Vending Machine before a consumer pays 1 PHP to fill a plastic bag with a small water volume. The longest route water takes from source to consumer is illustrated in Figure 3.16.

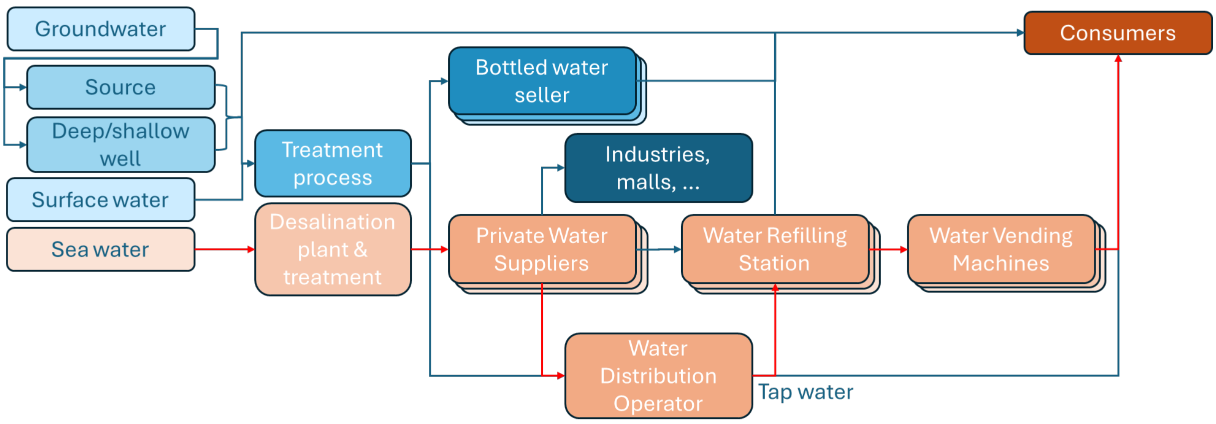


Figure 3.16: The worst path taken by water from source to end-consumer

[13]I. Adant, *Building up an Integrated Methodology for Water Resources Assessment and Management in Urban Coastal Areas* (BIMWAM)

4 Conclusions and discussion on local water expertise in Metro Cebu

On the national level, the water expertise is too scattered due to the fragmented framework of the water sector, as identified in numerous reviews and policy briefs. The water resources management needs to be combined into a single entity as advised by those policy briefs, proposing the establishment of a Department of Water Resources.

The fragmented framework can also be found at the local level of water monitoring. The overlapping jurisdictions cause inefficient water resource use, management, planning and monitoring. The stability of the water expertise is impacted by what happens at the local government level and, therefore, by elections. Indeed, part of the personnel is renewed each time a mayor's term of office ends (unstable expertise). The percentage of people with a fixed position, unaffected by a change of power within the LGU, is low. The negative effects on the water supply of the power battle between Metro Cebu Water District and the Local Water Utilities Administration), during the crucial water crisis period in 2024, demonstrates the impact of politics.

There has been a noticeable increase in the number of players (water vendors) in Metro Cebu, creating competition for water sources. Water vending machines can be found in large numbers in the area's densely populated districts. Water refilling stations continue to multiply. Even though water is not defined as an economic good in national laws and policies but rather as a common good, the water market is very profitable for private investors. The fact that water is not being treated as a commodity at the policy level (laws) leads to an inability to make market mechanisms work on a large scale [98].

To reduce the considerable gap between demand and supply of water, an optimal combination of different water sources (underground, surface and sea) is required. However, Metro Cebu faces a number of challenges, like many other urban centres in the Philippines:

- **Rapid economic growth and urbanization** in the region are increasing pressure on water resources.
- **Saltwater intrusion** into coastal aquifers is severely limiting the use of subsoil.
- **Groundwater, surface waters and seawater are polluted** by untreated waste discharged into the environment. There are deficiencies in the treatment and disposal of wastewater and garbage.
- Like the rest of the Philippines, Metro Cebu is subject to an **unfavourable climate**, and the typhoon season often results in the disruption of supply networks due to pollution of catchments and damage to supply infrastructure. Extreme droughts during the dry season exacerbate water scarcity. *El Niño* phenomenon is worsening the situation with climate change increasing the duration and intensity of droughts and rains.
- **Fragmented expertise and responsibilities** cause hindered policy and decision-making as well as inefficient management. The **scattered expertise** needs to be reinforced but presents trouble renewing itself.
- **Lack of data** on water pollution, extraction and availability. The lack of data creates uncertainty about the water sector's future and prevents concrete decisions from being taken.

- **Lack of resources** (budget, time, manpower and equipment) to perform necessary inspections, audits and monitoring activities.
- **Lack of understanding the adverse effects of continued low-mineral water intake** impacting the health of citizens.
- **Lack of citizens' trust** in the quality and quantity of tap water.
- **Inefficient path of water** from sources to customers. Multiplying actors in water sector, exacerbating lack of law enforcement.

In summary, Metro Cebu's water crisis has reached a critical stage. Faced with this water crisis, there is a growing awareness that the problem must be solved by developing water management and expertise capacities. It is necessary to consider ways to create conditions for effective **coordination** among actors for unified expertise and policy making, while also working on restoring **consumer trust** in the water sector.

This calls into question the way in which water expertise is organised and equipped and raises the question of investment in new technologies. In particular, an optimal combination of different water sources requires the deployment of a strategy for **monitoring** and managing the quality of the various water sources. Water management policies must be based on evidence like water balance studies as well as groundwater and surface quality and quantity water assessment to determine priorities and design a phased approach to the water crisis. Informed decision-making where the problem and situation are fully understood is crucial to sustainable management, correct risk assessment and adequate resulting planning. The lack of inventory data needs to be addressed. Identifying problems in producing information on the state of resources and issues encountered for creating a scientific knowledge base on the said state is essential. Water resource assessment needs to be able to be renewed when necessary (e.g., in cases of extreme climatic events or suspicion of repeated pollution), and should be gradually deepened to achieve an updated, stabilised, and effective functioning of expertise.

The data should also be available to citizens, especially about the water utility processes and testing results, to better regain their trust. To achieve this, it is essential to support local skills development through research and innovative initiatives.

Metro Cebu is, therefore, an exemplary study ground for water management and expertise issues, where the development and sharing of scientific knowledge fuels reflection on the strategies to put in place for the sustainable management and monitoring of aquifers and surface waters. **Data collection, coordination, and trust restoration** are three intertwined issues that involve questions about expertise and the design of monitoring tools. According to many stakeholders, current water monitoring methods need to be reviewed and made more effective. Many stress the importance of rapid and accurate in-situ data collection.

Given the advantages of portable sensors like their user-friendliness, accessibility and immediate results, as well as the economic cost of implementing alternative quality measurements, it is meaningful to focus on the design of such sensors and the corresponding expertise systems that can serve data collection. Portable sensors can enable effective assessment of water resources, which is crucial to exit the water crisis. A more detailed analysis of the monitoring needs of the various stakeholders is provided in the following chapters.

Chapter 4

Equipment Selection, Validation and Experimental Outcomes

The following two chapters summarise the equipment and methods used in this study. The first chapter focuses on the sensors considered for fieldwork in this study. First, the protocol for selecting those sensors is introduced, the chosen sensors are described, and their usage is explained. Second, the method used to validate the different sensors is outlined. Then, the data generated by the sensors in situ are compared with existing historical data. The various steps followed for data collection are described. Finally, in-situ portable sensor results are compared to results obtained in the laboratory.

1 Selection of sensors & description of selected equipment

Sensors for this study were selected based on the market analysis described in Chapter 2 (Section 3) and on the following criteria:

1. **Portable Sensors**: This study focuses on portable water quality sensors that allow on-site measurements. Sensors that are benchtop, need power from electrical sockets, or need manipulations unsuitable for fieldwork were not considered.

2. **Analysed water quality parameters:** Sensors were selected based on critical parameters specific to the context of Metro Cebu, i.e. important water quality parameters that are tested locally based on the Philippine National Standards for Drinking Water, the Water Quality Guidelines and the General Effluent Standards, as well as parameters corresponding to common pollution in Metro Cebu. As stated in Section 3.3 of Chapter 3, Metro Cebu's ground- and surface water is highly polluted. It is impacted by Saltwater Intrusion, high nitrate levels and rivers present high Biological Oxygen Demand, Fecal Coliform contamination, etc. Usual levels of pollution can be found in public data such as reports published by the Environmental Management Bureau (see Appendix B).

3. **Detection range**: The sensors need to be able to detect the expected concentration ranges of the critical parameters (which vary with the type of water analysed) and detect if water quality parameter concentrations comply with the permissible limits listed in the standards.

4. **Price**: This study focuses on low-cost sensors, i.e. sensors that are affordable and available for most stakeholders of the local water sector (ideally <50 EUR, max

200 EUR), individuals included. The initial purchase costs of different sensors were compared, as well as operational costs (costs of maintenance and calibration over the sensors' lifespan), and the least expensive options were considered.

5. **Type of sensor**: Different types of portable sensors were selected: paper test strips (with and without numerical conversion of results), test bottles and digital sensors. See Section 3 of Chapter 2 for a more detailed description and images of those different types of sensors that are classified based on their design and method of measurement.

The choice between different sensors was based on the listed criteria and, as Metro Cebu is known for its high temperatures and humidity, digital sensors analysing parameters impacted by temperature, such as pH, Electrical Conductivity and Dissolved Oxygen (see Section 1.3), provided with automatic temperature compensation were preferred as well as humidity-protected devices. These criteria have been used to establish a choice between sensors but are not present in all the selected sensors.

The focus parameters identified as well are their corresponding guideline value in PNSDW, WQG and GES are presented in Table 4.1 (see Table 3.1 in Section 2.2 of Chapter 3 and Figures B.4 and B.5 in Appendix B). Some relevant parameters to Metro Cebu's water quality were not considered, as no low-cost portable sensor is available on the market (see shortcomings of commercial portable sensors in Section 3.4 of Chapter 2). As a reminder, no low-cost portable sensor exist for TSS, BOD, COD, turbidity and qualitative bacteria measurements. The guideline values of the WQG and GES were selected for a Class C river, i.e. fishery water (see Table 3.2 in Section 2.2 in Chapter 3), which is the classification of the Butuanon River in Metro Cebu as of 2022. Some essential monitoring parameters (e.g., EC or alkalinity) do not have guideline values because they are not considered harmful to human health or the environment. The selected sensors are listed in Tables 4.2, 4.3, 4.4, 4.5 and 4.6. Their usage is further detailed in Appendix D.

Parameter	**PNSDW**	**WQG**	**GES**
Coliform (E. coli)	<1 MPM/100mL (Most Probable Number)[1]	Fecal Coliform: 200 MPN/100mL	Fecal Coliform: 400 MPN/100mL; Total Coliform: 10,000 MPN/100mL
Carbonate Hardness	/	/	/
Copper	1 mg/L	0.2 mg/L	1 mg/L
DO	/	min 5 mg/L	/ (BOD & COD indicated)
Electrical Conductivity	/	/	/
TDS	600 mg/L	/ (TSS: 80 mg/L)	/ (TSS: 100 mg/L)
Fluoride	1.5 mg/L	1 mg/L	2 mg/L
Free Chlorine	0.3 mg/L min and 1.5 mg/L max	/	/
Total Alkalinity	/	/	/
Total Chlorine	/	/	/
Total Hardness	300 mg/L	/	/
Iron	1 mg/L	1.5 mg/L	35 mg/L
Lead	0.01 mg/L	0.05 mg/L	0.1 mg/L
Manganese	0.4 mg/L	0.2 mg/L	2 mg/L
Nitrates	NO_3^-: 50 mg/L	NO_3-N: 7 mg/L	NO_3-N: 14 mg/L
Nitrites	3 mg/L	/	/
pH	6.5 - 8.5	6.0 - 9.0	6.0 - 9.5

Table 4.1: Focus Parameters and their corresponding maximum allowable level for drinking water (PNSDW), surface water (WQG) and wastewater (GES)

1.1 Bacteria absence/presence tests

For bacteriological parameters, the focus was set on detecting the presence of coliforms due to their importance in water quality monitoring and their emphasis in national standards for assessing the bacteriological quality of water. In the Philippines, it is a parameter that needs to be evaluated monthly for nearly all water sources [109]. It is one of the primary parameters for assessing surface water quality [111]. As digital, rapid, and low-cost portable sensors for detecting bacteria are not available on the market (see Section 3.4 of Chapter 2), bacteria test bottles indicating the absence or presence of coliform bacteria contamination above a certain detection limit (qualitative result) were chosen (see Table 4.2 where their characteristics are summarised).

The operation of bacteria bottle tests is described in detail in Section 2.1.2 of Chapter 2 and their use is explained in Appendix D. As a reminder, after a certain incubation time, a colour change indicates the presence of coliform bacteria (from which E. coli) and some bottles can indicate the presence of E. coli through fluorescence. Any colour change after the incubation time is not considered relevant. Bottles need to be stored in dry and cool environments, below 27°C.


Brand	SimplexHealth	Medasa	Aquavial
Parameter analysed	Coliform & E. Coli	Coliform	Coliform
Detection limit	1 CFU/100ml	1 CFU/10 ml	1 CFU/ml
Incubation time	24 hours to 48 hours	24 hours to 48 hours	24 hours to 72 hours
Size of sample	100 ml	12 ml	5 ml
Price per bottle	15.43 €	7.49 €	9.48 €

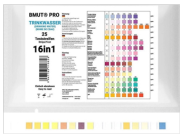
Table 4.2: Selected coliform test kits description

1.2 Paper strip indicators

The test strips were selected based on their semi-quantitative measurement range for specific parameters. Various paper-based indicators were purchased, including universal pH test paper and test strips designed to measure different parameters within specific ranges. The number of analysed parameters varies. One of the selected test strips is combined with a smartphone app (*JBL PROSCAN-App*), which scans the analysis strip placed on a colour chart after immersion in the water sample to determine the concentrations of the parameters. After the required reaction time, the app takes a picture of the test strip and translates it into numerical results. One disadvantage is that the only way to get results is via the app (doing it visually if the application does not work is impossible). The manganese test strip requires adding reagents to the sample by dipping two other strips before using the measurement strip. The operation of paper strip indicators is

[1] The Maximum Allowable Level using Membrane Filtration Technique.

described in Section 2.1.2 in Chapter 2 and their use is further detailed in Appendix D. Paper indicators need to be stored under dry and cool conditions. Table 4.3 summarises the selected paper test strips.

	BMUT test strip 16 in 1	Smardy Blue test strip	PRO JBL SCAN test strip	SimplexHealth test strip 5 in 1	Universal pH paper	SenSafe Manganese test strip	BMUT Total Hardness test strip
Parameters	Total Hardness, Free Chlorine, Iron, Copper, Lead, Nitrates, Nitrites, Potassium monopersulphate, Total Chlorine, Fluoride, Cyanuric Acid, Ammonium chloride, Bromine, Total alkalinity, Carbonate Hardness, pH	Free Chlorine, Iron, Copper, Lead, Nitrates, Nitrites, Total hardness, Total alkalinity, pH	Nitrites, Nitrates, Total Hardness, Carbonate Harness, pH, Chlorine, CO_2	Nitrites, Nitrates, Total Hardness, Total alkalinity, pH	pH	Manganese	Total Hardness
Numerical results	No	No	Yes	No	No	No	No
Reagents	No	No	No	No	No	Yes	No
Price per strip	0.19 € if bought by pack of 100; 0.48 € if bought by pack of 25	0.85 €	1 €	1.2 €	7.9 € for 5m; <0.02 € per measure	1.2 €	0.36 €

Table 4.3: Selected Test Strips Description

1.3 Digital sensors

Several digital sensors were selected for this study based on the parameters relevant to the context. However, some were excluded because the price of portable sensors for those parameters was too high (BOD, COD, TSS and turbidity). Parameters already covered by paper test strips, besides pH, were not considered due to budgetary limitations. The parameters measured by the selected digital sensors are Electrical Conductivity and Total Dissolved Solids (as those are general physicochemical parameters and allow for the detection of saltwater intrusion)[2], pH (as it is an essential parameter for water quality), and dissolved oxygen (essential for maintaining the balance of aquatic ecosystems and wastewater treatment processes). All digital sensors are powered by 1.5V battery cells.

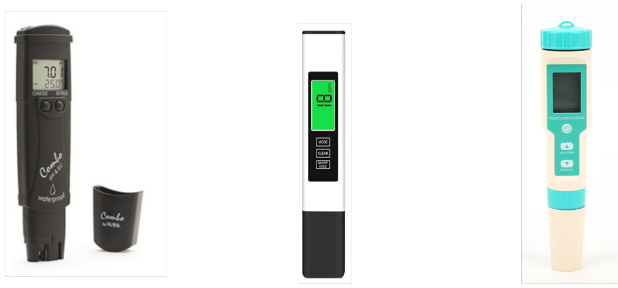
1.3.1 Electrical Conductivity and pH sensors

The pH digital portable sensors are equipped with a glass electrode to measure pH and conductivity is assessed with the 2 electrodes method (see Section 2.1.1 in Chapter 2). Digital EC meter selection was based on the expected salinity levels and conductivity range as Metro Cebu faces Saltwater Intrusion (see Section 3.3.1 in Chapter 3). Sensors require the ability to measure values higher than the freshwater range (higher than 1000 ppm of dissolved solids [5]), and Metro Cebu often shows conductivity values over 4000 μS/cm (as shown by Water Resource Center yearly monitoring).

The selected digital sensors for electrical conductivity and pH are a pH sensor from BMUT, an EC/TDS sensor from BMUT, an unbranded pH/EC/TDS/Salinity/SG/ORP sensor and a pH/EC/TDS sensor from Hanna Instruments (HI98130). All sensors have a temperature sensor that enables automatic temperature compensation. The HI98130

[2]As a reminder, Electrical Conductivity and Total Dissolved Solids are presented together as TDS values are based on EC measures (see Section 1.3.2 in Chapter 2)

features a replaceable pH electrode and graphite conductivity probes. The electrode of the unbranded sensor is also replaceable. The HI98130 also includes an adjustable temperature compensation factor for EC and TDS measurements. Additionally, for measurement accuracy, users can choose between a range of conductivity to TDS conversion factors; for the other sensors, it is fixed at 0.5. The HI98130 sensor also has a Battery Error Prevention System, which allows the meter to automatically shut off if there is insufficient power to obtain an accurate measurement. For pH electrodes, the main difference lies in the possibility of storing the sensor in a calibration solution (only possible for the HI98130 sensor). The specifications and descriptions of the sensors are summarised in Tables 4.4 and 4.5. The cells highlighted in blue are comparable attributes between digital sensors regardless of their analysed parameter(s).



	Parameter	HI98130	BMUT EC/TDS sensor	Unbranded sensor C-600
Range	EC	0.00 to 20.00 mS/cm	0 to 9999 µS/cm	0 – 10000 µS/cm; 10.1 – 19.99 mS/cm; 20.1 – 400.0 mS/cm (10.1 – 200.0 mS/cm is effective range)
	TDS	0.00 to 10.00 g/L (ppt)	0 to 9999 ppm	0 – 10000 ppm; 10.1 – 200.0 ppt (10.1 – 100.0 ppt is the effective range)
	Salinity	/		0.01 – 25.00%; 0 – 10000 ppm; 10.1 – 200.0 ppt
	ORP			±999 mV
	S.G.			1.000 – 1.222
Resolution	EC	0.01 mS/cm	1 mS/cm	1 µS/cm; 0.1 mS/cm
	TDS	0.01 ppt (g/L)	1 ppm	0.1 ppm; 0.1 ppt
	Salinity	/		1 ppm; 0.1 ppt; 0.01%
	ORP			1 mV
	S.G.			0.001
Accuracy	EC/TDS	±2% F.S.	±2% F.S.	±2% F.S.
	Salinity	/		±0.1% (for 0.01% – 5.00%); ±1% (for 5.1%-25%); ±2% F.S.
	ORP			±2 mV
Operating Environment	/	0 – 50°C; max RH 100%	0.1 – 80 °C	0 – 60°C
Waterproof		Yes + designed to float	No	Yes (IP67)
Automatic Temperature Compensation		Yes, adjustable temperature coefficient factor	Yes, not adjustable	Yes, not adjustable
TDS Conversion Factor	EC/TDS	0.45 to 1.00	0.5	0.5
Battery Error Prevention System	/	Yes	No	No
Calibration	EC/TDS	One point at 12.88 mS/cm or 6.44 ppt (g/L)	No	One point at 1413 µS/cm, 12.88 mS/cm or 111.8 mS/cm
Replaceable electrode	/	No (only pH electrode)	No	Yes
Price sensor		179 €	14 €	25 €
Price 1 calibration solution		1.36 €	/	16.95 € for 250mL
Price electrode conservation solution		No conservation solution	No conservation solution	No conservation solution

Table 4.4: Selected EC/TDS sensors description



	HI98130	BMUT pH sensor	Unbranded sensor
Range	0.00 to 14.00 pH	0.00 to 14.00 pH	0.00 to 14.00 pH
Resolution	0.01 pH	0.01 pH	0.01 pH
Accuracy	±0.05 pH	±0.05 pH	±0.05 pH
Operating Environment	0 – 50°C; max RH 100%	0 – 60°C	0 – 60°C
Waterproof	Yes + designed to float	No	Yes (IP67)
Automatic Temperature Compensation	Yes	Yes	Yes
Battery Error Prevention System	Yes	No	No
Calibration	one or two-point with two sets of standard buffers (pH 4.01/7.01/10.01)	Three-point calibration (pH 4.00/6.86/9.18)	One or two or three-point calibration (pH 4.00/6.86/9.18)
Replaceable electrode	Yes for pH electrode	No	Yes
Price sensor	179 €	14 €	25 €
Price 1 calibration solution	1.36 €	0.2 € (powder needs to be mixed with distilled water)	0.2 € (powder needs to be mixed with distilled water)
Price conservation solution	19 € (500 mL of 3M KCl)	/	/

Table 4.5: Selected pH sensors description

1.3.2 Dissolved Oxygen sensor

The JPB-70A type pen is a dissolved oxygen sensor composed of two parts (the probe and the microcontroller unit). The probe is composed of a Clark electrode (see Section 2.1.1 in Chapter 2). The electrode needs to be maintained on a regular basis. It is provided with automatic temperature compensation. DO measurements are sensitive to salinity, and a correction might be needed if the sample's salinity is too high [42]. All selected sensors are summarised in Table 4.7.

Range	0 – 20 mg/L
Resolution	0.1 mg/L
Accuracy	±0.3 mg/L
Operating Environment	0 – 40°C
Waterproof	No
Automatic Temperature Compensation	Yes
Battery Error Prevention System	No
Calibration	two-point (zero DO and saturated DO)
Response time	< 30 seconds
Replaceable electrode	Yes
Price sensor	± 126.50 €
Price calibration solution (per unit)	1.81 €
Price electrode conservation solution (per unit)	11.66 €

Table 4.6: Selected Dissolved Oxygen sensor description

Sensor	Total Alkalinity	Carbonate Hardness	Free Chlorine	Total Chlorine	Coliforms (of which E. coli)	E. coli only	Copper	Dissolved Oxygen (DO)	EC/TDS	Fluoride	Total Hardness	Iron	Lead	Manganese	Nitrates	Nitrites	pH	Other Parameters
Simplex Health test bottle					X	X												
Medasa test bottle					X													
AquaVial test bottle					X													
JBL PRO SCAN test strip		X	X								X				X	X	X	CO_2 content from pH and alkalinity value via App
Smardy Blue test strip	X		X				X				X	X	X		X	X	X	
Universal pH paper																	X	
Simplex Health test strip	X										X				X	X	X	
SenSafe Manganese test strip														X				
BMUT test strip 16 in 1	X	X	X	X			X			X	X	X	X		X	X	X	Ammonium chloride, Bromine, Cyanuric acid, Potassium monopersulfate
BMUT Total Hardness test strip											X							
BMUT EC sensor									X									
BMUT pH sensor																	X	
Hanna Instruments EC/TDS/pH sensors (HI98130)									X								X	
Unbranded sensor									X								X	Salinity, ORP, S.G.
DO meter JPB-70A								X										

Table 4.7: Selected Sensors
Orange: Qualitative results
Blue: Semi-quantitative results
Turquoise: Numerical semi-quantitative results
Green: Quantitative results

2 Validation of sensors

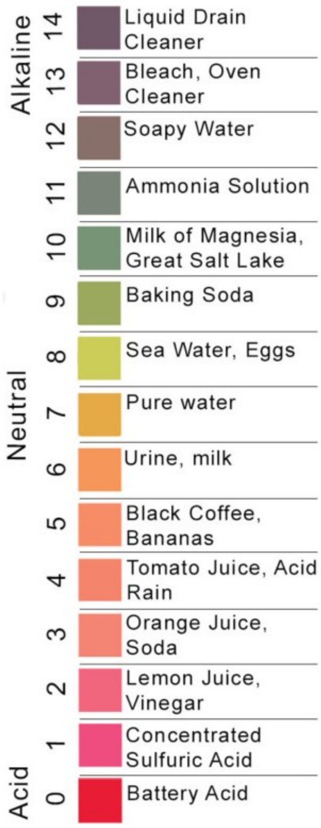
This section focuses on validating the selected sensors described in the previous section. The validation was based on a user-reproducible method. However, some sensors could not be validated easily without laboratory equipment. Those were validated in laboratory settings by comparing them to benchtop and traditional lab-based monitoring methods or by using laboratory equipment to obtain solutions of specific analyte concentrations.

2.1 User-reproducible sensor validation method

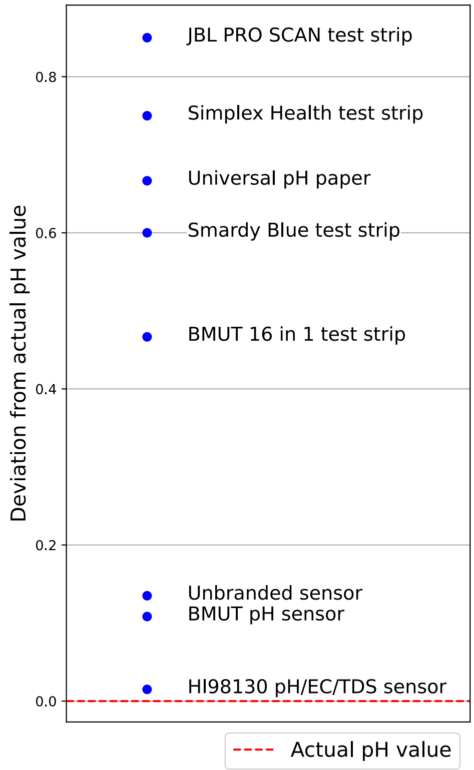
Validation of monitoring equipment is essential in giving users confidence in the sensors and trust in the data they generate. Most sensors were validated through a user-friendly process that is reproducible by citizens without needing laboratory equipment. This means the sensors were tested using affordable or available equipment for potential users like citizens. The reasoning behind this approach is to ensure that sensor validation is adapted to end-users, even those who do not have laboratory equipment at their disposal. Another purpose of such a method is to allow the demonstration of the use of the sensors without needing laboratory equipment.

For example, the validation of the different pH sensors (test strips, pH paper and digital sensors) is done by testing different types of liquids with known values of ranges of pH (see Figure 4.1a). The pH sensors validation, showing the average deviation of the results of the different sensors from the actual value, is presented in Figure 4.1b. The real value of the pH was determined by using solutions with known pH at reference temperature (e.g., commercial drinks, distilled water or calibration solutions of digital sensors). The figure shows that digital sensors have the highest accuracy, while test strips present lower accuracy due to their semi-quantitative nature. On average, the test strip used with an app analysing a picture of the strip shows results that can greatly vary from the actual value. This could be due to the sensitivity of the results to lighting. A similar method was used for EC meters (see Appendix C). Another user-reproducible validation example is the use of gardening fertiliser with a known concentration of nitrates to certify that test strips measuring nitrate levels give coherent results. This method allows for estimating the concentration of analytes in samples and observing if the sensors' results are coherent.

It is important to note that some of the validation procedures cannot be used to determine whether the accuracy of the tests is correct. In fact, without chemical solutions with precisely known concentrations, it can be challenging to identify the exact quantity of a component in a sample to evaluate the result provided by the tester. For example, it is not possible to validate the detection limit of the qualitative coliform and E. coli tests. Indeed, obtaining samples with and without coliform contamination to verify the qualitative aspect of the sensors (Presence/Absence) is feasible. However, citizens cannot access solutions with specific Culture-Forming Unit quantities to assess the detection limit of the various test bottles. If the detection limit wants to be tested, a laboratory setting and specific equipment are needed (see Section 2.2.3). Another limitation of this study is that the ability to validate specific sensors using this method depends entirely on the accessibility of the components analysed by said sensors in everyday life. Indeed, some analytes are more challenging to obtain, dissolve in a water sample, and, consequently, estimate their concentration in the sample. Table 4.8 lists the parameters analysed using a "citizen-accessible" method and the ones validated in a laboratory setting.



(a) pH Scale used as reference



(b) Average deviation of pH Sensors from the actual pH value

Figure 4.1: pH sensors "citizen-accessible" validation

Parameter	**Components for validation**
Electrical Conductivity	Salt (diluting salt in water raises EC)
TDS	Salt (diluting salt in water raises EC and thus TDS)
Fluoride	Mouthwash (230 ppm - 900 ppm), toothpaste (1,000 - 1,500 ppm)
Free Chlorine	Bleach and other chlorine-based disinfectants (± 52,500 ppm)
Total Chlorine	Idem Free Chloride
Total Hardness	Distilled water (<17 ppm of $CaCO_3$), water with high magnesium contents (>180 mg/l of $CaCO_3$), mixing two types of water will lead to intermediary results. Diluting chalk or baking soda increases hardness.
Carbonate Hardness	Idem Total Hardness
Total Alkalinity	Idem Total Hardness
Nitrates	Fertiliser (± 1,700 ppm)
Nitrites	Preservatives (± 150 ppm), organic pollution, compost (± 1 ppm)
pH	see pH Scale in Figure 4.1a
Copper	Laboratory tests: solutions with known concentration
Iron	Laboratory tests: solutions with known concentration
Lead	Laboratory tests: solutions with known concentration
Manganese	Laboratory tests: solutions with known concentration
Coliform (E. coli)	P/A check with contaminated water (river near farms, sewage water, ...) and bottled water; Attempt to laboratory validation of detection limit
DO	Milk frother or other kitchen utensil for mixing liquids used to saturate the solution with O_2, zero calibration solution (0 - 10 mg/L); Comparison with laboratory equipment

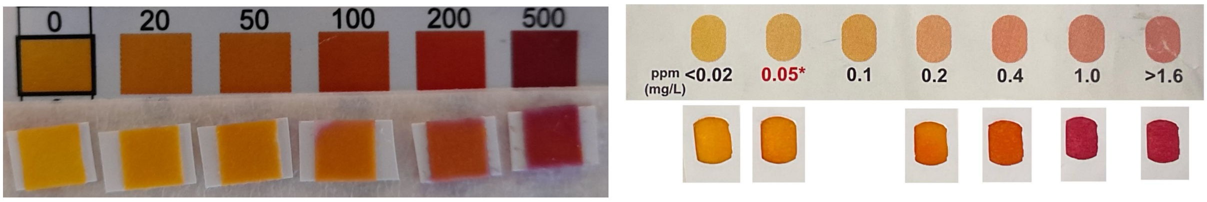
Table 4.8: Focus Parameters and their corresponding validation method

2.2 Less accessible sensor validation method

Further validation was performed for parameters like metals, which are more difficult to find in everyday life, DO and E. coli, for which it is difficult to obtain a sample with known concentrations, even approximately, for common end users. With laboratory equipment, it is possible to obtain solutions with known concentrations of elements.

2.2.1 Validation of metals detection with paper tests

To validate test strips detecting metals (Iron, Lead, Manganese, Copper), laboratory experiments were performed by dissolving known quantities of analytes in distilled water. For instance, to validate test strips measuring lead, $Pb(SO_4)_2$ was dissolved in control volumes of distilled water to obtain solutions with Pb concentrations of 0, 20, 50, 100, 200 and 500 ppm (corresponding to the colour chart). For Manganese, $Mn(SO_4)_2$ was used. In both cases, molar mass conversations were applied. Figures 4.2a and 4.2b contain the results obtained for Lead and Manganese (the results for Copper and Iron are presented in Appendix C).



(a) BMUT 16 in 1 test strip validation for lead (b) Sensafe Manganese test strip validation

Figure 4.2: Lead and Manganese test strips "citizen-accessible' validation

Validation results show that the colour chart sometimes presents colours that are difficult to distinguish and not always in line with those obtained. This reduces user-friendliness. The manganese test is particularly challenging in this regard (see Figure 4.2b) as the colour scale shows very similar colours and plainer colours than the results. This test also showed interference from other metals with the same valence number, such as iron.

2.2.2 Validation of digital Dissolved Oxygen sensor

Further testing to validate the DO sensor was done with laboratory equipment. The user-reproducible validation method allows the observation of increasing dissolved O_2 values when the test solution is mixed. Still, the values provided by the sensor can not be compared with known solution concentrations except in a zero DO calibration solution or when saturation of the solution is assumed Indeed, after the liquid has been stirred for a long time, saturation is usually reached, and saturation values of dissolved oxygen for different temperatures are known. The measurements of the meter were thus further validated by comparing them with the ones of two other laboratory sensors: a multi-parameter lab benchtop meter for pH, conductivity, dissolved oxygen and turbidity measurement (inoLab Multi 9310 IDS) as well as a fibre optic oxygen meter (OXY-4 mini from PreSens)[3]. The characteristics of the used sensors are listed in Table 4.9. The

[3]The device is composed of a polymer optical fibre to transfer excitation light to the sensor spot which returns a response to the meter. The sensor spot allows non-invasive optical oxygen sensors. It does not automatically correct measurements with the temperature as it does not measure it. The temperature readings must be done manually and encoded in the software for temperature compensation.

validation was carried out by comparing the results of the three sensors after calibration, with one- or two-points, depending on the sensor (zero DO and saturated DO solutions). The results, shown in Figure 4.3, indicate that the portable DO meter gives similar values to the two other sensors (mean absolute error of 0.23 mg/L), sometimes with a slower response time. The portable meter values take more time to display stable values than the two other sensors. This is due to the Clark electrode needing to be stirred for accurate measurements, increasing measurement time (see Section 2.1.1 in Chapter 2). Dissolved oxygen values were measured in an oxygen-saturated water solution, into which nitrogen was bubbled to reduce the saturation progressively. The zero DO solution was obtained by dissolving sodium sulfite (Na_2SO_3), an oxygen scavenger, in distilled water ($Na_2SO_3 + O_2 = Na_2SO_4$) and saturating it with nitrogen.

	OXY-4 mini (PreSens)	Multiparameter Benchtop Meter (Multi 9310 - inoLab)	Portable DO sensor (JPB-70A)
Power Supply	Mains operation	Mains operation, USB or battery	Battery
Measurement method	Optical measurement based on photoluminescence, contactless measurement, parallel measurement of 4 samples	Optical measurement based on photoluminescence	Clark electrode
Value display	Connected to computer with software	Memory or logged on computer (Excel Add-in)	LCD display
Range	0 – 45 mg/L	0 – 20 mg/L	0 – 20 mg/L
Resolution	0.01 mg/L	0.01 mg/L	0.1 mg/L
Accuracy	± 0.004 mg/L at 0.091 mg/L ± 0.04 mg/L at 9.1 mg/L	± 1.5 %	±0.3 mg/L
Measurement temperature range	From 0°C to 50 °C	From 0°C to 50 °C	From 0°C to 40 °C
Automatic Temperature Compensation	No (manual temperature compensation)	Yes	Yes
Response time (t_{90})	< 40 seconds	< 30 seconds	< 30 seconds
Calibration	Two-point calibration with oxygen-free environment (nitrogen, sodium sulfite) and air-saturated environment	One-point calibration with oxygen-free environment (sodium sulfite)	Two-point calibration with oxygen-free environment (sodium sulfite) and air-saturated environment

Table 4.9: Specifications of DO meters comparison

2.2.3 Validation of coliforms and E. coli test bottles

The several bacteria test bottles that were purchased to determine the presence or absence of bacteria have different detection limits (see Table 4.2). The qualitative aspect of the test bottles was validated with a "citizen-adapted" method. Indeed, validating this aspect is done by testing pure, uncontaminated water and water known to have been infected by faecal matter (rivers, etc.). However, to fully determine the validity of these tests, it is also necessary to determine whether the detection limit is valid. This involves obtaining solutions with specific coliform bacteria concentrations corresponding to the detection limits. This can be done in the laboratory by growing bacteria and diluting them progressively by factors of 10 to obtain solutions with low bacterial concentrations. The resulting solutions can be quantified using the membrane filtration or heterotrophic plate count methods and then used as a test solution if the order of magnitude matches

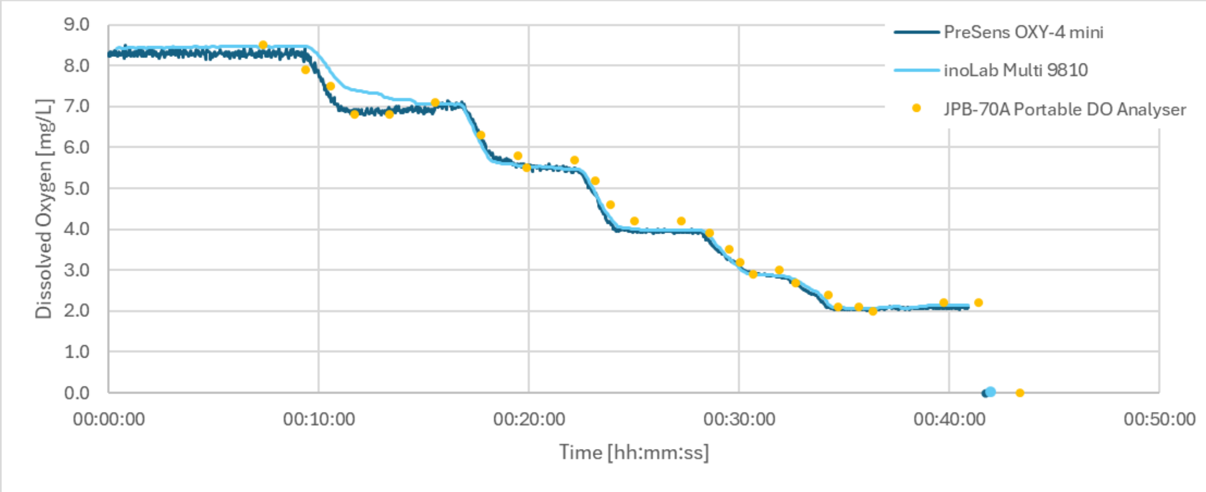


Figure 4.3: Comparison of DO measurements in water deoxygenated gradually with three sensors (OXY-4 mini and benchtop meter taking measurements every two seconds and five seconds, respectively)

the detection limit. Unfortunately, the experiment conducted in the laboratory was unsuccessful due to faulty equipment and contamination, resulting in inconclusive tests. Traditional bacteriology testing methods that involve plate counts are time-consuming and require specialised equipment, reagents and an experienced laboratory technician to avoid contamination compromising the experiment results.

3 Experimental Results

The data generated from the water quality monitoring performed in Metro Cebu was compared to historical water quality data. Additionally, a comparison was made between on-site measurements and corresponding laboratory results. Comparisons were also conducted between sensor data and laboratory equipment data.

3.1 Locations of experiments

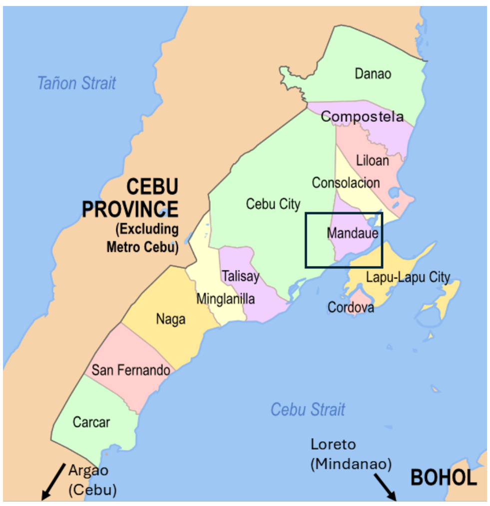


Figure 4.4: Location of experiments with sensors

Experiments with the sensors brought on-site were performed in Argao (Cebu), Cebu City, Mandaue City (Metro Cebu) and Loreto (Mindanao). The experiments were possible through collaboration with the Water Resource Center of the University of San Carlos (WRC-USC). They were performed on the wells they regularly monitor in Metro Cebu and their project sites in Argao and Loreto. Argao is one of the municipalities in the Cebu Province. It is situated south of Metro Cebu. The rivers and springs of the municipality were tested. Loreto is a municipality of the Province of Agusan del Sur (Mindanao), and groundwater extracted through wells was tested. Part of the experiments were performed by WRC or USC staff/students to receive their feedback on the sensors (this is detailed in the next chapter).

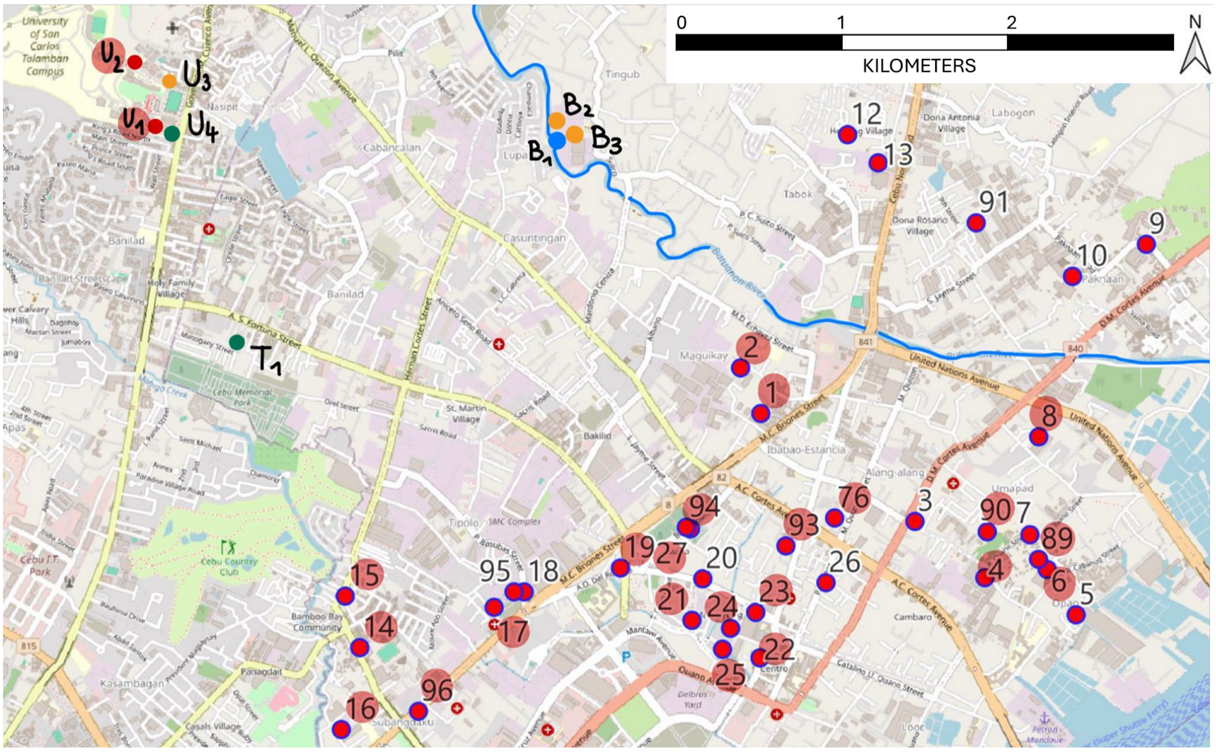


Figure 4.5: Location of water quality monitoring performed in Metro Cebu
Legend: Red (groundwater monitoring wells of WRC): highlighted in red (= test performed) & not highlighted (= test not performed); Blue (surface water); Green (tap water); Orange (wastewater).

Figure 4.5 shows a map of the various locations for water quality monitoring performed in Metro Cebu. The markers on the map represent the different sampling points scattered throughout the city, and their colour indicates the type of water analysed (tap water, well water, surface water, and wastewater).

- U_{1-4}: Part of the experiments were conducted on the University of San Carlos Talamban Campus. The campus has wells to provide for most of its water needs (the water district, MCWD, provides 10% of the water usage) and a treatment plant (supervised by the Pollution Control Officer).
- B_{1-3}: Some sampling tests were done along the Butuanon River, which is at the centre of the Mandaue and Cebu Cities river rehabilitation projects and the venue for the ClimateCafe 2024 project (RiverScan Challenge) organised by USC in partnership with Dutch universities (see Section 3.2.8 in Chapter 3). The river's water was tested as well as industrial and residential wastewater discharged in the river.
- 1,2, ...: Many sampling points are situated in densely populated central urban areas. Those red dots with an identification number correspond to community-owned or private wells scattered across the city that the WRC monitors. The part of those wells analysed during fieldwork have their identification number highlighted in red. Some tests could not be realised because the wells were not functioning or were abandoned. The groundwater extracted from those wells is mainly used for laundry and washing. However, well n°8 is an exception as communities use it as drinking water due to the absence of bacteria (but high salinity).

Context of Use of Sensors	Surface water	Groundwater	Distributed water	Wastewater
ClimateCafe River Scan Challenge 2024	Butuanon River			
Argao (Cebu) Fieldwork with members WRC	Rivers			
Metro Cebu Fieldwork with members WRC		Wells		
Loreto (Mindanao) Fieldwork by members WRC		Wells, Spring		
Talamban Campus of University of San Carlos Fieldwork		Wells	Tap water	Wastewater Treatment Plant

Table 4.10: Summary of the context of the use of sensors and the corresponding type of water

3.2 Comparison with historical data

The data collected through the various experiments performed in Metro Cebu was compared to historical water quality data available from reliable stakeholders. For surface water and rivers, the results are compared with data published by the EMB VII in their annual water quality monitoring reports (2022, 2023). For groundwater monitoring, the results were compared with WRC's annual monitoring (2019, 2024). Examples of comparison are shown in Table 4.11.

	Parameter	Sensor	Historical data	Fieldwork
Wells (n°8)	Electrical conductivity [mS/cm]	pH/EC/TDS HI98130	5.79	4.71
	Nitrate (NO_3) [mg/L]	Smardy paper test strip	41.7	50
	pH [-]	pH/EC/TDS HI98130	7.09	7.08
Butuanon River (Tingub)	Dissolved Oxygen [mg/L]	DO sensor (JPB-70A)	4.16	3.5

Table 4.11: Historical data comparison examples

No values were detected that were out of the expected ranges. Electrical conductivity, for example, corresponded to expected results and was coherent with the WRC's monitoring. Where historical data indicated high SWI, wells presented very elevated EC values (sometimes higher than 2500 $\mu S/cm$[4], e.g., well n°8). This well was used as drinking water, and no bacteria were detected, which was expected because elevated concentrations of salt inhibit the growth of bacterial species like coliforms [133]. Nitrate levels were coherent with historical data, with discrepancies due to the semi-quantitative nature of test strips. pH monitoring performed with the digital sensors was coherent, with a deviation from the actual value for the paper test strips similar to the one obtained during the validation test of the sensors. Butuanon River's DO levels were coherent with EMB VII's data sampled at the closest sampling point (Tingub Bridge).

3.3 Comparison with laboratory results & transport bias

This experiment was performed on the USC Talamban campus with the Water Laboratory of the Department of Chemistry. The water from two wells providing water to the campus and the treated wastewater were analysed on-site while samples were collected and brought to the Water Laboratory for analysis. The on-site measurements with the selected sensors and the laboratory results were compared. Those in the lab were taken after the sample

[4] European Union recommendation for maximum conductivity in drinking water.

had been transported, 4 hours later. During laboratory analysis, comparisons were also conducted between sensor data and laboratory equipment data by simultaneously doing tests on identical samples. Knowing the difference in results between the portable sensors and the laboratory equipment allows us, in the second experiment, to attribute any greater difference to the time difference between measurement and the transport bias.

The different parameters of the experiment were selected with the help of the campus Pollution Control Officer, Ms. Esmeralda S. Cuizon. They are summarised in Table 4.12 with the corresponding portable sensors used for on-site measurements and the equipment used by the laboratory. pH and EC were measured with similar technologies on-site and in the lab (Hach and Thermo Orion benchtop sensors with a pH glass electrode and conductivity meter made of two electrodes), all provided with automatic temperature compensation. DO was measured with a Clark electrode for the portable sensors and the Wrinkler titration method in the Laboratory. The rest of the parameters were measured on-site with test strips.

Parameter	**Portable Sensors**	**Laboratory equipment**	**Laboratory charge per sample (PHP)**[5]
Electrical Conductivity	HI98130 (EC BMUT and Unbranded sensor for comparison)	Conductivity Meter	150.00
pH	HI98130 (ph BMUT and Unbranded sensor for comparison)	Electrometric	150.00
Dissolved Oxygen	DO portable sensors (JPB-70A)	Azide Modification (Winkler Method)	1,300.00
Nitrate	JBL PRO SCAN test strip (BMUT test strip 16 in 1 and SimplexHealth paper strip for comparison)	UV Spectrophometric Screening	1,000.00
Residual Chlorine	JBL PRO SCAN test strip (BMUT test strip 16 in 1 for comparison)	Iodometric Titration	485.00
Total Hardness	BMUT Hardness test strip (SimplexHealth paper strip for comparison)	Titrimetric (EDTA)	443.00

Table 4.12: Parameters and corresponding equipment with charge per sample

As stated before, the comparison of on-site measurements with the results provided by the Water Laboratory can highlight the transport bias occurring with the analysed samples. The water sample's characteristics can be altered during collection, transport, and storage before the laboratory analyses the sample. These changes can occur due to various factors, explained further, leading to inaccurate results. This stresses the importance of in-situ measurements and, thus, portable sensors.

The longer the time between sample collection and analysis, the higher the chances of changing the sample's chemical, physical, or biological properties. Chemical reactions can continue in the sample during transport, thus altering the concentrations of various

[5]The indicated prices are those charged by the Water Laboratory of the Department of Chemistry of the University of San Carlos as of August 2023. In 2024, 1 PHP is approximately 0.016 EUR.

substances. When the temperature changes during transport, it can affect the activity of bacteria and the stability of certain compounds [42]. As stated before in Section 1.3.1 of Chapter 2, pH, EC and DO are temperature dependent. If a digital sensor is used, temperature compensation is essential for correcting temperature-related measurement biases, however, it cannot mitigate transport bias caused by physical, chemical, or biological changes during the time between sampling and measure. For example, changes in DO levels caused by biological consumption or gas exchange can occur during transport. Indeed, microorganisms in the sample may consume oxygen, or chemical reactions can happen, reducing DO levels over time. Oxygen might equilibrate with the headspace gas in the sample bottle. If the bottle is not sealed correctly, the sample is exposed to air, and oxygen can diffuse into or out of the sample, changing its DO content. For the other parameters, changes in electrical conductivity can be due to the evaporation of water from the sample that concentrates ions. By producing acidic or basic metabolic byproducts, microbial activity and gas exchange can change the pH level [42, 44]. Nitrate, residual chloride and hardness will be impacted due to biological activity, chemical activity or volatilisation as well. When transporting samples, one way to mitigate the bias is to add reagents or to refrigerate the sample which is not ideal during fieldwork.

Part of the results of this experiment is shown in Table 4.13. The average differences between measurements on the exact same sample and measurements done in situ and, after transportation, in the lab are given to highlight the transport bias. The differences are more visible for parameters that need immediate measures like pH, EC and DO because their value can vary rapidly with time.

Parameter	**On-site (portable sensors)** (Well: 31.5°C; Wastewater: 30.4°C)	**Laboratory measurement** (28°C)	**Average difference between measurements on exact same sample**	**Average difference between in-situ and lab measurements**
Electrical Conductivity [μ S/cm]	Well: 730	Well: 688	12	42
pH [-]	Well: 6.92 Wastewater: 7.95	Well: 6.95 Wastewater: 7.99	< 0.01	0.04
Dissolved Oxygen [mg O_2/L]	Wastewater: 7.6	Wastewater: 7.25	0.25	0.35
Nitrate [mg NO_3^-/L]	Well: 25	Well: 23.8	/	/
Residual Chlorine [mg Cl_2/L]	Wastewater: 0 [6]	Wastewater: Less than 0.21	/	/
Total Hardness [mg C_aCO_3/L]	Well: 425 with BMUT hardness test strip; 300 with SimplexHealth test strip	Well: 338	/	/

Table 4.13: Parameters and corresponding results of on-site and laboratory measurements

For other parameters, the difference between in-situ and laboratory measurements is not as obvious. One reason is that the portable sensors (test strips) are less precise because their results are semi-quantitative. This means that the difference between measurements on the same sample with laboratory equipment and the test strips can vary significantly depending on whether the analyte concentration is close to a value of the semi-quantitative scale. One example to illustrate this is the difference between the semi-quantitative ranges

[6] The Residual Chlorine levels were very low on the experiment date because of a lack of disinfectant.

of the BMUT hardness test strip and the SimplexHealth test strip, resulting in varying discrepancies with the laboratory results as shown in Table 4.13. Indeed, the BMUT test has a semi-quantitative range of 0-25-50-120-250-*425*, and the SimplexHealth has a semi-quantitative range of 0-25-75-50-*300*-1000, which when compared to the reading provided by the laboratory, give different error values. Comparing average differences between laboratory equipment and portable test results on the same samples taken simultaneously and those observed between in-situ measurements (portable sensors) and laboratory measurements (benchtop equipment) is thus insignificant. However, this can be used to demonstrate that the test strips correctly provide the range of the parameter. The differences between measurements on the same sample for the dissolved oxygen are due to different measurement methods.

The use of the sensors helped further draw aspects of design that need to be rated by end users on top of the already identified specifications during the literature and market overview. The importance of the various sensor specifications according to local stakeholders is assessed in the next chapter.

Chapter 5

Design Specifications Determination: Method and Results

This chapter regroups the results of this study performed with the equipment detailed and validated in the previous chapter. First, the method used to receive feedback from individuals who used those sensors is described. Then, the method used to identify design priorities and specifications of sensors based on the stakeholders' needs is described. Thereafter, the different interviewed users and stakeholders are enumerated. Conclusions on specifications for sensors are drawn based on the interviews of stakeholders and the utilisation of the sensors by different users. The importance of trust is highlighted in the stakeholders' and users' answers. The user-friendliness of the different selected sensors and some other equipment is quantified and contrasted with their price and precision. Finally, the compliance of the sensors with needs is assessed, and innovations needed to improve current portable sensor offer are listed.

1 Method for feedback on on-site use of selected sensors

In real-life scenarios, the various devices were evaluated and compared based on their ease of use and technical specifications. This was done by potential end users (listed in Section 4) who are part of the stakeholder institutions listed in Chapter 3. Those users performed their usual monitoring activities with the selected sensors. The sensors brought from Belgium to Metro Cebu were thus tested on-site by others to monitor water quality. This section describes the method used to receive feedback on other people's use of the sensors. The asked questions are based on identified specific design elements of some of the sensors (type, results, handling, etc.) through literature as well as own use and experience.

Several questions were presented to the users on the sensors brought to Cebu:

- **Identification of sensors**: Users were asked to specify which sensors they used.
- **Overall satisfaction and feedback**: Users were requested to provide an overall assessment of their experience with the sensors. This approach was intended to capture their first impressions without influencing their responses.
- **User-friendliness ranking:** If multiple sensors were used, participants were asked to rank them in terms of user-friendliness.
- **Trust in results**: How reliable did users find the results provided by the sensors?

- **Precision of results**: Were the results precise enough for their needs (qualitative or (semi-)quantitative)?
- **Purchase consideration**: Would users consider purchasing sensors presented to them? If so, at what price?
- **Use of test strips**: For those who used test strips, feedback was sought on the ease of comparing colours with the provided colour chart.
- **Comparison with previously used sensors, if any**: Users who had experience with other sensors were asked to compare their experiences (previously used sensors vs. brought sensors).

2 Method for identification of design priorities for stakeholders

Meetings were held with representatives of most of the stakeholders of Metro Cebu's water sector described in Section 3.2 in Chapter 3. The questions asked to the different stakeholders with a water-related mandate to identify design priorities for sensors are listed below in Section 2.1. Additionally, discussions were held with citizens, mostly informal settlers (introduced in Section 3.3.3 in Chapter 3), and the questions are listed in Section 2.2. Questions were adapted for citizens, compared to institutions with water-related functions, because the hypothesis was set that the knowledge about water quality parameters and sensor specifications was non-existent. The interviewed stakeholders and citizens are listed in Table 5.3 in Section 5.1.

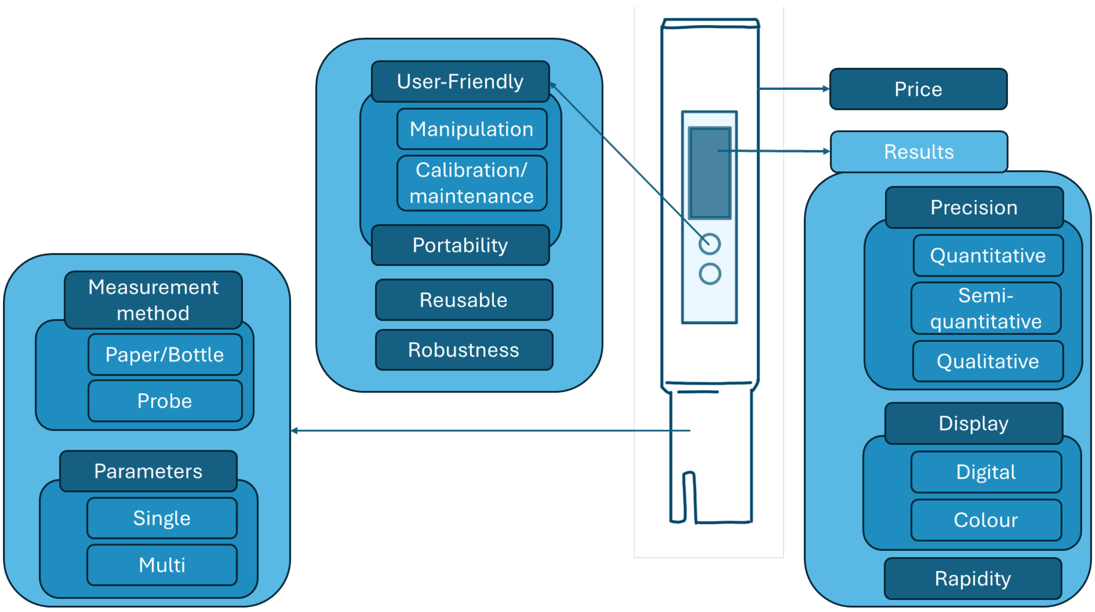


Figure 5.1: Considered Specifications of a Portable Sensor

The literature review and the manipulation of existing sensors of the previous chapter helped shape the main specifications of portable sensors that need to be weighted by end-users included in Figure 5.1. It structures an overview of the various attributes and specifications related to the design and use of portable water quality sensors that are considered in this study. For the quantification method, paper-based sensors and test bottles using colorimetric transduction were differentiated with sensors that transduce analyte concentration in digital results through electrodes (probe)[1]. Questions on the importance of those main specifications helped shape the stakeholder needs, i.e. they were asked to classify those specifications depending on level of importance.

2.1 Questions for stakeholders with water-related mandates

Questions asked to institutions with water-related functions:

- **Role in local water quality sector**:
  - **Type of water:** identification of the type of water for which quality is relevant to the stakeholder's mandate: distribution water, wastewater, surface water or groundwater.
  - **Purpose/Use of water**: Primary use of the type of water: consumption, household activities (e.g., laundry, showering), or environmental purposes.
- **Expertise and practices in water quality**
  - **Expertise**: What is their level of expertise in water quality monitoring and how is it managed?
  - **Water Quality Measurements**: Are water quality measurements conducted? If so, what are the frequency of the measurements, the parameters measured, the type of sensor used and the reason behind the monitoring (law, increasing pollution or other reasons)?
- **Usage and perspectives on portable sensors**
  - **Interest in portable sensors**: Are portable sensors used or considered for water monitoring? What benefits are perceived in using portable sensors?
  - **Previous experience with sensors**: Feedback on the use of the already purchased sensors (see previous section for the questions related to the feedback on the use of sensors).
- **Specifications for an ideal sensor**
  - **Parameters of interest:** What parameters are crucial for the monitoring needs?
  - **Ideal sensor discussion**: What specifications would define an "ideal" sensor corresponding to their needs?
  - **Importance of specifications:** Which focus specifications (see Figure 5.1) have very high, high, medium, low or very low importance? Ranking the focus specifications from most to least important when purchasing a sensor. Identify the specifications where stakeholders are least willing to compromise.
  - **Expected precision**: What level of precision and accuracy is expected from a sensor?
  - **Trade-offs with price**: Identify possible trade-offs between price and any of the other specifications that might be considered. For example, would they accept to pay more for a more user-friendly sensor?

[1]Those concepts are defined in Section 2.1 of Chapter 2.

- **Trade-offs with precision**: Identify possible trade-offs between precision and any of the other specifications that might be considered. For example, would a less precise sensor be considered if it were portable or easier to use?

- **Trust in sensor results**: Identification of specifications of sensor inducing more trust in provided results by:
  - Analysing if the trust is greater for qualitative vs. quantitative results, digital vs. colour results. Analysing the influence of the price, the brand and the look as well as the calibration, maintenance and manipulation process on the trust in the sensor. The impact of portability on trust was also considered.
  - Ranking different types of results for trustworthiness (see Table 5.1 for the type of results).

Results transmitted in real-time from sensor to lap-top/smartphone (IoT system)
Results stored on memory of sensor and retrieved later
Results displayed on screen of sensor and thus need to be written down
Results are colours (example: paper tests), need to recover the semi-quantitative results by comparing the colour to a colour chart
Semi-quantitative results are shown on app after taking a picture of test strip
Results are qualitative (change of colour indicating absence/presence)

Table 5.1: Type of result provided by a sensor

2.2 Questions for citizens

The following questions were asked to citizens, mostly to informal settlers living around the Butuanon River (described in Section 3.3.3 in Chapter 3):

- What water resources are community members using (for drinking water, cooking water, showering or laundry) and why?
- How do community members assess the water quality (visually, smell, etc.)?
- Would they be interested in having access to data about the water quality of their water source or the river?

If interviewed informal settlers showed interest in knowing more about their water or the river quality, they were asked questions about the type of information that interests them, such as the classification of the river near where they live, the level of danger, specific water quality parameters, or the safety of the water for drinking, swimming, or skin contact. They were also asked whether they were interested in improving the river's water quality and if they would like to be involved in such efforts. Additionally, the interview explored their interest in taking measurements themselves and if they had considered purchasing water quality monitoring equipment (easy to use, affordable, and accessible) to do so and, if they did, what characteristics they would prioritise in such equipment.

Informal settlers' and citizens' answers were used to evaluate their knowledge about water quality in general (parameters, monitoring, etc.) as well as to determine participants' interest in water quality issues and the extent to which they wish to be involved in related processes and decision-making.

Based on the answers of participants in fieldwork and interviewed stakeholders, classification of the different specifications is obtained. To quantify the results of the different rankings provided by the stakeholders, those rankings were translated into numerical scores and averaged. The answers of the different stakeholders were not weighted with their level of authority or level of expertise. Indeed, in many cases, the stakeholders with the most power are those with more resources, political influence, or technical expertise. By weighing the answers, the opinion of less powerful institutions (non-governmental water sellers, research institutes, laboratories), despite being primary beneficiaries of water monitoring technologies, would have less importance. In the worst case, limited influence could lead to the chosen technologies not aligning with their actual needs or preferences. Preferences of less-powerful institutions should not be overlooked as their opinion is crucial for the successful implementation of community-focused technologies [64].

3 Method for evaluating sensor compliance with identified needs

Most specifications can be quantified easily and compared between sensors. Indeed, the price, number of parameters, reusability, robustness, portability and result specifications (rapidity, precision and type of display) can be found in datasheets. Compliance with user needs is thus easily evaluated. Unlike those quantitative specifications, user-friendliness is more complex to quantify, and the next section will describe the method used to do so.

3.1 Method for quantification of user-friendliness

The user-friendliness of a sensor depends on the facility of use during the three following phases:

- **Measurements**: Measurements require a number of steps specific to each sensor and some measurements need reagents (additional costs and manipulations).
- **Maintenance**: Single-use sensors only require to be kept in suitable conditions (dry and cool). Maintenance of a reusable sensor consists of cleaning the sensor after use to avoid cross-contamination between samples, and some sensors are required to be stored in a preservation solution to avoid electrode degradation. Electrochemical electrodes, like pH glass electrodes, for example, must often be kept in storage solutions to prevent the electrode from drying out. Maintenance also includes inspecting the sensors for any signs of damage.
- **Calibration**: The need for calibration is only valid for reusable sensors (no single use). However, not all digital sensors have the possibility to be calibrated and the regularity of calibration varies with the type of sensor. Calibration requires several steps, with the procedure varying from one sensor to the other. If needed, it almost always involves the purchase of calibration solutions with determined levels of the concerned parameter.

To quantify the ease of performing those three categories of usage, the number of steps needed for each phase was counted for the selected sensors as well as for other sensors where the steps of use are known, i.e. portable sensors used by the WRC (see Appendix D). The user-friendliness of the three categories is then compared to the price and precision of the concerned sensors in Section 5.3.1.

The frequency of measurement depends on the purpose of the sensor. The frequency of maintenance and calibration is different depending on the type of sensor, the frequency at which measurements are taken, as well as other aspects such as the variation in the environments in which measurements are taken. Indeed, calibration is often needed for better accuracy when the measurement range or the temperature changes, for example. Indeed, better accuracy is obtained if the calibration solution's temperature is close to that of the water samples [42]. Because the frequency of maintenance and calibration depends on the use of the sensor, the three phases can not simply be aggregated. They are thus separately compared to price and precision.

4 Results of feedback on on-site use of selected sensors

Table 5.2 lists all the participants who used the sensors brought in Metro Cebu to assess water quality during fieldwork and the corresponding type of the analysed water as well as the used sensors. They were asked the questions listed in Section 1.

- The Pollution Control Officer of the Talamban Campus of the University of San Carlos, Ms. Esmeralda S. Cuizon, tested the use of some paper strips and digital sensors on groundwater from the wells and the treated wastewater of the campus.
- Students from the Department of Civil Engineering, who participated in the ClimateCafe RiverScan Challenge 2024, tested some of the sensors to assess the water quality of the Butuanon River as well as the wastewater of the communities living along the river and the water discharged by industries nearby. This was done in the Barangay they were interviewing.
- Water Resource Center staff members used the different sensors for fieldwork activities in Argao and Loreto, assessing the quality of rivers, springs and wells. For example, the Sensafe Manganese test strip was used to test wells with known contamination.
- Fieldwork to assess the water quality of part of wells monitored by the WRC in Metro Cebu was conducted with the staff member who usually performs the annual groundwater monitoring.

The locations of those fieldwork activities can be found in Figure 4.5 in Section 3.1 of Chapter 4. Users of the sensors did not all use water quality sensors before but all had knowledge about water quality parameters. Only the use and manipulations during measurements are considered here, the maintenance and calibrations of the sensors are not taken into account for the user-friendliness ranking.

Level of Authority	Users of Sensors	Sensors used	Surface water	Groundwater	Distributed water	Wastewater
University of San Carlos (USC)	Pollution Control Officer of Talamban campus	Some paper strips and digital sensors		X		X
	Department of Civil Engineering students	Some paper strips, bacteria test bottles and digital sensors	X			X
Research & consultancy	Water Resource Center (WRC) staff	All sensors	X	X		

Table 5.2: Users of the brought portable sensors

The overall satisfaction and feedback on the use of the sensors, as well as feedback on previously used sensors, helped confirm the specifications of portable sensors on which this study is focusing. For example, it was confirmed, through attributes like sensor lifetime, battery life, temperature resistance and waterproof index, which were identified by users as important aspects, that robustness[2] is a specification to focus on. Previously used sensors and the brought sensors were mainly compared based on user-friendliness, the number of output parameters (amount of data generated by sensor) and precision.

Figure 5.2: Ranking of user-friendliness of the different sensors
1. HI98130 pH/EC/TDS; 2. BMUT pH; 3. BMUT EC/TDS; 4. Unbranded PH/EC/TDS/Salt/S.G./ORP; 5. JBL PRO SCAN test strip; 6. DO sensor; 7. Universal pH paper; 8. BMUT Hardness test strip; 9. Medasa and Aquavial test bottles; 10. SimplexHealth test bottle; 11. SimplexHealth test strip; 12. Smardy Blue test strip; 13. BMUT 16 in 1; 14. Manganese test strip

Figure 5.2 contains the sensors ranked by the users in terms of user-friendliness of the measurement process. The identified specifications impacting the ease of the sensors are listed below. The recommended sensor designs to maximise user-friendliness are indicated in bold.

- **Digital result display**: for the test strips, the difficulty of comparing colours with the provided colour chart, even after taking a picture of the results to compare the colours later, made the sensors that provided numerical results easier to use. Regarding colour indicating the presence/absence of contamination or colour that needs to be compared to a chart, the latter result display was considered less user-friendly because more difficult to assess. This specification is linked to the measurement method (paper/bottle or probe) but not always, as paper test strips can also give digital results (combined with a smartphone).

- **Minimal time before stability of measurement**: for digital sensors, the HI98130 pH/EC/TDS was preferred to the others, as it clearly indicates when the measure reported by the sensor is stable and can be preserved. The DO sensor requires stirring the probe gently (see Section 2.1.1 in Chapter 2) and the time before stabilisation is longer than other sensors (mostly $>$ 5 seconds, see Section 2.2.2 in Chapter 4). For the test strips, the test strip combined with an app that has a timer indicating when the picture can be taken was preferred. Digital sensors have an HOLD function where the correct result value can be kept displayed by the sensor, this makes the use of the sensor easier than test strips for which the measures needs to be taken after a fixed number of seconds and for which colours displayed after that time are no longer valid results. For bacteria test bottles, the results also need to be recovered after a specific incubation time depending on the temperature.

- **Fewer manipulations needed to obtain result**: For digital sensors, most only need to be dipped in water and wait for the result to stabilise. For test strips, most

[2] i.e. environmental tolerance, such as chemical resistance to humidity, temperature fluctuations, corrosion, and pollutants or mechanical durability, which is its capability of withstanding shocks and functioning in heavily polluted waters with sediments or rocks for example. Overall, a robust sensor is characterised by a long operational life with minimal maintenance requirements.

are dip-and-read test strips where the only manipulations needed are dipping the strip, waiting a specific time and then comparing the colour obtained with the chart. The manganese test strip, on the other hand, needs more manipulation steps as a sample of a specific quantity is needed in which two reagents present on strips need to be dipped for a few seconds before the test strip can be dipped and the colour compared. For the bacteria test bottles, the process is composed of sample collection and colour change detection after incubation time.

- **Rapid Results**: Digital results are the fastest on average even though some need more time for the result to be stable. For paper test trips, as the colour comparison to obtain results can be tricky, the process can take some time and using an app that translates the results is faster. Bottle test kits take at least 24 hours before the results is shown. Longer measurement processes are less user-friendly.
- **Less parameters to analyse**: Sensors with fewer parameters to analyse are considered easier to use. For digital sensors, this means that the results of the wanted parameter are directly shown, with no need to choose which parameter to display, and no additional stabilisation time is needed when switching parameters. This does not change the perceived user-friendliness by much but allows a classification of the sensors. For test strips, the more parameters to analyse, the more colour needs to be compared to the chart, which can be laborious (even if a picture of the colours is taken). Moreover, the colour comparison needs to be done rapidly as later colour changes are not valid. Between the different bacteria test bottles, the use is very similar. The bottle measuring coliforms and E. coli needed one more manipulation step (check fluorescence) and was thus classified as less easy to use than the two others.
- **Results stored automatically (on the smartphone app)**: The only sensor providing results that can be stored is the JBL PRO SCAN test strip, where the app stores the data online automatically if the phone is connected to the internet. For all the other sensors, the results need to be written down, or a photo of the displayed value needs to be taken.

Overall, feedback on paper test strips was mainly negative as colour comparison is difficult and subjective. Paper strips combined with a smartphone tackled this problem, but issues were raised due to variations in outcomes when different smartphones were used or when the lighting changed. The accuracy of the results provided by the different sensors varies, and while the appeal of semi-quantitative and qualitative results is understood (for low-cost, frequent results that can be used to detect unusual contamination or for citizen-science projects), more accurate and precise sensors are preferred by most, often to comply with law or for comparison purposes.

The purchase consideration is limited by budget and is directly linked with the adequacy of the sensors for the user's needs (mostly in terms of parameters, accuracy and precision) and their trust in the results, which depends, among others, on user-friendliness.

The trust of users and its importance when designing a sensor is further described in Section 5.2.1. The answers of the users helped shape questions for assessing stakeholder's needs and their considerations on specific design priorities were incorporated in the results described hereafter.

5 Results: identified design priorities for stakeholders

5.1 Interviewed local stakeholders

The below-mentioned stakeholders are detailed in Section 3.2 in Chapter 3 and were asked the questions listed in Section 2.1. Table 5.3 summarises the different stakeholders interviewed on the design and specifications of sensors and the respecting water type for which its quality is relevant to the stakeholder. Appendix B contains a visual representation of the stakeholders. Moreover, discussions with local laboratory equipment and sensors distributors like *Yana Chemodities* and *Krypton* were held to understand what type of clients were purchasing sensors, especially portable ones, as well as what was the origin of water quality monitoring equipment.

<table>
<tr><th>Level of Authority</th><th>Interrogated Local Stakeholders</th><th>Surface water</th><th>Ground water</th><th>Distributed water</th><th>Waste water</th></tr>
<tr><td>Citizens</td><td>Including Informal Settlers (along the Butuanon River)</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td rowspan="4">University of San Carlos (USC)</td><td>Pollution Control Officer of Talamban campus</td><td></td><td>X</td><td></td><td>X</td></tr>
<tr><td>Department of Chemistry</td><td rowspan="2">X</td><td rowspan="2">X</td><td rowspan="2">X</td><td rowspan="2">X</td></tr>
<tr><td>Water Laboratory</td></tr>
<tr><td>Department of Civil Engineering</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Research & consultancy</td><td>Water Resource Center (WRC)</td><td>X</td><td>X</td><td></td><td></td></tr>
<tr><td rowspan="3">Government</td><td>Environment and Natural Resources Office (MCENRO, CCENRO)</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Environmental Management Bureau (EMB – R7)</td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td>Barangay Officials (Mandaue City, Barangay Tingub, Purok 2)</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td rowspan="4">Water Sellers</td><td>Water Distribution Operator (Metro Cebu Water District - MCWD) – Water Quality Laboratory</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Water Refilling Stations</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Private Piped Water Seller (Pilipinas Water Resources Inc. - PWRI)</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Water Vending Machines</td><td></td><td></td><td>X</td><td></td></tr>
</table>

Table 5.3: Interviewed local stakeholders and their respective water type(s)

The discussions with communities living along the riverbanks of Butuanon River were held by students participating in the ClimateCafe RiverScan Challenge 2024 who collected the answers from the informal settlers. Informal settlers, citizens living very close to the rivers where habitation is prohibited, were recruited with the aid of local Barangay Officers. Communities living in six different barangays along the river (from upstream to downstream) were interviewed, which accounts for around 100 settlers. Students were also asked about their understanding of water-related issues.

5.2 Assessed stakeholders needs

The assessment of the stakeholder's needs was done by asking the questions listed in Section 2. As identified in Chapter 3, local expertise in water quality is confirmed to be lacking in quantity by all stakeholders. Only a few individuals are experts, and renewing expertise once those people leave their functions can be challenging. The **circulation of data and knowledge is limited** (i) in terms of transparency towards the public, which leads to a lack of visibility and understanding of the issue among citizens (ii) in terms of the sharing of data collected between players.

Collaboration between institutions is complex and time-consuming. Numerous institutions are working on similar areas[3]. However, the monitoring is not properly co-ordinated, leading to **duplicated monitoring efforts** and making it difficult to assess the impact of potential improvement measures taken as the area covered depends on the mandate of institutions. Stakeholders often require similar equipment, leading to potential **duplication of hardware**. This is sometimes preferred, as equipment differences, such as different measurement methods, can cause data among stakeholders to be difficult to compare. Sharing equipment and coordinating measurement activities among different stakeholders could enhance efficiency and consistency in monitoring, ensuring a more comprehensive understanding of water quality improvements and resource optimisation.

Citizens' interest in water crisis issues is high, as it is an ongoing problem in Metro Cebu that impacts the daily lives of many (not enough or too much water, depending on the season). Water quality issues are concerning for many, even more for poorer populations who do not have the same access to other sources of drinking water besides well water and piped water. Informal settlers living along the riverbanks, who are impacted by its quality and quantity, show interest in being involved in projects related to the rehabilitation of the river. Informal settlers, therefore, participated in the fieldwork done by USC students for the RiverScan Challenge. However, most, if not all, of the participants were women. This shows the **gender-based responsibilities in water-related tasks** within households. The assumption of non-existent knowledge about water quality parameters and monitoring techniques was verified for most interrogated citizens, besides for students in water-related studies.

Based on this, it is possible to evaluate the feasibility of citizen science projects in Metro Cebu, like around the Butuanon River. **Citizens show interest in being involved in monitoring processes** but a citizen science monitoring project would only be possible provided that citizens are trained beforehand in the use of the sensors and also in the basic principles of water quality. As knowledge is lacking, citizen science projects for water quality monitoring would only be possible with **highly user-friendly equipment**. Getting a diverse group of citizens on board can be more complicated because responsibilities are not shared equally between genders. Obviously, **incentives are needed to keep citizens motivated** for the project, and the project needs to benefit them. For informal settlers, **including them in the exploration of solutions and in decision-making** with real outcomes is something they are looking for as many feel ignored by government decisions. As a reminder, living so close to the rivers is not permitted by the state for sanitary and security purposes, leaving the settlers in a precarious and vulnerable situation and often overlooked in political decision-making. Some citizens are involved in data gathering in exchange for financial compensation as some agencies pay trained residents close to rivers outside Metro Cebu to perform daily readings of simple sensors (visual pluviometers) and to monitor digital sensors staying on-site.

5.2.1 Impact of trust

Trust plays a crucial role in the water sector. It shapes consumers' choices for drinking water sources (see Chapter 3.4.2 in Chapter 3). From the point of view of sensors, it is important that users have confidence in the measurements process. If they don't, they won't have confidence in the results. A sensor providing results that do not inspire

[3] For example, EMB VII, WRC, MCENRO, CCENRO, university researchers and BRW WQMA are focusing, to a certain extent, on water quality in the Butuanon river (see Section 3.2 in Chapter 3).

confidence is a concrete example of technology dissociated from user needs. This must be avoided at all costs when designing a sensor. Confidence is influenced by many factors, such as the user's knowledge of water quality and specifications of sensors, but also aspects that are more complicated to assess, such as previous experience with sensors and feedback received from other users, as well as the global context. Indeed, trust is often not specific to one person but is shared with a whole group through their shared stories and experiences.

Interviewed stakeholders and users who provided feedback on the manipulations of the sensors identified specifications that increase or reduce their trust in the results provided by sensors. Those are illustrated in Figure 5.2. Trust in sensors largely depends on the type of results they provide and the ease of interpretation (precision and display) as well as user-friendliness.

The different types of results were ranked as shown in Figure 5.4. **Quantitative digital results** with **minimal human intervention** are more trusted. Indeed, digital sensors that produce numerical results tend to be more trusted because they offer precise, quantifiable data. Presence/absence results (qualitative), such as those from binary test strips or bacteria test bottles, are simple for users to interpret but do not inspire enough confidence for drinking water, which is one type of water where qualitative results could be relevant. As stated before in the summary on user feedback, the difficulty of comparing the colours of test strips with the provided colour chart was often criticised, and the option where results were given numerically by an app after a picture was taken was preferred in terms of confidence in the outcome. However, trust in the app on the smartphone was also sometimes questioned due to the effect of lighting. All indicated that their trust in paper test strips (numerical or colour results) would increase if their accuracy was proven by comparing the provided results with laboratory measurements. When observing the user-friendliness and trust in type of result rankings (Figures 5.3 and 5.2), one can see that they do not always correlate as trust also encompasses other specifications like precision and measurement method.

As soon as users are faced with a difficulty when manipulating a sensor (trouble comparing colours or values not stable enough), their confidence is reduced. User-friendliness is thus a requirement for trust in the sensors. Test strips and sensors that require more manual manipulation often inspire less confidence. This is because user error or variability in the testing process can affect the reliability of the results. As a consequence, users generally have more confidence in sensors that are more user-friendly, minimise human intervention and provide straightforward, numerical data. The increased confidence in the results provided by sensors with the least possible human intervention means that digital sensors, where the entire measurement process is black-boxed, are considered to be more reliable.

Reputation and brand reliability are aspects not mentioned in Figure 5.2 but were identified as relevant by most stakeholders. Indeed, sensors from well-known and reputable manufacturers often garner more trust because of their established track records. The number of parameters analysed was considered by some as relevant as they had more trust in single parameter sensors because multi-parameters could present inferences due to different calibration or storage solutions. However, the majority did not consider it relevant.

Specifications that enhance user trust include **quantitative precision obtained through a probe**, **clear data interpretation features**, **user-friendly interfaces and manipulations, calibration and maintenance procedures**, as well as the robustness of sensors.

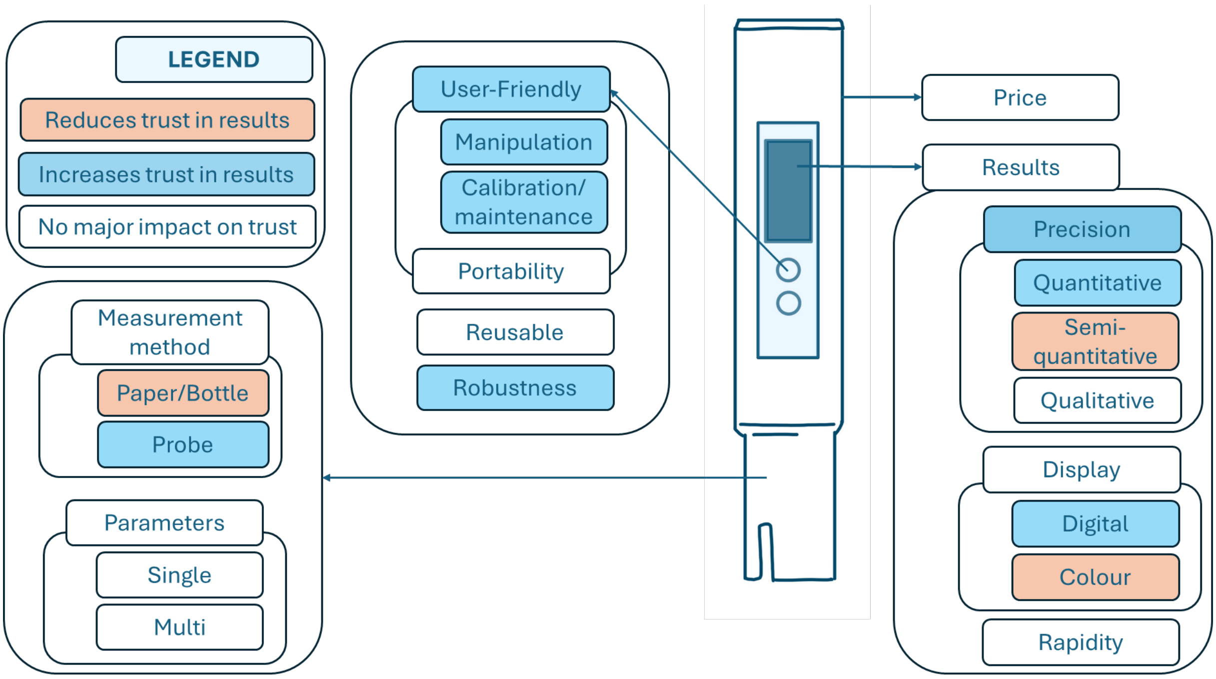


Figure 5.3: Influence of the specifications on trust in sensor

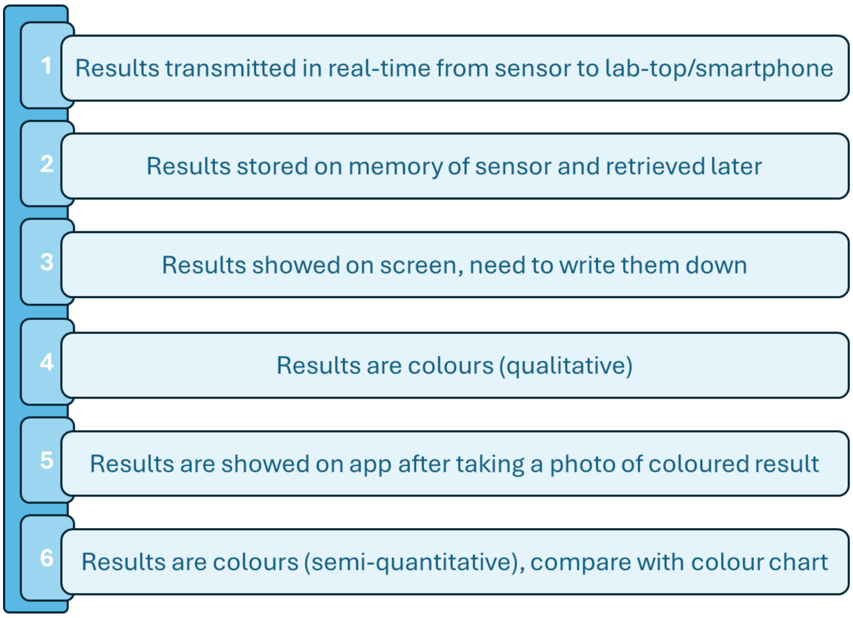


Figure 5.4: Ranking of type of result reading by the trust they generate

Figure 5.5 illustrates the needs of different specifications (specifications that did not inspire trust and thus did not correspond to any needs are removed) and their classification organised according to their significance for various stakeholders and users. Specifications prioritisation follows the coloured legend. The three most important specifications of *portable* sensors identified are precision, price and user-friendliness.

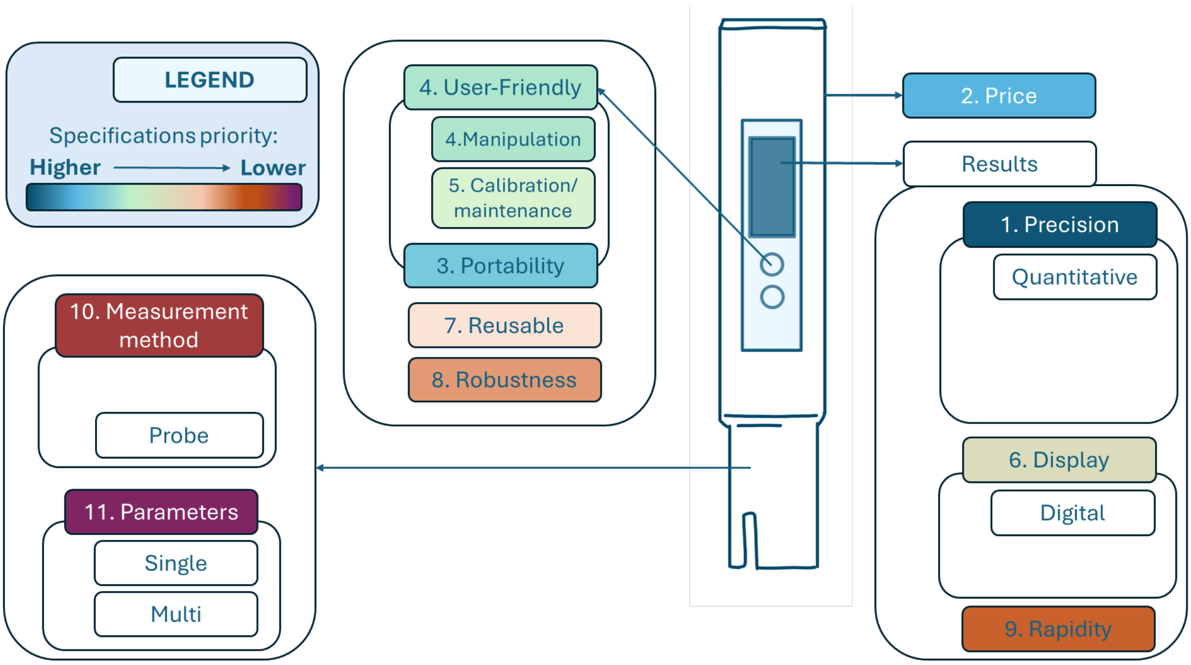


Figure 5.5: Priority in design specifications for interrogated stakeholders

5.2.2 Relevant specifications for sensor design

Portability All stakeholders indicate a strong interest in portable sensors as those reduce monitoring costs (laboratory measurements are a costlier option in the long run), provide in-situ measurements (mostly in real-time) and make monitoring in remote areas possible. Portability is crucial for effective in-situ water quality measurements because it eliminates the potential biases associated with transporting samples to a lab (see Section 3.3), which is particularly challenging in areas like Metro Cebu due to the remoteness of sampling areas, the distance between sites and laboratories and the well-known heavy traffic in the city. Transport, when challenging, can reduce the trust in results provided by the laboratory. Some stakeholders are also considering sensors staying on-site as they would provide real-time data and reduce travel and staffing costs. However, budget constraints and the large number of monitoring locations pose significant challenges, along with security concerns such as theft and vandalism, which prevent the widespread implementation of fixed, in-situ solutions despite their benefits. Portable sensors are thus the preferred option as they do not present those issues.

However, some players also have to comply with measurement standards and can only use certain accredited measurement techniques. This can create a mismatch between existing portable technologies and those actually used in the field. Exceptions are made for more regular monitoring where compliance with standards is not required. High-accuracy technologies require training and are difficult to use outside sophisticated labs, limiting portability. However, the accuracy of portable digital sensors is often sufficient for stakeholders' needs.

Relevant parameters The parameters and their ranges relevant for the stakeholders are mostly determined by national laws and standards, which vary based on the type of water use (guidelines for ambient water, effluent water, and drinking water)[4]. The focus

[4]Ambient water quality is governed by the Water Quality Guidelines and its monitoring by the Ambient Water Quality Monitoring Manual; Effluent water monitoring is governed by the General Effluent

is set on general physicochemical parameters (pH, TDS, EC, ...) and coliforms. Their relevant range sometimes also depends on existing pollution. For example, Fecal coliforms in the Butuanon River have orders of magnitude from 50,000 to 50,000,000 MPN/100mL (see Figure 3.12 in Chapter 3) which are higher than the 400 MPN/100mL limit of a Class C river [112]. Parameters posing recurring pollution issues, such as nitrates and salinity, or parameters needing frequent monitoring are also relevant. The frequency of testing also depends on the variability of specific parameters, as some may fluctuate throughout the year, requiring more frequent assessment to ensure compliance with regulations (e.g., DO varies with rainfall and temperatures [140]). Table 5.4 contains the identified parameters by the stakeholders.

Type of Water	Relevant Parameters for point-of-use monitoring
Surface water	BOD, Chloride, Color, DO, Fecal Coliform, Nitrate, pH, Phosphate, T°, TSS
Groundwater	Can vary with the purpose of water (if for drinking cf. Distributed water), with local composition of rocks and pollution Example: EC, TDS, nitrate, Manganese, Fecal Coliform, Iron, pH, etc.
Distributed water	Thermotolerant Coliform (from which E. Coli), Arsenic, Cadmium, Lead, Nitrate, Turbidity, pH, Colour, TSS, Chlorine Residual
Wastewater	Relevant parameters depend on the type of activity of industry/institutions rejecting water (see General Effluent Standards described in Section 2.2 Chapter 3)

Table 5.4: Relevant Parameters identified by Stakeholders according to the types of water

The number of parameters analysed by a sensor was not considered important by the stakeholders (no preference between single and multi-parameter sensors).

Precision All stakeholders prefer to obtain quantitative and as accurate as possible results, but all have different requirements for maximal allowable error margins, depending on their mandate and the type of water concerned. The most important aspect of a sensor for all is to achieve that level of required precision, otherwise the sensor is useless. However, there can be a trade-off between the precision of the result and the price for frequent monitoring outside of the legal framework (more frequent measures than what the standards and law stipulate). For example, the institutions treating water have to submit monitoring reports from third-party laboratories frequently but might be interested in having more regular, inexpensive, less precise tests of residual chlorine to be sure treatment is done correctly.

Price The budget of the various players has a major impact on their choices and their access to the various technologies. In the case of public players, this budget is linked to the government's priorities and agenda. Moreover, they rely on auctions, meaning the supplier who bids the lowest price "wins" the contract, limiting their ability to choose themselves. For others, price limits their access to certain technologies because they are too expensive. For example, as stated before, some would like to buy more sensors or install permanent in-situ sensors but don't have the budget. Budget considerations include money, equipment, manpower and time. Besides the price/precision trade-off explained above, more trade-offs are possible with price in the case of waste or surface water and are illustrated in Figure 5.6. For drinking water, no trade-off with price is possible when it reduces precision or causes less accurate measurement methods.

Standards and follows the Effluent Quality Monitoring Manual while drinking water quality adheres to the Philippine National Standards for Drinking Water.

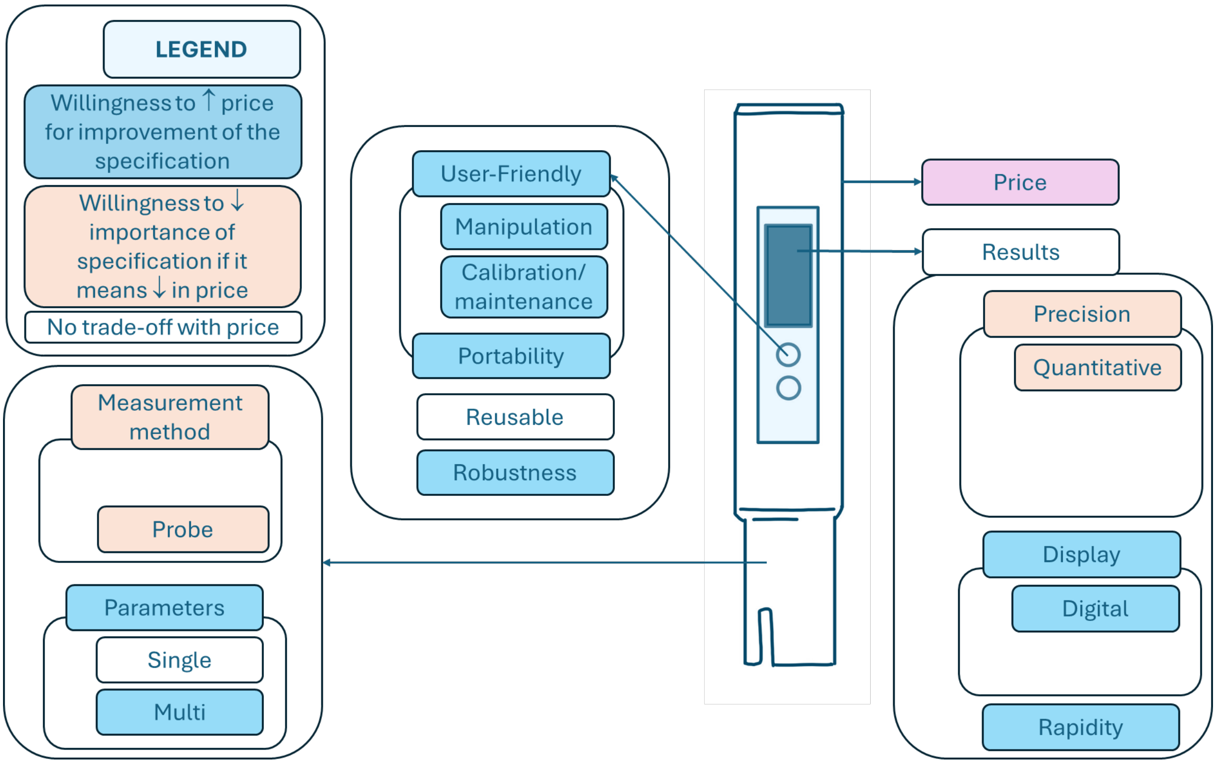


Figure 5.6: Trade-offs with price for surface or waste water analysis

User-friendliness To ensure the effective use of portable sensors in challenging environments and increase the trust in sensor output, users emphasise the need for ease of handling and measurement. Many suggest designing sensors to be worn as backpacks for hands-free mobility or operated with one hand, as accessing water can be difficult in some areas. Users who are trained staff but not experts require straightforward operation and maintenance. If needed, training and demonstration of the use of sensors should easy to access. It needs to be memorable and cover measurement, calibration and maintenance procedures. Calibration should be simple and infrequent to avoid the high costs of calibration solutions and loss of trust in results due to too complex procedures.

Calibration and maintenance Calibration should be possible outside laboratory conditions (no need for specific equipment) and ideally possible on the field.µ Maintenance of reusable sensors requires cleaning between measurements, necessitating distilled water, whose availability in the context of sensor development needs to be considered[5]. Electrochemical sensors with ion-selective electrodes are less convenient because they must be stored in specific preservation solutions to prevent degradation (see Section 2.1.1 on electrochemical sensors). Ideally, the storage should also be portable by providing the sensors with a cap that can be filled with calibration solution, for example. Frequent replacement of those probes is necessary as the electrodes degrade quickly. Additionally, the preservation solution can cause corrosion of the other electrodes over time in the case of multi-parameter sensors. Ensuring that proper maintenance procedures are followed is crucial to prolong the lifespan and accuracy.

Robustness Portable sensors should ideally be robust as they are used in the field and affected by local conditions and transfers to measurement sites. Durability and weather resistance are crucial to protect the investment in these sensors, as some users report issues

[5]Distilled water is sold for drinking purposes in the Philippines so it is widely available (see Chapter 3).

with fragile equipment. This specification has less importance compared to others. However, local weather conditions impact the lifespan of sensors and their monitoring performance. Indeed, the combination of high humidity and elevated temperatures, characteristic of the climate in the Philippines (see Chapter 3), can significantly reduce the lifespan of sensors. Relative humidity, ranging from 71% to 85% [91], reaches levels higher than those typically recommended for electronic equipment (< 60%) [141], requiring correct use and preservation of non-waterproof sensors to avoid degradation. Temperatures in Metro Cebu can reach 37°C [82] and make the preservation and use of some sensors challenging (difficult to implement during fieldwork and cooled-down offices or refrigeration can be expensive). Sensors subject to extreme temperatures can potentially see their performance and accuracy be affected. To mitigate this, it is essential to avoid taking measurements in direct sunlight to prevent exposing sensors to temperatures exceeding their recommended limits. Sunlight also impacts the performance of smartphone apps reading test strip results. For digital sensors, as they are subject to high outdoor temperatures during fieldwork, it takes some time for the sensor temperature reading of the water sample to stabilise. The sensor must detect the correct temperature for correct values and automatic temperature compensation. Measurements can thus take longer with digital sensors due to the heat.

Rapidity Portability often goes with real-time results, except for absence/presence bacteria tests where an incubation time is needed. The rapidity of results from a portable sensor is a feature that stakeholders request, as it increases the sensor's throughput but it is not as important. However, for certain parameters (e.g. bacteriological), as the methods currently used are very slow (several days), a faster method than those used is desirable (immediate result is obviously the ideal). Rapidity should be optimised during the design process, but it is not the main focus. The key is to ensure that measurement times are within the same order of magnitude as those of the currently available measurement methods. **Reusability** is also not regarded as primordial by most of the interviewed stakeholders. **Measurement method** is required to be done with probes (no visual colorimetric results) bur the specific transduction method used is of little importance as long as the required precision is met.

5.3 Compliance of sensors with needs and required innovations

This section evaluates how the bought sensors and the portable sensor market meet the identified needs shown in Figure 5.5 and which innovations are required to achieve effective portable monitoring. Sensors are compared for the different specifications, and to do so, user-friendliness is first quantified, based on the method described in Section 3.1 (further detailed in Appendix D).

The portable sensor market was confirmed to be lacking sensors for specific parameters corresponding to the stakeholders' needs. The lack of low-cost portable sensors that are precise, fast and accessible to monitor certain parameters shapes the choices made by the various players in their monitoring methods. Indeed, many stakeholders are faced with the following choices: develop their own expertise in terms of monitoring and purchase portable test equipment or call on a third party to monitor water quality (accredited water quality laboratories are often more expensive, and transport can be challenging). As there are no low-cost portable sensors to monitor certain parameters that need to be monitored (fecal coliform is most often mentioned and BOD, turbidity and specific metal ions were also listed, see Section 3 in Chapter 2), this choice is not really one, and they find themselves obliged to use the services of a laboratory for the concerned parameters.

Therefore, it makes no sense to duplicate their monitoring costs and also buy sensors for other parameters and take time for fieldwork, as the transport of samples to the laboratory is done anyway.

5.3.1 Quantification of user-friendliness

The user-friendliness of the sensors was evaluated by quantifying the number of steps required in each of the three categories of usage, i.e. measurement, calibration and maintenance. As a reminder, the number of steps needed was counted for the selected sensors as well as other sensors where the steps of use were known, i.e. sensors used by the Water Resource Center (a HACH EC meter similar to the brought BMUT EC meter and a Solinst EC and groundwater level meter, see Appendix D). The steps were also compared to the use of a lateral flow bacteria test (WaterSafe 15-min test). In this section, the user-friendliness of the three categories of usage is correlated to the price and precision of the concerned sensors. It is important to note that user-friendliness is quantified based on the steps required for each phase of the sensor's use, while feedback from users of the sensors on their user-friendliness was based on many other aspects and took all the correlations with other specifications into account.

User-friendliness vs. Price Most often, increased user-friendliness is assumed to come with less costly sensors. However, Table 5.7 shows that some low-cost sensors can actually be difficult to handle. These sensors may require multiple steps involving human intervention, which reduces their user-friendliness (n° 14 - 18). For example, test strips that analyze more than five parameters at once require multiple complex colour comparisons. The sensor with the fewer steps towards results is the JBL PRO SCAN paper-strip sensor combined with an app, as most of the measurement process is automated, and the results are automatically stored[6]. The number of measurement steps required for portable digital sensors, bacteria bottle tests and one-parameter paper strips are close. Paper strips are less expensive per unit but, on the long run, the reusability of portable digital sensors makes them more cost-effective. Calibration and maintenance require more steps for digital sensors, as shown with grey highlighted cells in Table 5.7. Calibration and maintenance can represent additional costs that need to be considered by stakeholders when purchasing a sensor. Calibration and maintenance are not present for non-reusable, less costly sensors.

This unexpected relationship between user-friendliness and price is due to the fact that this study focuses on low-cost portable sensors. If we consider the broad spectrum of portable sensors (from bacteria test bottles and paper strips to professional single or multi-parameter probes), the abovementioned intuitive consideration that costly sensors are less user-friendly is valid. Indeed, those expensive portable sensors often require thorough training and laborious manipulations (have extremely long use instructions).

User-friendliness vs. Precision Accuracy for the considered sensors can be qualitative, semi-quantitative or quantitative (the categories are highlighted in Table 5.7). For quantitative results, more expensive digital sensors are needed. When comparing user-friendliness with precision, we can observe that paper-based strips (less accurate) occupy the least friendly spots of the classification (n° 16 - 18). However, as stated before, this is mostly due to their multi-parameter specification (many laborious colour comparisons are needed). The number of measurement steps required for portable digital sensors, one-parameter paper strips and bacteria test bottles are close, but their precision

[6] As a reminder, this sensor convenience perceived by users was reduced due to its sensitivity to lighting.

No.	Sensor	Steps measurement	Steps calibration	Steps maintenance	Price [EUR]
1	JBL PRO SCAN test strip	2	0	1	1
2	BMUT pH sensor	3	4	1	14
3	Hanna Instruments EC/TDS/pH sensors (HI98130)	4	2	2	179
4	AquaVial bacteria test bottle	4	0	1	9.48
5	Medasa bacteria test bottle	4	0	1	7.48
6	BMUT Total Hardness test strip	4	0	1	0.36
7	Universal pH paper	4	0	1	0.02
8	BMUT EC/TDS sensor	5	0	1	15
9	Hach EC/TDS sensor	5	0	1	85
10	DO meter JPB-70A	5	5	3	127
11	Solinst TLC meter	5	2	2	980
12	Simplex Health bacteria test bottle	5	0	1	15.43
13	WaterSafe bacteria later flow strip	5	0	1	9.97
14	SenSafe Manganese test strip	7	0	1	1.2
15	Unbranded sensor	13	4	1	25
16	Simplex Health test strip 7 in 1	22	0	1	1.2
17	Smardy Blue test strip 9 in 1	28	0	1	0.85
18	BMUT test strip 16 in 1	49	0	1	0.19

Figure 5.7: Quantification of user-friendliness
Legend: Green = bottle sensors, Blue = test strip sensors, Light Blue = digital sensors, Grey = higher values

is very different (quantitative, semi-quantitative and qualitative, respectively). This means user-friendliness does not limit precision. In general, as shown in the market overview, to obtain higher accuracy for most parameters, more complex instrumentation is needed which brings higher costs and less user-friendliness.

Both comparisons show that user-friendliness can be obtained with low and high-cost as well as high precision sensors. However, **combining low-cost, user-friendliness and high precision is more challenging**.

5.3.2 Compliance of each type of sensors with the identified needs and innovations required

Paper-based indicators do not answer the needs of most stakeholders in terms of precision, in terms user-friendliness and in terms of the resulting confidence in the results. The **bacteria test bottles** providing qualitative results do not reply to the need for more precise results and are not trusted for drinking water analysis but were easy to use. Both paper test strips and bacteria presence/absence tests were not adapted to the local weather conditions as they needed to be stored in cooler environments during warmer months (usually below 27°C, cooled-down offices or refrigeration can be expensive).

Digital sensors are the ones corresponding the best to the users' needs but do not reply to all of them (measurement, calibration and maintenance user-friendliness, robustness and cost). Some sensors, like the DO sensor, need calibration that is unadapted to fieldwork and time-consuming maintenance. Indeed, during the two-point calibration for the DO portable sensors, a saturated DO solution is obtained by using a milk frother to agitate the liquid (in laboratory conditions, saturation is obtained by bubbling oxygen into a water sample) during at least 30 minutes. This is thus not optimal for fieldwork conditions. Other sensors require little to no maintenance and calibration and are very low-cost, but this makes them less accurate as time goes by (lower robustness). Indeed, this is due to the fact that many sensor electrodes, such as ion-selective electrodes, need high maintenance and have a limited lifetime due to electrode degradation. Not maintaining such sensors makes them more user-friendly but reduces their lifespan. Sensors with optimal maintenance and calibration for fieldwork are often more accurate, have a longer lifetime, and can have user-friendly manipulations, but they are expensive. The EC/TDS/pH Hanna Instrument sensor, for example, is provided with a calibration solution pack that is adapted for fieldwork. This digital sensor was the one ranking highest in all design priorities identified besides cost (it is the most expensive sensor selected). Moreover, on the market, some portable sensors with high accuracy and robustness and can be easy to use, but they are not affordable and sometimes not very accessible (no reseller in the Philippines). This leads to the conclusion that price is a main limitation for access to certain technologies replying to the user's needs.

Integrating **Internet of Things** and the analytical capabilities of sensors while processing the resulting data with modern analytics and geographic information systems can enable continuous monitoring, increasing the spatial and temporal range of measurements and providing meaningful information on the distribution of water contaminants. **Citizen Science** has similar technical advantages. However, as optimal low-cost sensors are lacking and such strategies need the deployment of many sensors, it is not conceivable for the time being if performed by local stakeholders with limited budgets. Developing very low-cost quantitative sensors that are easy to use and correspond to the precision needs will enhance possibilities for citizen monitoring projects and crowdsourcing in resource-limited areas.

Integrating portable devices with smartphones can lower equipment costs and simplify field deployment. However, reproducibility is fundamental (no external light interference on results, for example), and the interface needs to be user-friendly. To gain the trust of users, a comparison with laboratory-based technologies is necessary.

As stated in Section 3.4 where shortcomings of existing and "in development stage" technologies were addressed, many studies on water quality detection methods are being done, trying to address limitations of existing sensors, but there is a lack of translation to commercially available sensors. Advancements in sensors incorporating microfluidics, lateral flow, paper-based substrates, nanomaterials and other technological aspects are countless; however, both technical and non-technical challenges remain and need to be tackled.

Promising point-of-use devices (such as paper-based assays, lateral flow assays and lab-on-a-chip devices) must be combined with transduction technologies that provide analytical results. Visual colorimetric results are not satisfactory because trust-inducing quantitative results are required. Research should focus on improving performances of miniaturised precise detection methods, portability and user-friendliness to meet stakeholders' needs for precise quantitative in-situ measurements while keeping affordability in mind during design. For example, better specificity in complex water matrices can be obtained through innovative recognition elements as well as through exploring possible receptors for rapid and specific binding [35]. The challenges faced by specific methods need to be addressed. However, studies should not only focus on conceptualising design priorities and should include extensive testing of actual sensor prototypes in the field to validate their innovations and asses user-friendliness.

Innovations are needed to develop **low-cost, user-friendly, digital quantitative sensors**. Innovations are needed to broaden the scope of the sensor market in terms of parameters but a focus should also be set on already widely monitored parameters (coliforms, turbidity, BOD, ...) for which portable sensors are not affordable. The following aspects are fundamental to future sensor development:

- Making existing technologies with high precision for general parameters more **affordable** to end-users and more **user-friendly**, i.e., more acessible in resource-limited areas.
- **Optimisation of portability and user-friendliness** should be done during all stages: measurements, calibration and maintenance.
- REASSURED sensors should be developed and commercialised, but they need to be **digital and quantitative with a primary focus on affordability, precision and user-friendliness**, as well as with keeping robustness and deliverability to end users in mind.
- **Standards for portability and user-friendliness** should be defined to compare different sensors easily based on those criteria without interpreting data sheets. Users should be able to compare user-friendliness between different options when buying sensors, as it is one of their main requests.
- Understanding users' needs and adapting them to real designs of sensors should be a common standard practice among sensor developers. More research on **user-centred design in the sensor development** domain is needed.

6 Summary on stakeholders needs

To determine the design of a water quality monitoring sensor adapted to a specific location, such as that in Metro Cebu, several elements have to be taken into consideration. It is necessary to understand the context and interview the local stakeholders who carry out monitoring in order to understand their needs as well as the hurdles faced for water quality monitoring. Ideally, the sensor development process should involve users on an iterative basis throughout all stages to obtain a tailor-made sensor for the needs of the location. Consensus between stakeholders was obtained as a large majority identified **precision, price and user-friendliness as the most important specifications for a portable sensor**. Those were the ones where the least trade-offs were accepted.

Portability is needed for sensors developed for Metro Cebu. The sampling sites of stakeholders are often in remote areas, and the transportation of samples is sometimes long (several hours to nearly a day). Portability does not always mean user-friendly equipment, as expressed by negative feedback received by users on previously used too heavy or too complicated equipment. Optimising portability is linked with maximising user-friendliness, and vice-versa. Handling the sensors must be quick and easy.

Having the required **precision**, corresponding to the mandate of the stakeholders, and the intended purpose of the sensor, is the most important specification for a sensor. If the sensor does not meet the expected precision of the user, it loses its usefulness.

Price is a determinant of access to technology. Metro-Cebu is a resource-limited area; budget impacts time, manpower and equipment available for water quality monitoring. The lack of those resources reduces the ability to monitor the water supply. **User-friendliness** is a very important specification for portable sensors that comes after precision and price. It also greatly impacts trust in sensors. Additional costs or laborious procedures of calibration and maintenance should be avoided.

The initial introduction of a product significantly affects how well consumers can use it. Evaluating the necessity for user training is crucial for successful implementation and ensuring user satisfaction. If possible, use should be simple so as not to need training. However, when needed, including training is crucial to avoid developing a technology that cannot be used accordingly by local experts. Training needs to be easy to remember. Instructions for sensor operation should be clear and detailed while avoiding unnecessary long manuals.

Sensors need to be **robust** and withstand extreme weather conditions without the need for additional costs to preserve investment in portable sensors. This is considered less primordial by stakeholders compared to price, precision and user-friendliness.

The less **human intervention** in the measurement process, the greater the trust in the provided results and the better the user-friendliness. This can be counter-intuitive as this means measurement processes that are back-boxed are more trusted. **Trust** in laboratory measurements is high, trust in a sensor can be gained by proving accuracy by comparing with it results with laboratory measurements. Trust is the highest in digital quantitative results, the higher the precision of the sensor, the higher the trust in the given values. However, most players are satisfied with a precision that is lower than that of laboratory equipment.

There is a need for **local expertise development** in terms of quality monitoring devices and techniques. Ideally, stakeholders should not have to rely on foreign countries (and thus be heavily impacted by exchange rates) for purchases, repairs, etc. It's important to be able to find replacement parts easily (accessible maintenance). Creating a sensor with a technology that local stakeholders cannot appropriate (in terms of expertise, parts, etc.) needs to be avoided. Taking the accessibility of the sensor and its maintenance/calibration processes into account during the design of the sensor is important (supply chain). Moreover, sensors should ideally be **developed along with local experts** in order to avoid expertise in technology vanishing once the sensor is developed.

This work focuses primarily on the needs of professionals conducting water quality measurements and possess expertise in this area. Regarding the involvement of citizens, a conclusion supporting the possibility of citizen science projects along the Butuanon River was made: they are feasible and can be implemented as long as a fair counterpart is provided to participants and mechanisms to keep them motivated are put in place. This approach can engage the community in monitoring water quality, allowing non-experts to contribute valuable data while raising awareness and understanding of local water issues. However, knowledge of water quality issues and monitoring is very limited, so the training and learning phase of the projects will be long but are of utmost importance as a lack of knowledge can lead citizens to misinterpret the data generated. Moreover, citizen science by local stakeholders is difficult to consider due to high costs.

Chapter 6

Discussion

At the end of this study, a number of observations can be made about the method followed to carry out experiments and the results obtained. The investigation of stakeholders' needs was based on assumptions of water quality management needs that were identified from the literature and on-site testing with the sensors. Those identified focus specifications were used to understand the preferences of interviewed stakeholders regarding sensor design.

Building connections with local organisations is crucial for identifying sensor use cases and establishing design priorities because these partners offer valuable insights into the water sector's framework or the specific needs and challenges within communities (e.g., Barangay captains and officials). Engaging with research facilities from the relevant disciplines that have established connections with pertinent stakeholders allows for leveraging existing relationships and expertise, facilitating the development of sensors tailored to real-world conditions and requirements. It can also help overcome language barriers. This collaborative approach ensures that the sensors are practical, effective, and aligned with the local context, ultimately enhancing the success and impact of the sensor development project.

The major limitation of this study is the sample of interviewed stakeholders, which may not be representative of all water-related entities in Metro Cebu. The study tried to encompass many levels of authority (from citizens to government). Answers were often based on experience and opinion, so interrogating more stakeholders would be relevant as they might have other backgrounds.
The approach is very global, as many different types of stakeholders are interviewed. This helps underline the design priorities that are common to all of these stakeholders. It also shows that the method can be applied to different types of stakeholders (different types of institutions, different roles or mandates, and different types of water worked with). However, when designing a sensor, a more specific context needs to be drawn (fewer focus analytes and one type of application).

Informal settlers, as well as the few students and citizens interviewed, showed little to no knowledge of water quality monitoring (depending on the student's studies). During this study, most of the interviewed stakeholders were staff from agencies and institutions that have water-related mandates and are working, directly or indirectly, with water quality. This means that their answers were shaped by their mandates and obligations regarding their roles in the water sector as well as their expertise. Therefore, the type of question needs to be adapted for participants with less expertise.

Informal settlers were recruited through Barangay officials. Interviews were done on a weekday, impacting participation diversity. Participants were only women, showing the heavily gendered responsibility for household water management [2]. Women often bear responsibility for water-related tasks, this needs to be taken into account if studies are done with citizens. This study did not analyse enough data on the use of sensors by the broad public to be able to draw general conclusions about the interest of citizens in owning water quality monitoring devices. The potential impact of low-cost available sensors on trust in water is not known. However, confidence is a major factor in determining the outlook for the water sector. It is vital to avoid introducing technologies whose users do not understand the impact of the results. To cope with user mistrust, access to data on water quality must be transparent and systematic, coupled with explanations so that the results can be understood.

Bringing, demonstrating, and observing users of physical prototypes is highly relevant for tailor-made design. In this work, most interviewed stakeholders had knowledge of water quality issues and monitoring besides citizens. Tests performed in the presence of citizens were done on industrial/residential wastewater and in rivers known to be polluted. If a similar interviewing approach to understand *drinking* water monitoring needs is used with citizens, researchers will face more challenges when demonstrating a test because it can provide alarming results. Citizen Science water monitoring projects done in the Netherlands showed that even though the results of testing were sometimes contaminated, good training of the participants on water quality parameters and the origin/consequence of contamination will not decrease the consumer's trust in the company distributing water. On the contrary, transparency made them more confident [66]. However, there is no proof that this is the case in every context, and it might not be the case for Metro Cebu as there is a high mistrust in water quality from some sources. Citizen science projects related to drinking water should be planned with caution.

Technology brought on-site and on which feedback is given only comprises low-cost portable sensors. No professional portable multiparameter, for example, that can cost thousands of euros, is considered. However, those professional probes reply more to the needs of professional stakeholders whose mandates are related to water quality monitoring in terms of precision and data recording capabilities but are costly and less user-friendly. Some stakeholders with higher budgets use very expensive multiparameter probes but many are not satisfied with portability (too heavy, not easily transportable), lack of user-friendliness for three use stages, robustness and other aspects. Performing additional research on those types of sensors and their shortcomings by using them on-site and receiving further user feedback would be pertinent. Moreover, in some cases, groundwater is monitored by directly lowering a probe attached to its microcontroller to a long cable in wells. Sensors providing this type of measurement are interesting to consider.

Chapter 7

Conclusion

Access to drinking water is fundamental, and regular in-situ water quality monitoring is essential to limit the risks of drinking water from unsafe sources. However, most traditional monitoring sensors present shortcomings. Within the development of low-cost portable sensors with the potential to cope with monitoring challenges, this master's thesis aims to identify the design specifications of sensors that respond to the needs of stakeholders involved in water inspection. The study takes place in an exemplary water-scarce area, Metro Cebu, in the Philippines. To draw design and specification priorities for portable sensors that assess water quality parameters, the study seeks to understand the current portable sensors market and the context of Metro Cebu, i.e., the local water expertise and the needs of institutions facing specific water-related challenges.

In a first step, the parameters used to assess water quality and the techniques used to measure them are detailed. The measurement methods used by traditional sensors and those being researched and developed were outlined. A market overview of portable sensors showed the lack of existing point-of-use REASSURED sensors (real-time affordable, ease-of-sample collection, sensitive, specific, user-friendly, rapid, equipment-free, delivered). Indeed, the sensors currently on the market were shown to have several shortcomings as they do not present an optimal combination of those specifications. Moreover, it was highlighted that many studies focus on the technology used and forget to consider end-users in the design of sensors. By not taking end-user needs into account, there is a high risk of dissociation between these needs and the final product. Emerging monitoring strategies like Citizen Science, which can enhance the spatial and temporal monitoring scope, show considerable potential to improve water monitoring. This strategy would greatly benefit from the development of adequate point-of-use sensors. The current lack of affordable portable sensors on the market exacerbates resource-limited areas' struggle to develop efficient water monitoring.

The Philippines is a country that presents high water pollution and scarcity. Moreover, the water sector suffers from inefficient management and a lack of law enforcement. In a second step, the country's fragmented jurisdiction on water resources management was described. Lack of clear division of responsibilities, effective collaboration between institutions (in decision-making, projects, data collection and measuring equipment), efficient management and protection of resources was illustrated. Metro Cebu is one of the largest agglomerations in the Philippines and, like most of the country's cities, has a water service that needs to be improved. Neither in terms of quality nor quantity does Metro Cebu's water meet the needs of its consumers. To plan efficient steps towards Integrated Water Resource Management, those must be based on water quality and quantity resource data. Relevant stakeholders in the water sector of Metro Cebu were identified thanks to the partnership with a local research and consultancy centre, the Water Resource Center.

In a third step, the method followed in this study to assess stakeholders' needs and challenges to efficient water monitoring was described. It consists of evaluating existing portable sensors and understanding the extent to which these can already respond to local needs. To do this, sensors have been selected based on the market study carried out and identified relevant parameters for the context based on historical data and national standards. The sensors were validated through a user-reproducible approach, and results were compared with historical data and laboratory equipment. Portability was demonstrated to avoid transport bias. The sensors were tested in fieldwork to assess whether they were adapted to the local situation, in terms of robustness to local conditions (high temperature, humidity, water matrix) and user needs. Use feedback was received by allowing people from different identified institutions to experiment with the sensors in different contexts and describe their experiences. Trust in sensors was evaluated, and it showed that confidence is a major requirement for a sensor to be accepted by users. In a fourth step, numerous interviews were conducted with local stakeholders to identify their needs in terms of water quality monitoring sensors.

Following feedback from citizens, their level of water issues understanding was evaluated, assessing the potential for Citizen Science projects along the most polluted river of Metro Cebu. Citizens' knowledge of water quality and its impact on health is based on many beliefs. Although water quality is a concern for many people, few are properly informed about the challenges and importance of water quality monitoring. This implies that Citizen Science projects show potential but require eliminating biased beliefs and increasing understanding of water quality, as well as proper training and involvement of local communities, particularly in areas where trust in water sources varies. Caution is needed as misinterpretation of data needs to be avoided and studies must never impact trust negatively. Moreover, the lack of public awareness of the crucial role of water resource management and the lack of trust in some resources can be tackled through transparency of monitoring data.

Following feedback and interviews with local stakeholders, it was possible to determine the specifications to be prioritised in the design of sensors to meet the needs of stakeholders. In short, all stakeholders view portable sensors as a method to improve the efficiency of measurements in terms of time, budget and accuracy with in real-time data (remove transport bias). It was identified that the price of the sensors was a major factor in the choice of sensors and determined access to technology. Additionally, the precision required was linked to the institution's roles and the type of water at stake since both determine the constraints (laws, guidelines, objectives...) that each institution has to follow. The user-friendliness, including the ease of use, calibration and maintenance of the sensors, was identified by a large majority as being an essential element for sensor design and for the confidence in the results brought by such a specification. Nearly all stakeholders interviewed were ready to trade-off with price for better user-friendliness, provided that prices did not exceed their budget. In short, the majority identified precision, price and user-friendliness as the most important specifications of portable sensors. Compliance of existing sensors with the identified needs was assessed, concluding that digital quantitative sensors were the most in line with the users' needs but lacked the optimal combination of affordability, calibration and maintenance user-friendliness or accuracy that lasts over time. Required innovations were identified and depended on the focus analyte. For some general analytes (such as pH, EC and TDS), low-cost sensors exist, but simultaneous maximisation of the three criteria is not yet attained. For others, the affordability of already commercialised technologies needed to be improved. When no commercial sensors exist for specific parameters, research is required to miniaturise transducing methods that can be integrated into a portable sensor. In resource-limited areas, monitoring strategies based on the Internet of Things and Citizen Science performed by local stakeholders, who have limited budgets, require the development of extremely affordable sensors with required precision and are thus not feasible at the moment. Focus should be set on developing low-cost digital point-of-use sensors that have high accuracy and user-friendliness. As trust in sensors needs to be maximised, colorimetric paper-based sensors are not an optimal approach. Ideally, the sensor development process should involve users on an iterative basis throughout all stages to obtain a tailor-made sensor for Metro Cebu's needs. Research should not only focus on conceptualising design priorities but should also include extensive testing of actual sensor prototypes in the field.

In summary, on-site experiments and interviews with local institutions showed that portable sensors could significantly contribute to stakeholders with water-related mandates that need sustainable, renewed and effective water monitoring systems. Research on point-of-use sensors needs to focus on developing digital quantitative devices that are affordable, precise and user-friendly during all stages (measurement, maintenance and calibration). Developing such a sensor that meets the three criteria identified during this study cannot be done without implying stakeholders at each stage of its development and testing. Understanding users' needs and translating them into the design of sensors should be a common practice. Standards for portability and user-friendliness should be defined. This study shows that engaging with users in resource-limited environments to understand their monitoring requirements is achievable and can enhance the chances of creating a sensor that aligns with their needs and for which users' trust is maximised.

Appendices

Appendix A

Water Quality Monitoring Generalities

Water Quality Parameters Monitoring Methods

This section is based on the description of analytical methods in the WHO Guidelines. Further description and analytical achievability of the different methods for the different parameters can be found in Annex 4 of the WHO Guidelines for Drinking Water Quality document [24].

Volumetric titration involves analyzing chemicals by reacting them with a standardized titrant until an endpoint is reached, indicated by a colour change, change in electrical potential, or pH value.

Colorimetric methods measure the intensity of color produced by a reaction, with absorbance measured using light of a suitable wavelength, and concentrations determined from calibration curves (see Section 2.1.2).

Ion-selective electrodes measure ionic concentrations based on potential changes related to ion concentration (see Section 2.1.1).

Atomic Absorption Spectrometry (AAS) measures metal concentrations by detecting light absorbed by atoms in the vapour state, following the Beer-Lambert law. In **Flame Atomic Absorption Spectrometry (FAAS)**, a sample is atomized in a flame. **Electrothermal Atomic Absorption Spectrometry (EAAS)** uses an electrically heated atomizer or graphit furnace instead of a flame.

Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) uses a high-temperature argon plasma to excite atoms in a sample aerosol, causing them to emit light at specific wavelengths. These emissions are separated by a monochromator, and their intensities are measured by a detector to identify and quantify different elements. **Inductively Coupled Plasma Mass Spectrometry (ICP-MS)** follows a similar process but uses a mass spectrometer to separate ions by mass/charge ratio for precise element determination.

Chromatography is a technique used to separate compounds based on their different affinities between two phases: the stationary phase and the mobile phase. In this process, a sample is injected into a column containing the stationary phase, and compounds move at different rates through the column due to varying interactions with the stationary phase. In **ion chromatography**, an ion exchanger is used, and colorimetric, electrometric or titrimetric detectors can be used for determining individual anions. **High-performance liquid chromatography (HPLC)** uses a liquid mobile phase and stationnary phase. Different detectors, such as absorbance or conductivity, for compound detection. **Gas chromatography (GC)** separates and quantifies trace organic compounds by using a gas mobile phase and a liquid stationary phase. **Chromatography/mass spectrometry (GC-MS)** combines GC with mass spectrometry to ionize and separate fragments by mass for detailed analysis. The purge-and-trap GC-MS method enhances the detection of volatile compounds.

Enzyme-linked immunosorbent assay (ELISA) uses antibodies that can bind to the target chemical and enzymes for specific chemical detection via a colorimetric reaction proportional to the quantity of the chemical of interest.

REASSURED criteria

In 2006, the WHO Sexually Transmitted Diseases Diagnostics Initiative introduced the ASSURED (Affordable, Sensitive, Specific, User-friendly, Rapid/Robust, Equipment-free, and Deliverable to end users) criteria for point-of-care tests. This criteria can be applied to all point-of-use sensing applications. Since then, advancements in digital technology and portable tests gave new possibilities for point-of-use sensors and the acronym REASSURED was proposed [50, 142]:

- **R**eal-time: Tests should allow to create and maintain continuous, immediate, and synchronised communication or data exchange.
- **E**ase of specimen collection: Samples should be simple and convenient to obtain (no pretreatment).
- **A**ffordable: Tests should be inexpensive, cost-effective and should not cause financial strain to buyers.
- **S**ensitivity: Tests should minimise or avoid false negatives.
- **S**pecificity: Diagnostics should have low false positive rates.
- **U**ser-friendliness: Tests should be easy to perform in 2–3 steps and require minimal user training with no prior knowledge of diagnostic testing.
- **R**apid and robust: Results should be available rapidly after sample collection. The sensor should be able to withstand conditions of use and the supply chain (temperature, humidity, time delays, mechanical stresses) without requiring additional, and often costly, transport and storage conditions such as refrigeration.
- **E**quipment-free & Environmental friendliness: Tests should not require any special equipment or should be operated with small portable devices that use solar or battery power. The effects on the environment of their use and the waste generated should be taken into account.
- **D**eliverable to end-users: The tests and reagents should be accessible to end-users. This required to consider supply chain logistics like selecting, procuring, shipping, storing, distributing and delivering the technology to ensure it is available to end-users in resource-limited settings.

Appendix B

Context of Metro Cebu, Philippines

This Section contains additional Figures and Tables describing the context of this study, both on the national level and on the local level of Metro Cebu.

The Climate of the Philippines

The Philippines has a tropical and maritime climate, characterised by high temperatures, significant humidity, and abundant rainfall. The mean annual temperature is 26.6 °C. Due to these high temperatures and the surrounding bodies of water, the country experiences high relative humidity, ranging from 71% in March to 85% in September. Additionally, the annual rainfall in the Philippines varies significantly, from 965 to 4,064 millimetres [91] [143] The country's climate is further classified into four types (see Figure B.1), which are based on rainfall distribution [91] :

- **Type I** – Two pronounced seasons: dry from November to April, and wet the rest of the year;
- **Type II** – No dry season with very pronounced maximum rainfall from December to February and wet the rest of the year;
- **Type III** – No very pronounced maximum rain period and short dry season, lasting from one to three months, either during December to February or March to May.
- **Type IV** – Rainfall more or less evenly distributed throughout the year, with no distinct dry season.

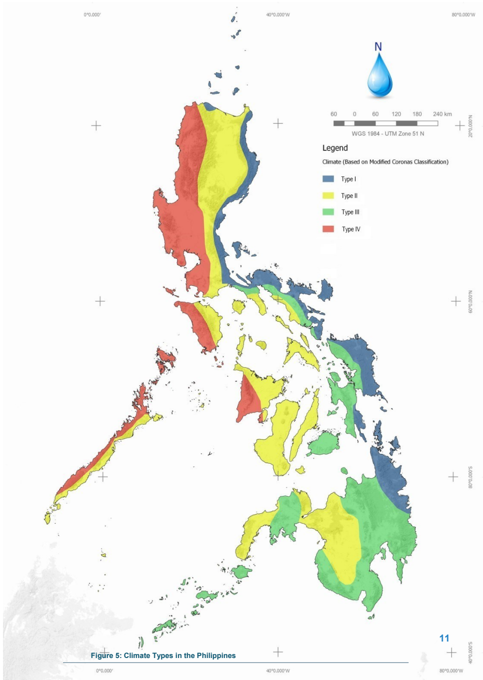
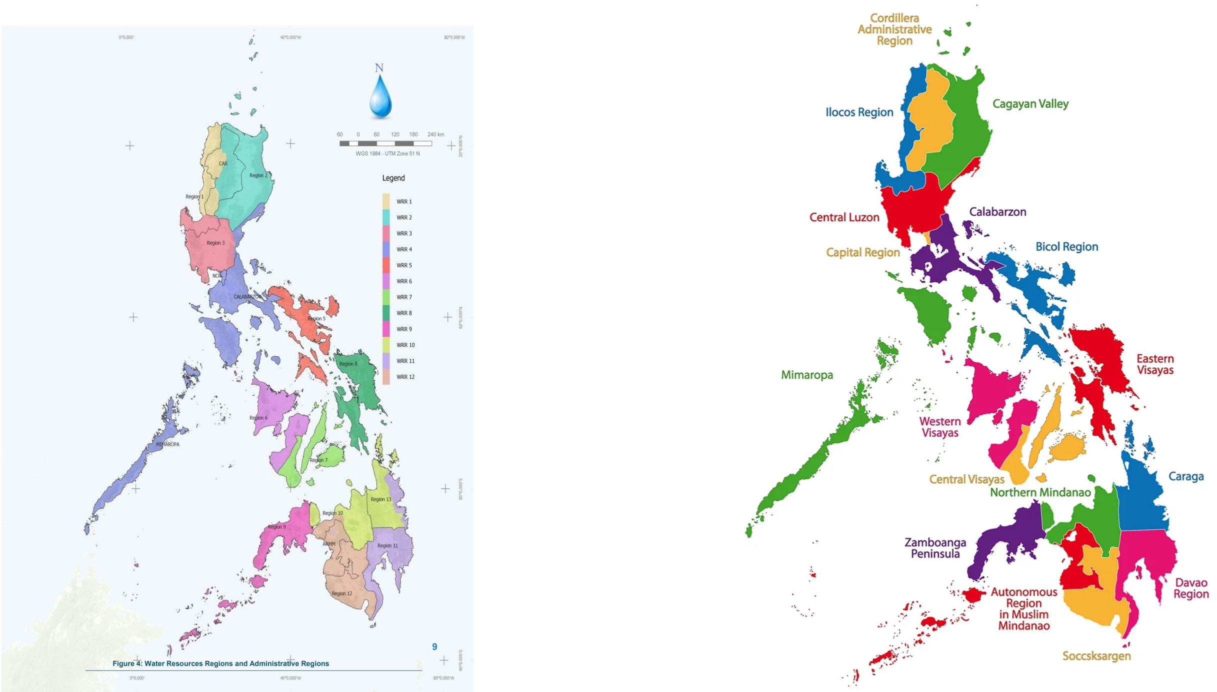


Figure B.1: Climate Regions in the Philippines [82]

The borders of the different Water Resource Regions of the Philippines do not coincide with the administrative regions as illustrated in Figure B.2. The different WRR's names are: Ilocos (WRR 1), Cagayan Valley (WRR 2), Central Luzon (WRR 3), Southern Tagalog (WRR 4), Bicol (WRR 5), Western Visayas (WRR 6), Central Visayas (WRR 7), Eastern Visayas (WRR 8), Southwestern Mindanao (WRR 9), Northern Mindanao (WRR 10), Southeastern Mindanao (WRR 11) & Southern Mindanao (WRR 12). The water availability per capita in each of the administrative regions is illustrated in Figure B.3.



(a) Water Resources Regions in the Philippines [82]

(b) Administrative regions in the Philippines [144]

Figure B.2: Border comparison between WRR and administrative regions

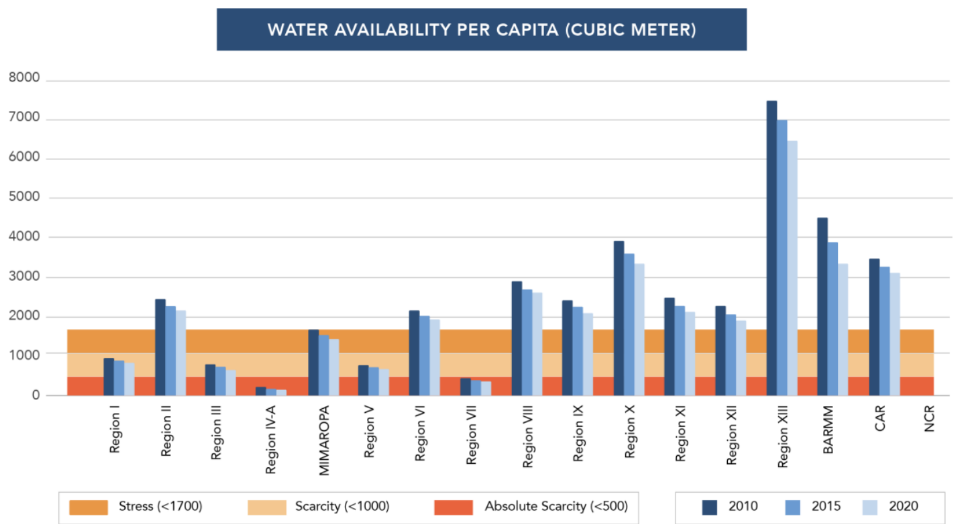


Figure B.3: Water Availability Per Capita By Administrative Region (2010-2020) [81]

Fragmented water sector in the Philippines

The Philippine Local Government structure is illustrated in Figure B.4. The description of the functions of different key agencies in the water sector is resumed in Table B.1. The table indicates which agency is responsible for resource, economic and operational/technical regulation for each type of water utility. The mandates distribution among the different agencies and stakeholders of the Philippine water sector are illustrated in Tables B.3 and B.5. Those tables were used to describe the fragmented sector in Figure 3.3 in Section 2.1 of Chapter 3. The regulatory involvement of different agencies in resource, technical/operations and economic regulation depending on the concerned water utility (water districts, private water utilities, community-based, etc.) is described in Table B.2. This table further describes the roles of the National Water Resources Board, Local Water Utilities Administration and Local Government Units in regulating Water Service Provider.

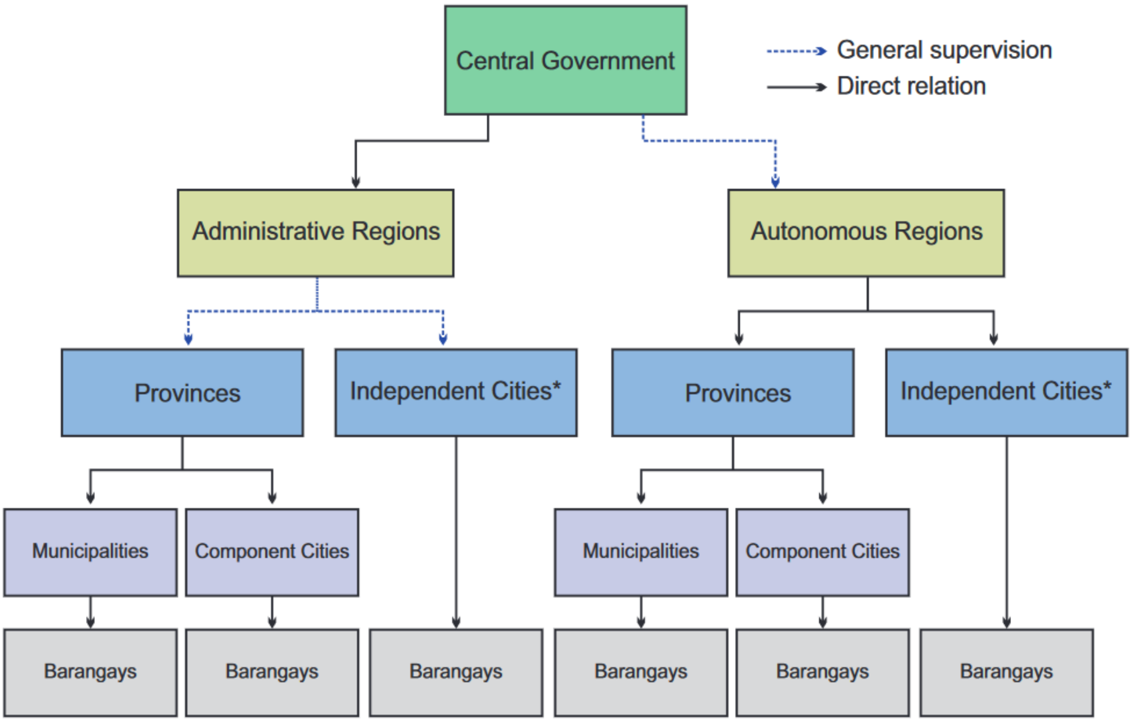


Figure B.4: Philippine local government structure [145].
∗ Cities that are independent of a province include highly urbanised cities and independent component cities. As of 2018, there are no cities independent from a province in the sole autonomous region of the country.

Department/ Agency	Description/Function
DENR	Responsible for the conservation, management, development, and proper use of the country's environmental and natural resources
NWRB	Regulates the utilization, exploitation, development, conservation, and protection of water resources
LWUA	A specialized lending institution for the development of provincial water districts that also exercises technical and economic regulation of water districts
DPWH	Responsible for major infrastructure projects including flood control and water resources projects
DOH	Sets standards for drinking water and monitor compliance
NIA	Responsible for the development and management of irrigation systems
NAPOCOR	In charge of the development of hydroelectric generation of power
MWSS	Provides water supply and sewerage services to Metro Manila, Rizal, and selected municipalities in Bulacan and Cavite through their two private concessionaires, Manila Water and Maynilad
MWSS-Regulatory Office (RO)	Reviews, monitors, and enforces rates and service standards of concessionaires
MMDA	Responsible for integrated flood control, drainage, and sewerage system for Metro Manila
LLDA	Develops the Laguna Lake region through management of water resources
NEDA	Develops policies and targets for the water supply and sanitation sector

Table B.1: Functions of Key Agencies in the Water Sector [100]

Water Utility	Resource Regulation	Technical / Operations Regulation	Economic Regulation
Water Districts	NWRB	LWUA, Optional NWRB	LWUA, Optional NWRB
Private Water Utilities with Certificate of Public Convenience	NWRB	NWRB	NWRB
LGU-Run Utilities	NWRB	LGU, Optional NWRB	LGU, Optional NWRB
Rural Waterworks and Sanitation Associations	NWRB	NWRB and LWUA	NWRB and LWUA (if with loans with LWUA)
Other CommunityBased Utilities	NWRB	NWRB	NWRB
Manila Water and Maynilad	NWRB	MWSS-Regulatory Office	MWSS-Regulatory Office

Table B.2: Regulatory Involvement of Water-Related Agencies [100]

Government Agencies																	
Functional Areas	NWRB	LWUA	DENR	LGUS	DPWH	DOH	NIA	NAPOCOR	PAGASA	DOF	MWSS	DILG	DOE	MMDA	DOT	LLDA	NEDA
Policy planning	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Data monitoring	•	•	•	•	•	•	•	•	•		•	•	•	•		•	
Scientific modeling									•							•	
Infrastructure and program development	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	
Operation of water facilities				•	•		•	•			•			•			
Regulatory functions	•	•	•	•		•					•		•	•		•	
Financing		•	•	•						•							•
Public relations, capacity development and IEC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Local RBO development			•														

Table B.3: Key government agencies and their water-related functions (as of 2012) [98]
NWRB National Water Resources Board, LWUA Local Water Utilities Administration, DENR Department of Environment and Natural Resources, LGUs Local Government Units, DOH Department of Health, NIA National Irrigation Administration, NAPOCOR or NPC National Power Corporation, PAGASA Philippine Atmospheric, Geophysical and Astronomical Services Administration, DOF Department of Finance, MWSS Metropolitan Waterworks and Sewerage System, DILG Department of Interior and Local Government, DOE Department of Energy, MMDA Metropolitan Manila Development Authority, DOT Department of Tourism, LLDA Laguna Lake Development Authority, NEDA National Economic and Development Authority

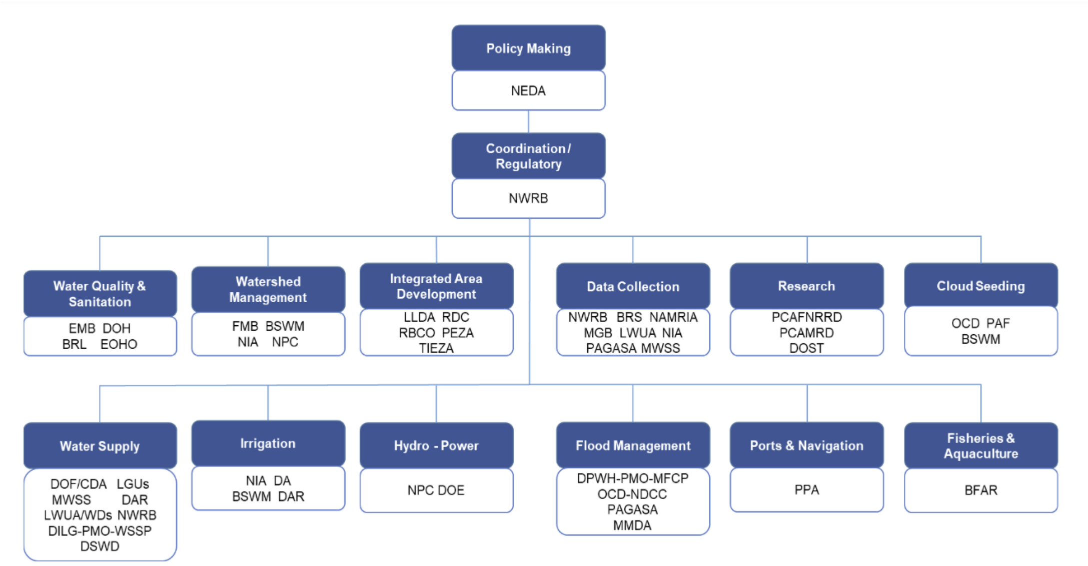


Figure B.5: Roles of water related agencies in function of sector (as of 2009) [82]
Bureau of Fisheries and Aquatic Resources (BFAR), Bureau of Research and Laboratories (BRL), Bureau of Research and Standards (BRS), Bureau of Soils and Water Management (BSWM), Cooperative Development Authority (CDA), Department of Agriculture (DA), Department of Agrarian Reform (DAR), Department of Science and Technology (DOST), Department of Social Welfare and Development (DSWD), Environmental and Occupation Health (EOHO), Environment Management Bureau (EMB), Forest Management Bureau (FMB), Major Flood Control Projects (MFCP), Mines and Geosciences Bureau (MGB), National Mapping and Resource Information Authority (NAMRINA), National Disaster Coordinating Council (NDCC), Office of Civil Defense (OCD), Philippine Air Force (PAF), Philippine Council for Agriculture, Forestry and Natural Resources Research and Development (PCAFNRRD), Philippine Council for Aquatic and Marine Research and Development (PCAMRD)[1], Philippine Economic Zone Authority (PEZA), project management office (PMO), Philippine Ports Authority (PPA), Project Management Office (PMO), River Basin Control Office (RBCO), Regional Development Council (RDC), Tourism Infrastructure and Enterprise Zone Authority (TIEZA) Water Districts (WDs), Water Supply and Sanitation Project (WSSP)

[1]The PCAFNRRD and PCAMRD were merged in the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (PCAARRD) in 2011.

Water Quality Guidelines and General Effluents Standards of the Philippines

Tables B.4 and B.5 contain the Water Quality Guidelines and General Effluents Standards for Primary Parameters listed in the DENR Administrative Order N° 2016-08. Those tables do not take the updates of 2021 into account.

Table 3. Water Quality Guidelines for Primary Parameters

Parameter	Unit	Water Body Classification								
		AA	**A**	**B**	**C**	**D**	**SA**	**SB**	**SC**	**SD**
BOD	mg/L	1	3	5	7	15	n/a	n/a	n/a	n/a
Chloride	mg/L	250	250	250	350	400	n/a	n/a	n/a	n/a
Color	TCU	5	50	50	75	150	5	50	75	150
Dissolved Oxygen[(a)] (Minimum)	mg/L	5	5	5	5	2	6	6	5	2
Fecal Coliform	MPN/100mL	<1.1	<1.1	100	200	400	<1.1	100	200	400
Nitrate as NO_3-N	mg/L	7	7	7	7	15	10	10	10	15
pH (Range)		6.5-8.5	6.5-8.5	6.5-8.5	6.5-9.0	6.0-9.0	7.0-8.5	7.0-8.5	6.5-8.5	6.0-9.0
Phosphate	mg/L	<0.003	0.5	0.5	0.5	5	0.1	0.5	0.5	5
Temperature[(b)]	°C	26-30	26-30	26-30	25-31	25-32	26-30	26-30	25-31	25-32
Total Suspended Solids	mg/L	25	50	65	80	110	25	50	80	110

Notes:

MPN/100mL – Most Probable Number per 100 milliliter

n/a – Not Applicable

TCU – True Color Unit

(a) Samples shall be taken from 9:00 AM to 4:00 PM.

(b) The natural background temperature as determined by EMB shall prevail if the temperature is lower or higher than the WQG; provided that the maximum increase is only up to 10 percent and that it will not cause any risk to human health and the environment.

Table B.4: Water Quality Guidelines for Primary Parameters [111]

Table 9. Effluent Standards[(g)]

Parameter	Unit	Water Body Classification								
		AA	**A**	**B**	**C**	**D**	**SA**	**SB**	**SC**	**SD**
Ammonia as NH_3-N	mg/L	NDA	0.5	0.5	0.5	7.5	NDA	0.5	0.5	7.5
BOD	mg/L	NDA	20	30	50	120	NDA	30	100	150
Boron	mg/L	NDA	2	2	3	12	NDA	2	20	80
Chloride	mg/L	NDA	350	350	450	500	NDA	n/a	n/a	n/a
COD	mg/L	NDA	60	60	100	200	NDA	60	200	300
Color	TCU	NDA	100	100	150	300	NDA	100	150	300
Cyanide as Free Cyanide	mg/L	NDA	0.14	0.14	0.2	0.4	NDA	0.04	0.2	0.4
Fluoride	mg/L	NDA	2	2	2	4	NDA	3	3	6
Nitrate as NO_3-N	mg/L	NDA	14	14	14	30	NDA	20	20	30
pH (Range)		NDA	6.0-9.0	6.0-9.0	6.0-9.5	5.5-9.5	NDA	6.5-9.0	6.0-9.0	5.5-9.5
Phosphate	mg/L	NDA	1	1	1	10	NDA	1	1	10
Selenium	mg/L	NDA	0.02	0.02	0.04	0.08	NDA	0.02	0.2	0.4
Sulfate	mg/L	NDA	500	500	550	1,000	NDA	500	550	1,000
Surfactants (MBAS)	mg/L	NDA	2	3	15	30	NDA	3	15	30
Temperature[(h)]	°C change	NDA	3	3	3	3	NDA	3	3	3
Total Suspended Solids	mg/L	NDA	70	85	100	150	NDA	70	100	150

Table B.5: Effluents Standards primary and secondary (inorganic) parameters (NDA = No Discharge Allowed) [111]

Metro Cebu

During the data collection phase of this study, Metro Cebu faced extreme weather conditions that impacted the water service of Metro Cebu Water District (MCWD). Figure B.6 shows an advisory published by the MCWD on their social platforms to inform citizens that their water sources and water production were affected by the dry spell happening in 2024.

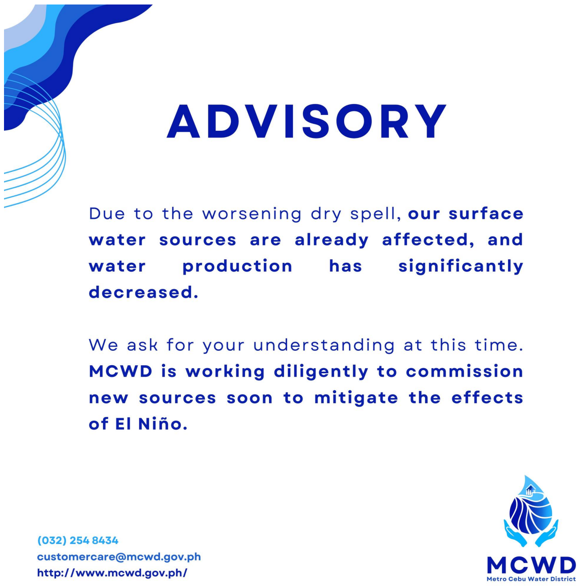


Figure B.6: MCWD Advisory concerning dry spell

Saltwater intrusion over the years in Metro Cebu

The following figure shows the saltwater intrusion in 1979, a few years after SWI was detected for the first time. The evolution of the 250 ppm salinity level line inland can be observed when compared to the 2022 salinity levels present in Section 3.3.1 in Chapter 3. Wells with a salinity level higher than this limit are unfit to be used for drinking water.

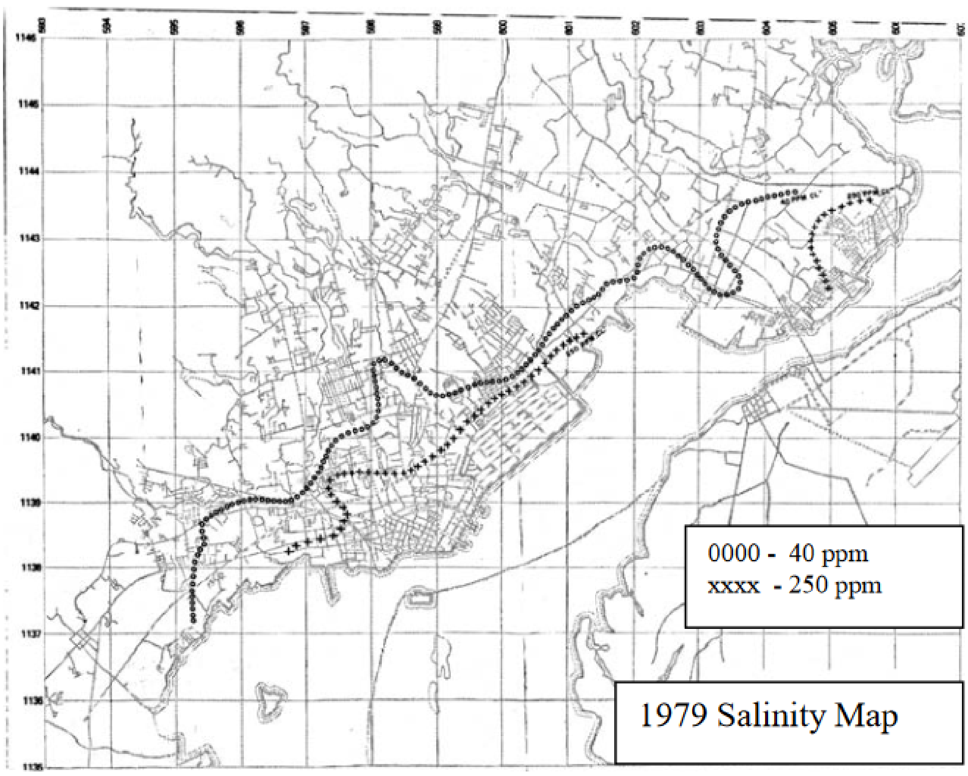


Figure B.7: SWI 1979 [17]

Butuanon River: Historical Water Quality Monitoring

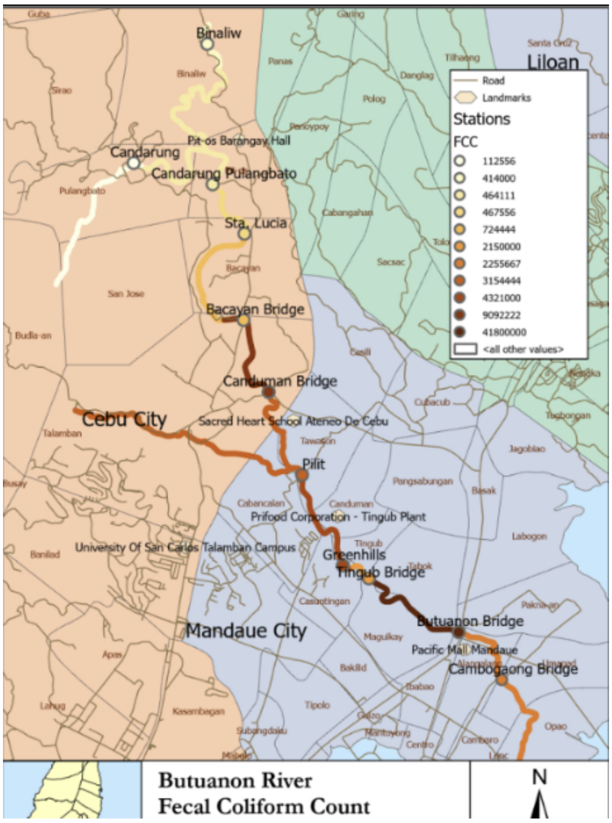


Figure B.8: Fecal Coliform Count (Riverscan Challenge)

In the **upstream** section of the Butuanon, people release wastewater from piggeries and poultry farms. The upstream portion is less urbanised and the water is still relatively clear. From the **midstream** to the **downstream** portion, industries and businesses along the riverbanks flush their wastewater into the river. Wastewater is supposed to be treated, but due to a lack of control by local authorities, untreated water is often dumped illegally. Multiple informal settlements, who live in the areas around the river that is supposed to be free of habitation for flood safety reasons, have formed around the river. As the majority of **informal settlers** do not have septic tanks or proper waste collection systems, their waste often ends up in the river: from plastics, papers, and diapers to septic, vegetable, and livestock wastes (see Figure B.9). A study analysing disposal practices of riverside dwellers living along the Butuanon River in 2012 showed that the majority of households (75%) dump solid waste (plastic, paper, diapers, etc.) and some (6.7%) dispose of human and animal waste into the river. In general, garbage composed of laundry wastewater, residual wastes and plastics is mostly thrown into the river instead of being disposed of through regular garbage collection [146]. Informal settlers along the riverbanks are concerned with its state, explaining that its colour sometimes changes from murky white to black, blaming industrial firms for polluting the river. They describe the smell as sometimes so strong it is unbearable, the stench increasing when the river flow is slow, and the water stagnates. They know how dangerous it is to come in contact with the river as community members fell in it and became heavily sick in the past. The **downstream** section of the river is considered biologically dead and is the exit point of the pollution from the river to the sea. Furthermore, the downstream portion also experiences flooding during heavy rainfall when the river overflows[2].

This section contains Geographic Information System maps done by Civil Engineering students of the University of San Carlos during a Metro Cebu River Scan Challenge. The maps depict the water quality based on several parameters with data from 2022 shared by the Environmental Management Bureau VII. The parameters used were the following: Biological Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Suspended Solids (Total Suspended Solids), Phosphate Concentration and Fecal Coliform Count. The water quality is tested monthly by the EMB VII at 11 sampling locations for primary parameters (the ones listed above and pH, Temperature, nitrates, chloride and colour) as well as for secondary parameters quarterly such as Ammonia, Oil and Grease and Heavy metals. The

[2] Interviews lead during the River Scan Challenge, 2024 [147]

sampling stations of the EMB VII for water quality monitoring of the Butuanon River are shown in Figure B.10. The figures following show the levels of different parameters across the various sampling points. The increase in pollution as the river flows through populated areas is clearly visible, with downstream portions heavily polluted compared to the upstream part of the river.

Figure B.9: Trash of nearby residents ending up in the Butuanon river [147]

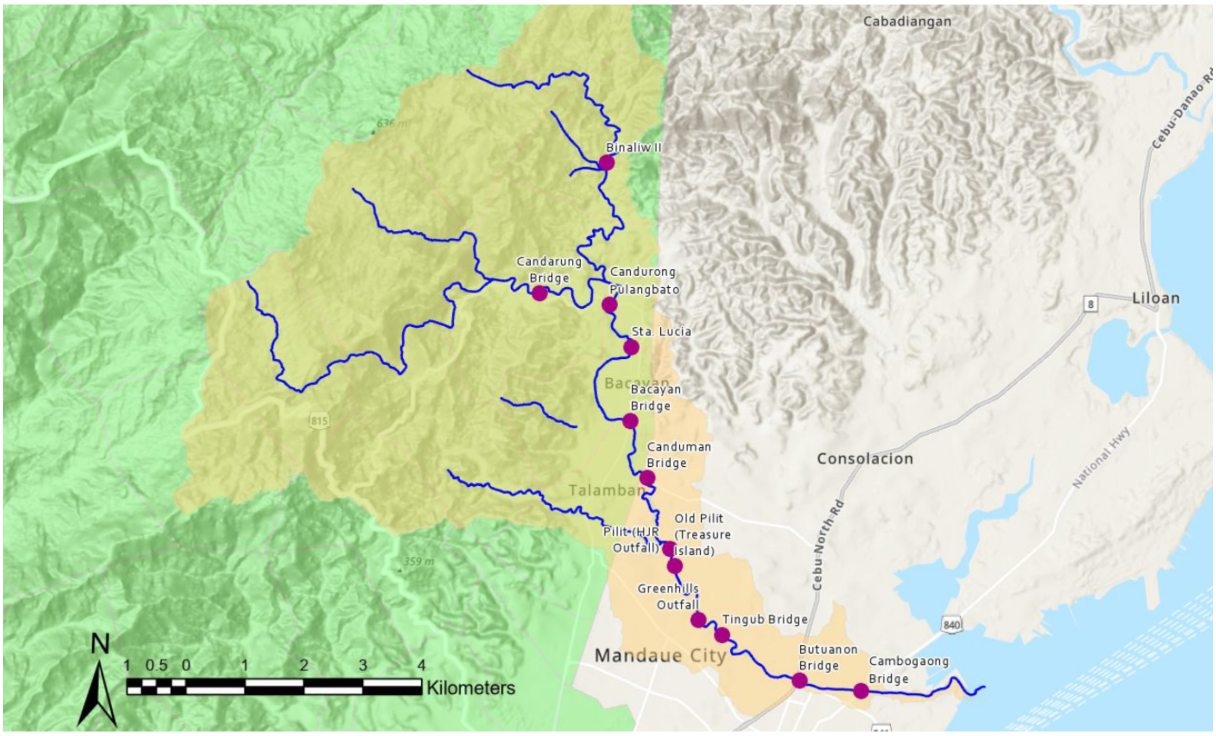


Figure B.10: EMB's 11 Sampling Stations for Water Quality Monitoring of Butuanon River (EMB VII, 2024)

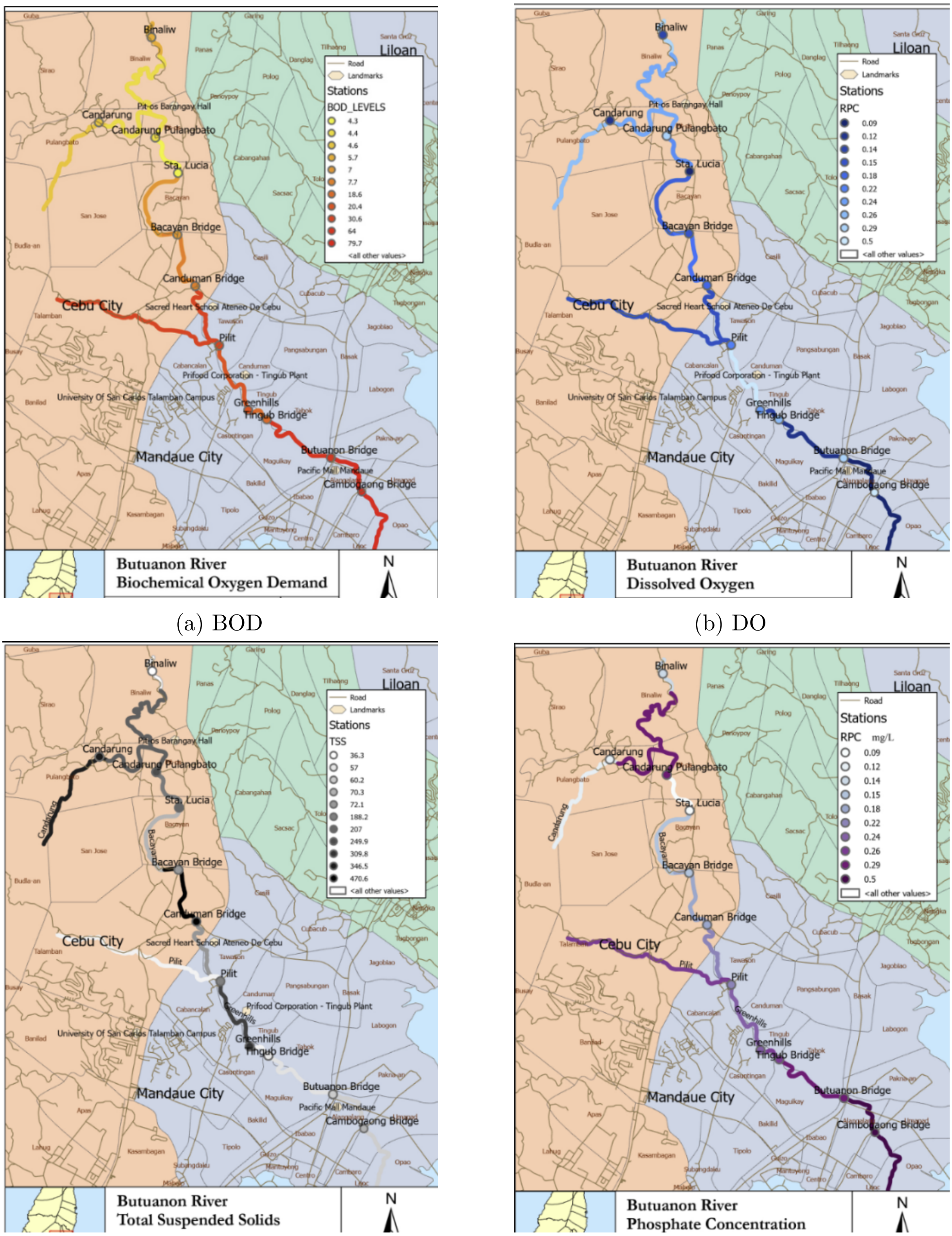


Figure B.11: Butuanon River BOD, DO, TSS and Phosphate levels (Riverscan Challenge)

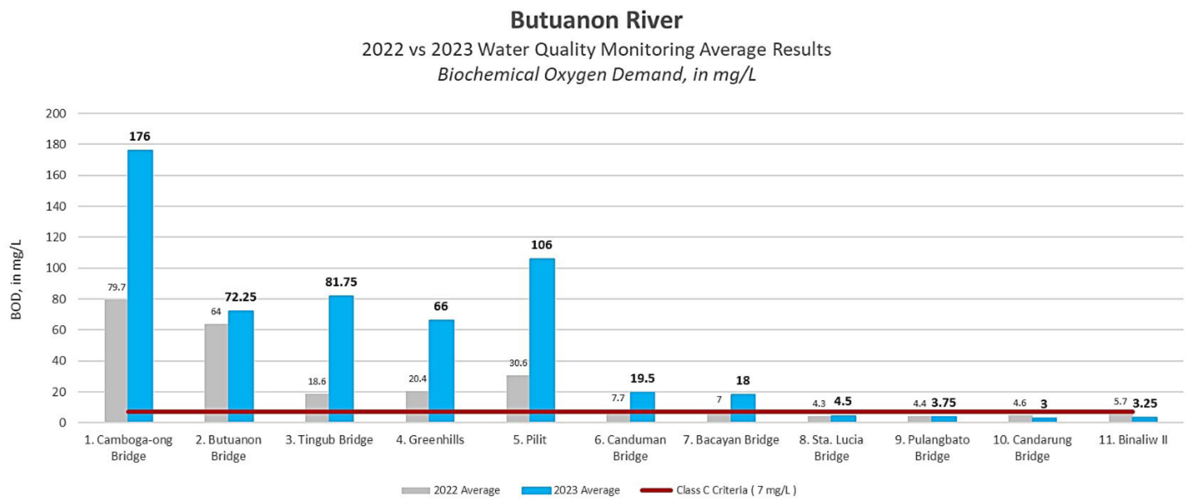


Figure B.12: Butuanon River - 2022 vs 2023 Water Quality Monitoring Average Results - Biochemical Oxygen Demand, in mg/L (EMB VII, 2024)

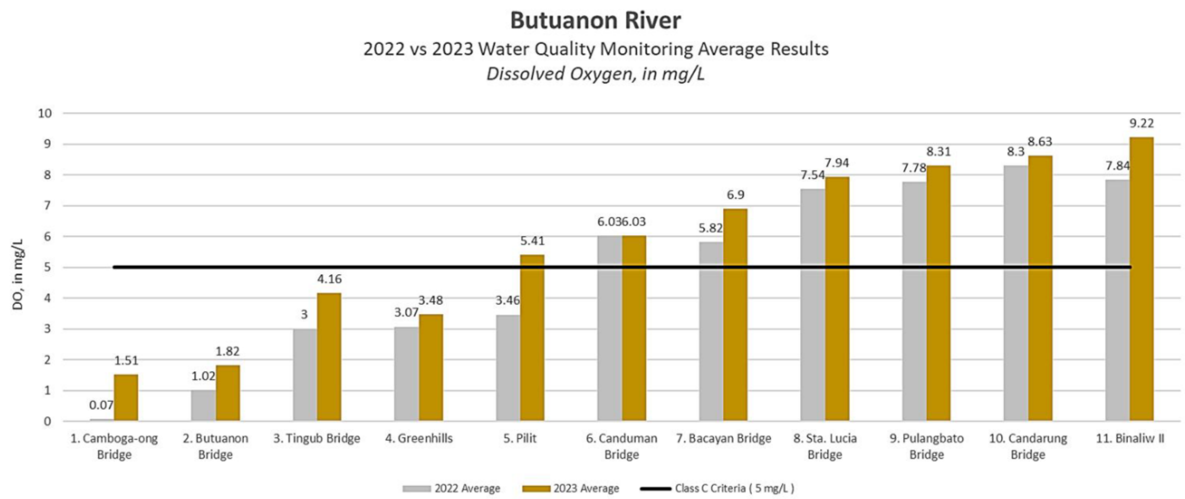
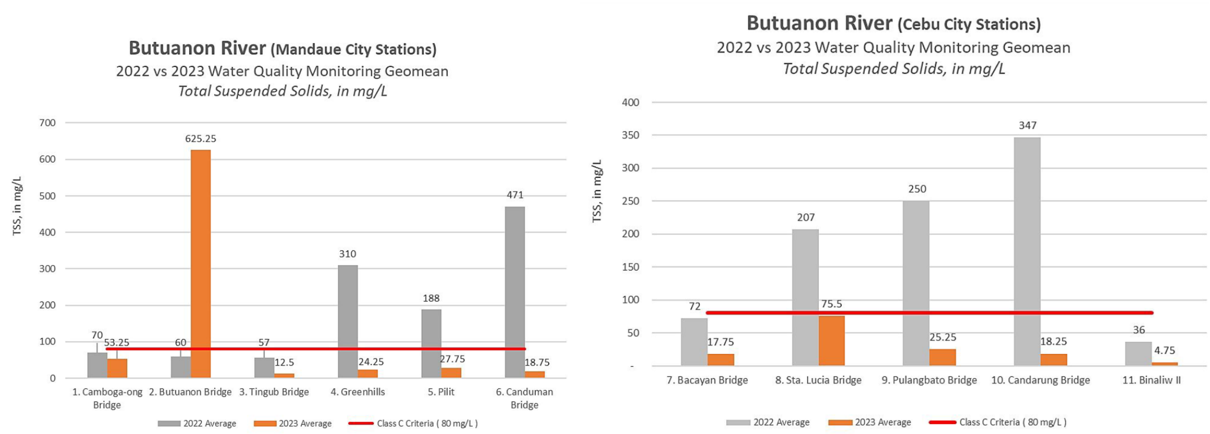


Figure B.13: Butuanon River - 2022 vs 2023 Water Quality Monitoring Average Results - Dissolved Oxygen, in mg/L (EMB VII, 2024)



(a) Mandaue City

(b) Cebu City

Figure B.14: Butuanon River - 2022 vs 2023 Water Quality Monitoring Geomean - TSS, in mg/L (EMB VII, 2024)

Interviewed stakeholders of Metro Cebu's water sector

Figure B.15 completes Figure 5.3 with a visual representation of the interviewed stakeholders.

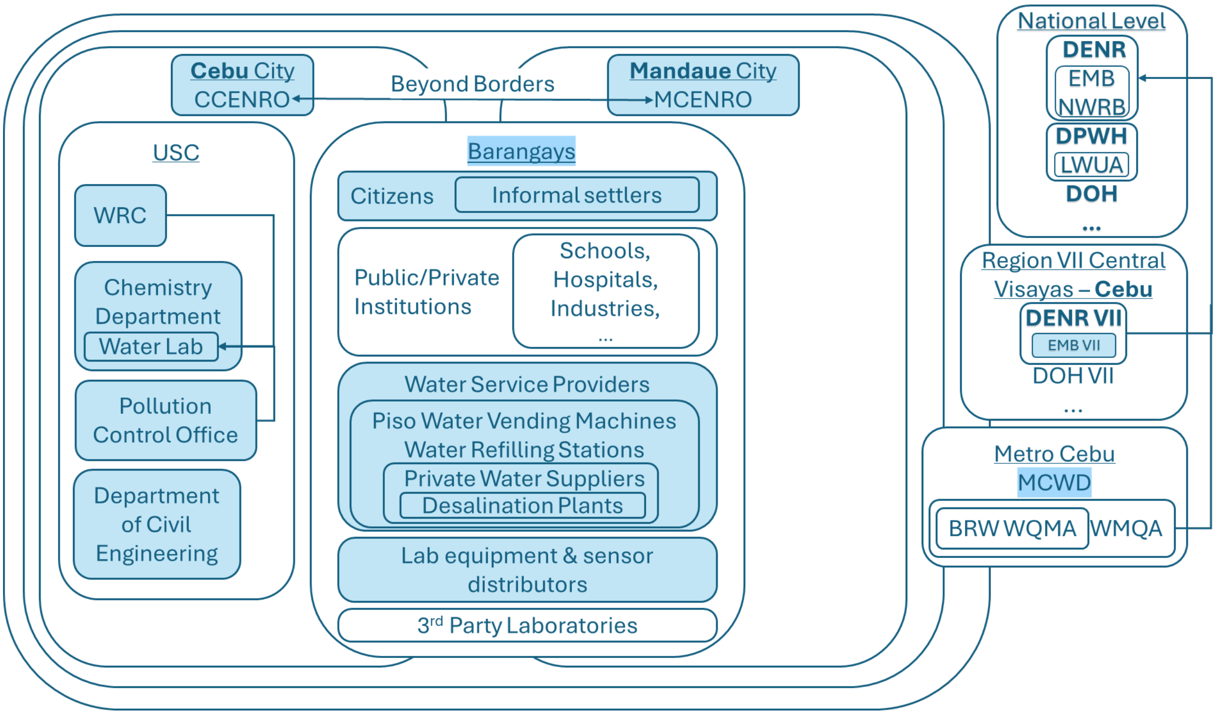
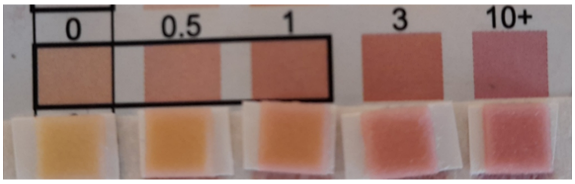


Figure B.15: Interviewed local stakeholders during this work

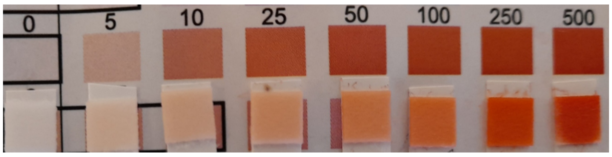
Appendix C

Sensor Validation

Figures C.1a and C.1b show the results of the validation method for Copper and Iron test strips, respectively. BMUT 16 in 1 and Smardy Blue test strips measure those parameters and provide identical validation results. Both pictures show that comparison of results with colour charts can be tricky. Figure C.2 shows the average deviation of the digital EC meters from the actual EC value. The sample used for the validation was a calibration sample of the HI98130 pH/EC/TDS meter. Calibration samples have known conductivity values for a large range of temperatures.



(a) Copper



(b) Iron

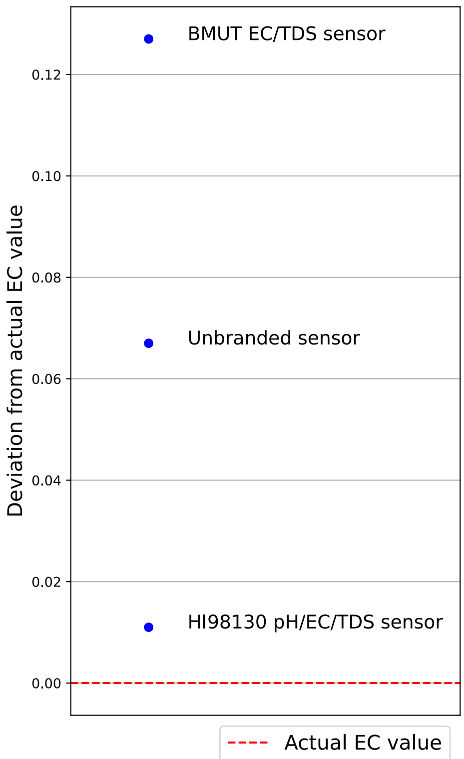


Figure C.2: Average deviation of EC Sensors from the actual EC value

Appendix D

User-friendliness Quantification of Sensors

This section contains a detailed description of the method followed to quantify the user-friendliness of the selected sensors by calculating the number of steps needed for measurement, calibration and maintenance procedures. We consider that the user wants to save the test results. Waiting time until measurement is displayed or can be analysed is considered a step if it is the user's task to monitor the time. For qualitative results, as results interpretation is straightforward, it is not considered as a step. Writing down results is considered as a step as opposed to sensors storing results automatically. The need to be stored in a dry and cool place applies to a lot of sensors and was considered as a step only if those conditions were restrictive enough to require a special storing environment in countries whose weather does not correspond to the requirements (need for storing temperature below 30°C). In most cases, comparing the length of the instructions of use is a good evaluation method to compare the user-friendliness and complexity of the sensors.

Bacteria Absence/Presence tests

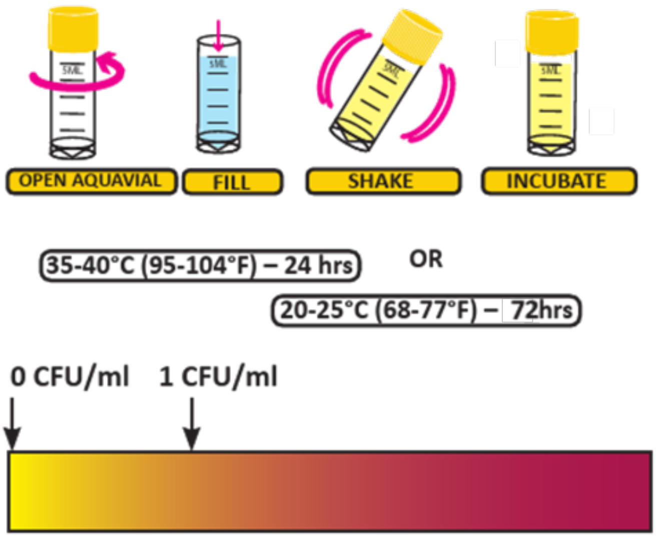
For the bacterial qualitative tests, the major difference between the selected sensors is the detection limit and the possibility of one of the tests also detecting the presence of E. coli. As seen in Figure D.1, these tests function as follows:

1. The test bottle needs to be filled with a specified quantity (100 ml, 12 ml or 5 ml, depending on the kit) of the water sample to be tested while avoiding external contamination. The bottle then needs to be sealed and shaken.

2. Incubation time: 24 to 48 or 72 hours (depending on the incubation temperature and test kit).

3. After incubation time, a colour change of the sample indicates the presence of coliform in the water above the specified detection limit. Clear yellow or no colour means no coliforms, while blue-green or purple (depending on the kit) means the sample tested positive for coliforms. One of the test kits, an enzyme substrate coliform test, allows E. coli presence detection by shining a blacklight on the sample (no fluorescence means no E. coli, while blue fluorescence means the sample tested positive for E. coli).

The method for measurement is simple and composed of 4 steps (sample collection, shake, incubate and write the result down) with one additional step to check fluorescence with a black light. No calibration or maintenance is needed besides the need to be stored in a cool and dry environment.



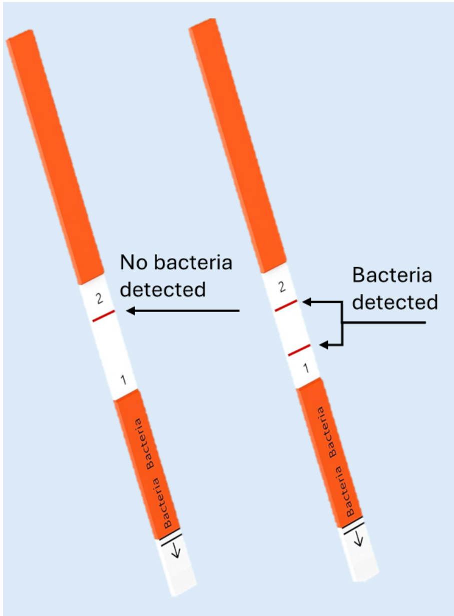


Figure D.1: Instructions for the use of Aquavial bacteria test bottle (left), Rapid Bacteria Test by Watersafe (right)

The user-friendliness of the selected portable coliform test kits was evaluated against one of the bacteria lateral flow test strips (see Figure D.1), which takes 15 minutes until qualitative results but has a very high detection level (1000 CFU/mL for coliform and non-coliform bacteria). This test's procedure consists of collecting the sample, swirling the strip for 5 minutes in the sample, waiting 10 minutes, write the result down (5 steps).

Paper-Based Indicators

For simple paper diptests, the test strip needs to be put into the water, results need to be read after a specific time that needs to be monitored, and results are obtained by comparing the colour change to a colour chart before being written down for each measured parameter (1 steps + 3 × number of parameters). For test strips with numerical results, the test strip is dipped into the water, and after a waiting time of 1 minute indicated by the app, a picture is taken, which gives immediate results that are stored on the app (2 steps). For test strips with reagents, like the Manganese test strip, the steps are described in Figure D.2 (7 steps).

Digital Sensors

For digital sensors, the use consists of dipping the sensor in the sample and writing down the results after they stabilise. The sensors indicating when the result is stable require one less step (1 + (1 or 2) × steps for measurements). Maintenance for all reusable sensors consists of cleaning the electrodes with distilled water. Some sensors require adding a conservation solution in the cap protecting the electrodes, and the DO sensor requires changing the cap of the electrodes regularly to avoid measuring with a polluted selective

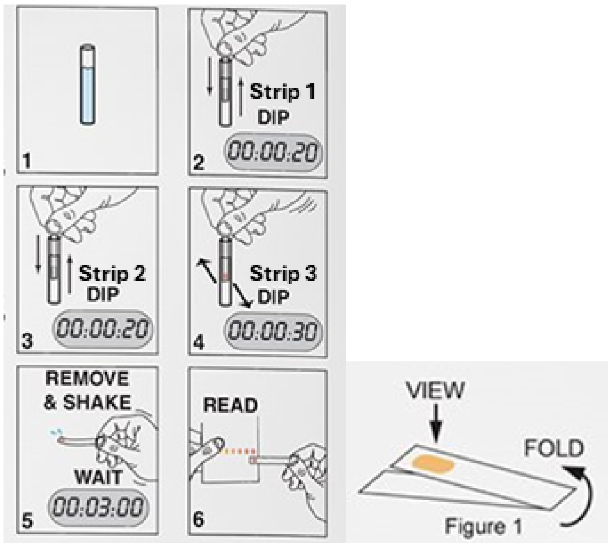


Figure D.2: Instructions for the use of Manganese aperture test strip

membrane (1, 2 or 3 steps for maintenance). Calibration varies from one sensor to the other, depending on the parameters analysed. Sensors with calibration are provided with one type of calibration solution that can be in a liquid state (in bottles or in sachets) or a solid state (salts that need to be diluted in a specific quantity of distilled water). Single-use liquid state solutions in sachets make calibration more accessible for on-site handling as there is no need for additional equipment, nor for mixing powder with precise quantities of distilled water and waiting until total dilution. Figure D.3a contains an example of single-use sampling solutions for the HI98130 sensor that can easily be used on-site as the sensor fits in the calibration solution packet. Ideally, refillable and cleanable calibration transportable sachets should be used to minimise waste. Standard buffer solutions for calibration can be bought independently from sensors in the wanted format. For comparison purposes, the calibration method proposed by the manufacturer was selected here.

The user-friendliness of the sensors used by the Water Resource Center for conductivity measurements was also computed. One is a portable HATCH EC sensor that has manipulations similar to the BMUT EC sensor. Another sensor is a heavier and less portable sensor used for groundwater level monitoring, and its probe is attached to a 150-meter cable (Solinst TLC meter, see Figure D.3b). During measurement, the probe is descended into the wells by unwinding the cable. It needs drying and cleaning of the cable that was in contact with the water as well.

(a) Portable calibration solution [42]

(b) Solinst TLC meter sensor for groundwater monitoring

(c) HACH Pocket Pro EC/TDS meter

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