Measuring surface water quality using a low-cost sensor kit within the context of rural Africa

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ABSTRACT

Monitoring water quality is done for a variety of reasons, including to determine whether water is suitable for drinking or agricultural purposes. In rural areas of Africa the traditional way of measuring water quality can be costly and time consuming. In this research, we have developed a low-cost water quality measuring device that designed to operate in the context of rural Africa. Firstly we select appropriate water quality sensors. Secondly we developed a water quality monitoring device that takes the contextual requirements and constraints of rural Africa into account. Lastly the device is evaluated and tested using water samples that were collected in rural Africa.

KEYWORDS

ICT4D, water quality monitoring, low-cost sensor kit, IoT4D

1 INTRODUCTION

Measuring surface water quality has been done for decades for a variety of reasons. Among those reasons are to find out whether water is drinkable or if it can be used for agricultural purposes [2]. Traditional methods to determine water quality can be time consuming and expensive [9]. Water samples are sent to a laboratory and those samples are analyzed there. Using this method of water analysis it is not possible to determine water quality ad hoc. For example in the context of rural Africa, a farmer wants to know if the water from the river can be used to water his or her crops. If the farmer has to wait a few weeks to find out whether the water at that moment is suitable for watering crops, the results are not relevant anymore when they arrive. The water composition could have been changed since the samples were taken. A more suitable method of determining the water quality would be a solution that provides information about the water quality instantly. This device should be affordable from a financial perspective. Using such a device has multiple advantages over traditional water quality measuring approach: water quality can be measured instantly, measurements can be taken continuously and measuring can be done by stakeholders itself instead of being dependent on a laboratory. A disadvantage of using a low-cost sensor kit is that fewer water parameters can be measured and these measures are potentially less accurate.

In this research, we will develop a low-cost water quality measuring device. This device (or sensor kit) is designed to function within the context of rural Africa. This means that there will be various requirements and constraints that are related to this context. To be able to develop the water quality measuring device, the following research questions will be answered:

1. *What is an effective design of a low-cost water quality measuring kit within the context of rural Africa?*
1.1 *What are the requirements and constraints of the system design with respect to the context of rural Africa?*
1.2 *What are appropriate sensors to measure water quality for the measuring kit?*

The meaning of the word effective in the first research question, is explained in more detail in the two subquestions. For the purpose of our research, we define effectiveness as how well the system conforms to the requirements and constraints. For example, if there is no internet connection available, alternative methods for connectivity should be included in the system design. Additionally, there is a trade-off between the building costs and measuring quality. This also involves the selection of appropriate sensors. Sensors are considered appropriate for this context, if they are low-cost and still provide correct information about water quality parameters.

2 RELATED LITERATURE

2.1 ICT4D context

In this research, we focus on implementing an ICT solution within rural Africa. This results in multiple requirements and constraints that are specifically related to this context. ICT research for development is called Information and Communication Technologies For Development (ICT4D or ICTD). More specifically, ICT4D is defined by Gyan as the use of ICT in socio-economic and international development. This includes disadvantaged population all over the world, but more often ICT4D is related to developing countries [5]. Ali et al. mentions three benchmarks that are important for successful ICT4D projects: context, community participation and sustainability. However, sustainability seems to be conflicting with ICT in general, which is changing often. Therefore Ali et al. qualifies sustainability of ICT4D projects as an unrealistic concept and that pursuing sustainability leads to project failures [1].

Implementing an ICT system within developing countries raises multiple challenges that are not obvious or present in first-world countries. Users of ICT systems often have limited education, are underemployed and have low incomes [12]. On the other hand, stakeholders of such systems are from different countries and have different sociocultural backgrounds [13], which can complicate determining the goals of a project. Pitula et al. described other challenges of the complicated context in which ICT4D projects operate, related to infrastructures, power supplies, connectivity and extreme operating conditions. Additionally three main components of ICT4D projects are described: 1) infrastructure development, 2) create ICT capacity and 3) providing the digital service. The first component relates to the required infrastructure to operate the system. The second component relates to the capacity to use and maintain the system. Finally, the third component relates to the value of the service itself [13]. Because network connection are extremely unreliable or not available at all in rural areas of developing countries, other techniques are used to make the web accessible. Research of Valkering et al. focuses on transmitting data via SMS in rural areas [19]. Most of the challenges listed above, are also relevant for our research. Solutions to overcome power and connectivity issues should be investigated in order to design a usable water quality measuring device for rural Africa.

According to Tongia et al. many ICT4D project fail either partially or completely. This is caused by a incomplete problem definition or by the metrics used for evaluation [17]. Other research confirms that most ICT systems for development do indeed fail [6, 13]. Among the reasons for failure is a gap between the design of the system and the reality. The findings of the previously mentioned researches are relevant for our research. It indicates that the ICT4D context should be taken into account in both the system design phase and other phases (like the evaluation phase) in order to succeed in this context.

2.2 Water quality measurement

Water quality can be determined using the physical, chemical and biological properties of water [18]. The Environmental Protection Agency of Ireland described 101 parameters to determine water quality. Below a selection of those parameters are listed and categorized by the previously mentioned quality property categories. Firstly, physical parameters include for example: pH and temperature. Secondly, chemical parameters include: dissolved oxygen and other measures of how much of a certain substance is present in water. Lastly, biological properties include measures of bacteria and viruses (e.g. salmonella) [16]. The listed properties are relevant for this research because they can be measured using low-cost sensors. A study of Rao et al. describes a low-costs water monitoring system that is measuring some of the parameters that were described earlier. This includes temperature, pH, electrical conductivity and dissolved oxygen [14]. The findings of Rao et al. are relevant for this research since they also involve building a low-cost water quality measuring system.

For amateur aquaponics and gardening, water quality monitoring often happens using low-cost sensor kits [1] [2]. These sensor are often controlled by Arduino prototyping boards. Due to the open-source nature of these projects, multiple tutorials are published online by the Arduino community. These amateur projects can be interesting to our research since the same goal is pursued: measuring water quality with cheap sensors. Although the goal is the same, the environment in which the device operates is different.

A Dutch NGO called AKVO is focusing on measuring water quality in a cost effective way using smartphones [3]. They use multiple methods in order to determine the quality, for example test strips are used to measure certain parameters. The smartphone camera is then used to photograph the test strip in order to capture and store the measuring results. AKVO has developed a lens for a smartphone camera as well. With this lens it is possible to determine certain water quality parameters [10]. Using a smartphone, the prices of sensors kits can decrease significantly. However, there are multiple downsides of method. The most obvious downside is that a smartphone is needed (which is not always available, especially in rural areas of Africa). Additionally, this method is not very suitable for monitoring water quality over a longer period of time (water quality cannot be measured autonomously). Our research differs from the previously discussed projects since we focus specifically on the use in rural Africa. The measuring kit will not be dependent on a smartphone and is therefore suitable for autonomous continuous water quality monitoring.

3 METHODOLOGY

3.1 Water quality parameter selection

In order to design the water quality measuring kit, water quality parameters are selected together with the appropriate sensors to measure these parameters. The parameters are selected based on their relevance in rural Africa. This means that parameters that are hard to measure (because of a high sensor price or a complicated procedure) are not included in this research. The parameters do provide information about the quality of surface water. The selection of the parameters has been done using a literature review. The final result of selecting water quality parameters is a table that contains information about each individual parameter.

3.2 Measuring kit design and development

Based on the table of water quality parameters, the appropriate sensors have been selected. The measurement device is using an Arduino micro controller unit (MCU) to control the sensors. We have chosen for Arduino because it is an inexpensive and open-source I/O board that is often used for prototyping [3]. Additionally, the availability of analog I/O pins is convenient for reading analog values from various (water) sensors.

The development of the kit includes research into the most appropriate power source, housing and communication method with respect to the context of rural Africa. As has been described in the related literature section, multiple challenging factors should be taken into account during the system development. To be able to find out how these constraints affect the design of the kit, the constraints are listed together with possible design options. A list of design options is shown below. This list is based on challenges found by Pitula et al. [13].

- **Power supply**: power net, battery, solar panels, smartphone battery
- **Connectivity**: using smartphone app, GPRS, LoRa, SMS, save on SD card
- **Communication**: using smartphone app, LCD screen, web interface
- **Operating conditions**: waterproof housing, industrial sensor, lab sensors

In the following sections, two different types of usage scenarios are being described. The system requirements and constraints are determined based on these scenarios.

[1] https://kijanigrows.com/
[2] https://www.cooking-hacks.com/documentation/tutorials/open-aquarium-aquaponics-fish-tank-monitoring-arduino/
[3] https://akvo.org/products/akvo-caddisfly/

3.2.1 Water quality measurement on demand. The water quality kit is designed to be used on demand. This means that when someone wants to know certain water quality parameters, he or she takes a sample of the water and puts in inside a cup. Afterwards the sensors of the measuring kit are also placed in the cup to measure the water quality. Using the measuring kit using this method has implications for the system design. Firstly, powering the kit becomes less of an issue since the kit could be powered by the user (e.g. via a smartphone or a power bank). Secondly, connectivity and communication can also be handled via the smartphone. Lastly, more (expensive) sensors could be connected to the kit because it will not be left unattended. In contrast to the continuous measuring scenario (that will be discussed in the next section) fewer sensors kits have to be created to be effective and that is another reason why sensor pricing is less of an issue. A disadvantage of this method, is that most water quality parameters are only relevant if measured for a longer period of time (like temperature, dissolved oxygen and oxidation reduction potential). This means that their value itself (without the ability to measure changes) is not very helpful in determining water quality. A continuous water quality measuring approach would overcome this problem.

3.2.2 Continuous autonomous water quality measurement. In contrast to measuring on demand, it is possible to do continues measurements. Multiple sensor kits will be placed at different locations and they will constantly collect information about water quality. This is done using an Internet of Things (IoT) approach, which will connect the sensors to the internet. This has implications on the system design, including questions regarding: how to power the system, how to communicate the data to the stakeholders and how to handle connectivity? Possible answers to these questions are: using solar power, communicate data via a web Graphical User Interface (GUI), connectivity via GPRS. Additionally, the pricing of the sensor kit becomes more important since the kits can be stolen or damaged and because multiple sensor kits have to be created.

3.3 Testing and evaluation

The device is built in multiple iterations. The first prototype has been shipped to rural Africa. The testing phase is focusing on multiple factors. Firstly, the sensors are tested to find out whether they provide accurate information about water quality. This testing is done using water samples collected from Ghana and Burkina Faso. Testing in a real life setting is done in The Netherlands. The sensor kit is placed at several rivers, lakes and canals. This is done both for testing the sensors and to test and evaluate overall system design.

In the end, the evaluation of the system focuses on answering the research questions that were stated in section one. This includes an answer to the first research question: *What is an effective design of a low-cost water quality measuring kit within the context of rural Africa?.* An answer is provided by the description of an effective design. This is done by evaluating the requirements and by testing different design option available to fulfill these requirements. An effective system should be able to correctly measure water quality parameters and make some conclusion about the actual water quality. In the evaluation the trade-off between building costs and measuring quality is explained. An optimal solution is determined for a system that is low-cost, but still provides relevant information about water quality. Depending on the usage scenario of the system, some design options could be in favor of others. The evaluation provides a clear overview of what design decisions were taken during the development of the kit, and what other design options are available. Since this research is still work in progress, the design decisions are not extensively discussed in the results. This will be done at a later stage of the research.

4 RESULTS

4.1 Water quality parameters

In Appendix A a table can be found with a list of six water quality parameters that are useful for this research. In this table the parameters are listed together with a description and a standard for drinking water. These standards come from both the United States Environmental Protection Agency (EPA) and the World Health Organization (WHO). Some of the parameters provide clear safety range for drinking water. For example, water with a pH below 6.5 should not be drunk. But a parameter like temperature does by itself not provide information about whether the water is drinkable or not. A bottle of water that has been heated by the sun can still be perfectly drinkable. However, when measured for a longer period of time, monitoring the water temperature can provide helpful insights into the water quality. The final parameter list is composed based on existing literature of research concerning water quality measurement [8, 14, 15, 18, 20]. According to Tuna et al. the following parameters are main parameters to measure water quality: electrical conductivity, dissolved oxygen, nitrate, pH, temperature, turbidity.

4.2 Development of the device

4.2.1 First iteration. The water quality kit of the first iteration has been shipped to Mali for testing in the field. This prototype contained the following sensors: temperature, turbidity, pH and TDS. In Table 1 a more detailed overview of the specific sensors and hardware of this device is listed. The housing of the device has been printed using a Ultimaker 3D printer. The total price of the kit is around 200USD. The price can be reduced by replacing the solar power bank, by a self built solar charging system (which has been done in iteration two).

Table 1: Hardware specification of first iteration device

Type	Description	Costs
Haoshi H-101	Industrial pH sensor	\$56.95
Linkit One	Development board for sensor control	\$59.00
DFRobot analog TDS sensor	TDS sensor	\$12.90
DS18B20	Temperature sensor	\$6.90
TSD-10	Turbidity sensor	\$9.90
Xtorm Magma	3000 mAh solar power bank	\$50.00

The device can operate both as "water quality tool on demand" or as "continuous autonomous water quality monitoring tool" (the two use cases described in section 3.2). For the first use case, a LCD screen on the device displays water quality parameters in real time. For the second use case, the data is sent to a server. The sensors were controlled with a Linkit One[4]. This device runs the same code as Arduino, but has multiple connectivity options built in. Among other things, GPRS and GPS are included. GPRS is used to send the sensors data, time and location to a server. GPS is used to determine the current location of the device. The device operates as follows:

(1) Set up device (connect sensors, turn on solar panel)
(2) Put the sensors in the water
(3) Water quality parameters appear on LCD screen. LCD background is green if the parameters are in a safe range, the background becomes red if values are outside the safe range
(4) Water quality parameters and location are sent to the server

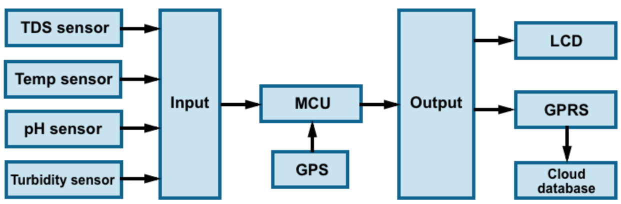

Figure 1: Block diagram of first iteration device

4.2.2 Second iteration. The second iteration of the device is currently being constructed. This iteration focuses on adding more sensors and on improving the construction of the device itself. Among the new sensors is an ORP sensor. When the first iteration device was shipped to rural Africa, some internal wires came loose. The second generation device will therefore be more robust to prevent this from happening. In this second iteration, two separate devices will be constructed. This is done in order to fulfill the requirements that are specific for the two use cases described in section 3.2. One device will be used to measure water quality on demand (an LCD screen will be used to communicate the sensor data to the user). The other device is made for continues water quality measurement, this means that the device has to be waterproof and it should work autonomously. No LCD screen will be connected to this device, sensor data is sent directly to the cloud. Figure 2 depicts a prototype of the device.

4.3 Online interface

The online interface displays the data that the device has sent to server. Using the time range selector, it is possible to monitor and compare water quality parameters over time. The map shows the location of where the device was used to measure water quality. The source code of the program can be found online[5]. Figure 3 shows a screenshot of how the interface looks like.

[4]http://wiki.seeedstudio.com/LinkIt_ONE/
[5]https://github.com/aoelen/compteur-deau

Figure 2: Prototype of autonomous second iteration device

4.4 Water quality data

The first iteration device did collect data from a well in Burkina Faso. The second iteration device has not been shipped to rural Africa, but has been tested in The Netherlands. This device is used to determine the quality of water samples that were collected at multiple locations in rural Africa. The collected data is publicly available, via: [11]. For the first iteration device that was tested in Burkina Faso, all measured values were within the safety range. However, some water samples that were tested using the second iteration device, did have a pH value that was below the EPA guideline (below pH 6.5).

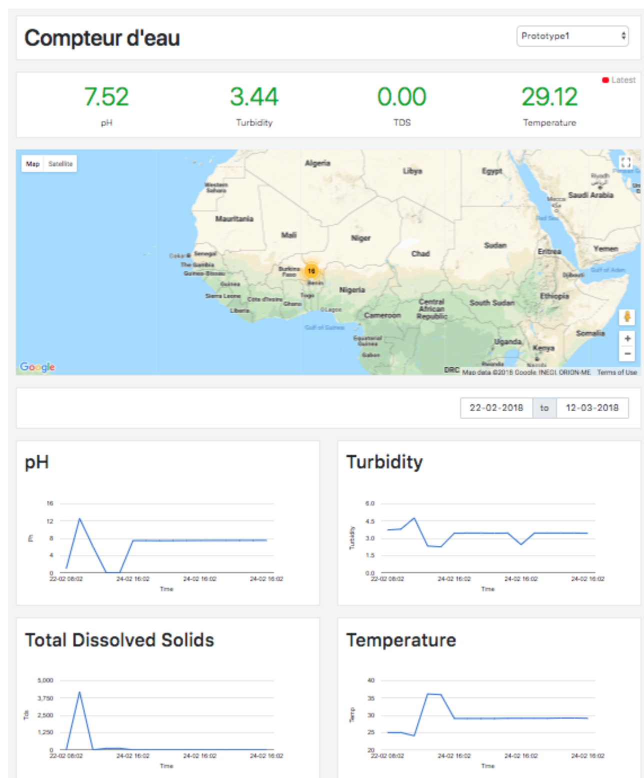

Figure 3: Online interface screenshot

5 DISCUSSION

This research is still work in progress. We expect to add more sensors in a later stage. Some hardware changes will be made to make the device more robust, and to make it better suitable for monitoring over a longer period of time. Additionally, a more detailed evaluation of the design decisions will be added.

5.1 Device usage

The first prototype has been shipped a rural Africa. The device was used by a researcher to measure the water quality at a certain location. After the researcher left, the device was given as a present to the locals. The device could have been used by them, to test the quality of different water sources. However, we did not receive any data from the device, which is an indication that the device is not used anymore. Therefore, one can question whether the water quality on demand use case, is a realistic scenario. In the end, such a device can never give a definitive result about whether the water is drinkable or not. This means that using the device on demand is less interesting to locals. The device is still useful for monitoring water quality over a longer period of time. The device in this scenario works autonomously, and therefore the previously described difficulty does not apply.

5.2 Sustainability

As has been described in the related literature section, sustainability of ICT4D projects is often used as benchmark to measure project success. A full sustainability study is out of scope for this research, however since sustainability is a crucial success factor of ICT4D projects we will discuss some aspects of this subject. Both the hardware and software of the device are open-source. Open-source for ICT4D projects has multiple advantages. With the respect to the hardware, the advantage is that parts can be replaced with other (similar) hardware without the help of the product developers. This is useful in multiple situations, e.g. if certain components break or if someone wants to extent the system. For some sensors a BNC connector has been used. This means that when a sensor probe stops working, it is possible to replace this probe by a sensor with the same BNC connection. Since this connection is a common standard, no internal parts need to be replaced. Additionally, the open-source software also ensures that the system can be expanded or adjusted by any stakeholder. In the end, by using and providing open-source hardware and software, we ensure that the original device developers do not have an crucial role for system operation. This benefits the overall sustainability of the water quality measuring device.

5.3 Future work

Only the first iteration device has been shipped to rural Africa. In order to ensure that the device is useful and capable for long-term operation, more devices should be tested in rural areas. Future research could focus on the actual deployment of the water quality measuring device. The feedback from stakeholders and the collected sensor data from the device, can be used to evaluate the device and to improve the overall system design.

In this research, we focused on using low-cost sensors to measure and monitor parameters specific to water quality. Low-cost sensor kits can be useful for other applications in the ICT4D context as well. For example, it is possible to develop low-cost weather stations using a similar setup as presented in this research. The sensors would be different, but many of the requirements and design options are the same. Another interesting research topic would be reusing old computer hardware. For example, computers have multiple sensors for measuring temperature, research could focus on how to reuse such sensors in similar projects.

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A LIST OF WATER QUALITY PARAMETERS

Parameter	**Description**	**Drinking water standard**	**Reference**
Total Dissolved Solids (TDS)	Parameter to measure the total amount of dissolved solids. A higher TDS might be an indication of pollution in the water.	<600 mg/l	WHO [4]
Dissolved oxygen (DO)	The amount of oxygen that is dissolved in the water. Low levels of dissolved oxygen can be due to high water temperatures or can be indicative for bacteria in the water.	No guideline	EPA[6]
Oxidation Reduction Potential (ORP)	The ability of water to either accept or release electrons. Bacteria are killed by increasing the ORP level.	No guideline	NSW[7]; EPA [7]
pH	Measure to determine whether the water is acidic (pH <7) or basic (pH >7). Water with a low pH contains elevated amounts of toxic metals.	6.5<pH<8.5	EPA[8]
Temperature	High water temperatures can cause the growth of microorganisms and can effect the taste and smell of the water.	No guideline	WHO [4]
Turbidity	Measures suspended particles in the water. The more particles, the more change of microorganisms in the water (which can be attached to the particles).	<5 NTU	WHO [4]