

Requirements collection for the design and development of a pervasive water quality monitoring photonic device

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ABSTRACT

In this paper we present the process of eliciting requirements for the a highly sensitive pervasive water monitoring photonic device, ranging from the review of the state of the art, to the design and conduction of surveys among key stakeholders (both internal to the project and external ones) who take interest in water quality monitoring, eventually leading to the elicitation of requirements that will drive the photonic device design and development. The photonic device will be developed in the context of the EU WaterSpy project.

CCS Concepts

• **Hardware** → **Emerging technologies** → **Emerging optical and photonic technologies**

Keywords

Water quality analysis; photonic device; requirements collection; user survey.

1. INTRODUCTION

Microbiology of drinking water has for more than 100 years been dominated by a conservative approach caused by a limited understanding of the indigenous bacterial flora, its function and related processes in treatment and distribution systems. This was mainly due to the lack of sensitive, fast and realistic methods to detect and quantify both the indigenous microbial cells and the presence of relevant pathogens. For the past time, routine monitoring and hygiene assessment focused on the detection of (1) cultivable heterotrophic microbes as a measure of the general microbiological quality of water, and (2) the detection of indicators for faecal pollution using plating methods. This is clearly evidenced by the current EC legislation, which requires the measurement of only three microbiological parameters, namely heterotrophic plate counts (HPC) and the two bacterial indicators

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PETRA '17, June 21-23, 2017, Island of Rhodes, Greece

© 2017 ACM. ISBN 978-1-4503-5227-7/17/06...\$15.00

DOI: <http://dx.doi.org/10.1145/3056540.3076203>

Escherichia coli and *Enterococcus* spp. This situation is similar to the rest of Europe and other industrialized countries.

There are significantly higher numbers of microbial cells in drinking water than what can be cultured on synthetic growth media. Total bacterial cell concentrations (determined for example with microscopy) are normally not considered during drinking water treatment as either design, operative or legislative parameter. A proper understanding of microbial survival and growth during drinking water treatment and distribution starts with the ability to quantify all the microorganisms accurately and rapidly. Some 90–99%, or even more, of the bacterial cells detected in aqueous and terrestrial environments cannot be cultivated in the laboratory with the methods presently used. This huge discrepancy between cultivable and total cell counts has been known for a considerable time and is commonly referred to as “the great plate count anomaly”. This raises the question of the viability of the fraction of non-cultivable bacterial cells.

In this context, the European Project WaterSpy aims at answering to the aforementioned limitations through the development of a novel, compact, cost-effective photonic device, operating in the spectral range of 6-10 μm and suitable for pervasive water quality sensing. The approach is based on the following key features: (i) The development of advanced QCL sources coupled with innovative, fibre-coupled, fast and sensitive, HOT photodetectors, in order to detect the fingerprint regions of the selected analytes of high priority in freshwater; (ii) The use of ATR spectroscopy techniques to maximize the SNR, but avoiding any long sample preparation procedure, such as pre-incubation; (iii) Use of adapted light modulation, detection and signal processing concept supporting highest sensitivity and specificity levels; (iv) Use of molecular recognition elements (MREs) of high specificity for binding on the surface the target bacteria in order to maximize SNR and bind even the single bacteria of the targeted strains; (v) Use of a novel sample pre-concentration technique, based on ultrasounds; (vi) The integration of the photonic sensors into a portable device used for large area water quality sensing.

The aim of this paper is to present the early stages of the process of eliciting requirements for the above described photonic device, ranging from the review of the state of the art, to the design and conduction of surveys among key stakeholders (both internal to the project and external ones) who take interest in water quality monitoring, eventually leading to the elicitation of requirements that will drive the photonic device design and development.

In this context the remainder of this paper is structured as follows: In Section 2 we present the key findings of a review of the state of the art in water quality monitoring methods, followed by a brief

presentation of the innovation potential of the high sensitivity portable photonic device to be developed in the context of WaterSpy. Section 3 presents the end-user survey process starting from the identification of target users and stakeholders, and moving on to the survey design and the analysis of results; this process drives the collection of requirements, which are briefly described in Section 4. Finally, Section 5 concludes the paper.

2. KEY FEATURES OF EXISTING WATER QUALITY MONITORING APPROACHES

A wide variety of instrumentations, methods and technologies have been developed for water quality monitoring and management (e.g. [1]-[5]). The methods can be generally grouped into three categories:

1. Methods that are capable of detecting chemical contaminants in the water (e.g. enzyme-based detection and gas chromatography)
2. Methods and technologies for detecting organic pollution in water samples such as bacteria (e.g. immunoassays, bio-optoelectronic sensor systems)
3. Concentration methods able to detect biological contaminants from water volumes (e.g. Hollow Fiber Ultrafiltration and Hydroxyapatite Whole Cell Capture)

A detailed presentation of the methods of each category is out of the scope of this paper. However, deriving a summary of the overall key features of these commercially available water quality early warning systems (EWSs) can help reveal the innovation potential of a new high sensitivity portable photonic device for pervasive water quality analysis, like the one to be developed in WaterSpy:

Parameters and sensitivity: Some of the existing EWSs can detect and quantify one specific toxic chemical, such as Arsenic, Cyanide, Mercury, while some can detect the existence of a group of toxins or harmful contaminants in water. The design objective of an EWS is to target contaminants and toxins at detection limits close to or below the maximum acceptable concentrations in drinkable water. A low detection limit of an EWS is also associated with high sensitivity as well as low false negative rates/miss-detection rates.

Accuracy (false positive/false alarm) and repeatability (consistency): Third party verification study is considered the most accredited protocol to evaluate the accuracy and consistency of the detection results.

Response time: EWSs using technologies such as colorimetry, IR, fluorescence, x-ray and Raman spectroscopy usually complete one sample analysis in 5-30 minutes. A gas/vapor detector using microchip surface acoustic wave technology (HAZMATCADTM) also claimed a typical time of less than 60 seconds to alarm, which may not be suitable for direct water sample analysis. The response time of the EWSs using bioassays and immunoassays, such as enzymes, organisms, ELISA/ELFA, varies from a few minutes to a couple of hours. Overall the response time of an EWS is determined by the applied analytical process, data processing process, sampling process and washing/calibration process. The development of an EMS always targets fast response time in order to justify its value proposition to save the crucial time in response to any adverse water quality incident.

Instrumentation: Some EWSs have realized full automation which can be used as continuous monitoring system. While some EMSs are compact and battery powered which can be easily transported and operated as a portable system.

Water sample requirements: Most EWSs using bioassays and immunoassays are not suitable for chlorinated water in drinking water distribution system or finished water in the treated plant. Also, in order to realize certain detection limits and remove the interfering particles (turbidity), pre-concentration and filtration of the water sample are commonly needed in sampling process before entering the analytical process. The development of an EMS should aim at minimize the time and efforts needed in the sampling process, which makes it easier to realize full automation and portability.

Operation and maintenance: The operation of the EWS instrument all requires specific technical training at various levels. Since the WaterSpy's end users are primarily positioned to be water utility operators, researchers, and engineering service providers, the technical training will be straightforward. The maintenance of EMSs using technologies such as colorimetry, IR, fluorescence, x-ray and Raman spectroscopy are generally less demanding than those using bioassays and immunoassays.

A review of the state of the art makes clear that optical devices which measure the absorption, diffraction, emission of beam of light are quite suitable to be used in an EWS for field water analysis or continuous monitoring. Therefore, the WaterSpy system is going to exploit the innovative optical devices to be developed among the consortium partners, and introduce the following innovation potentials (IPs) in the photonic water analysis:

IP1: *A new photonic detection array containing the integration of a light source, a detector, a sample preparation configuration, and a data acquisition component specifically developed to measure the optical properties of the water sample beyond the 2 μ m range of the infrared spectrum.*

The new photonic detection array will feature compact layout and low power consumption. Each component will be easy to replace and repair if necessary. The whole optical detection process will be completed in a few seconds with good consistency. The analytical data will be output to a computer by a USB or serial port connection. The detection results will be easy to interpret and output in Excel/Matlab for further data analysis and reporting process. The user interface will provide several useful operation functions, such as (1) check the status the light source (if the intensity is strong and consistent); (2) establish baselines and take reference; (3) check if the water sample is well prepared for optical analysis (turbidity and air bubbles may interfere with the signature spectra); (4) set up key parameters for data acquisition (integration time, scan average, target wavelengths et al).

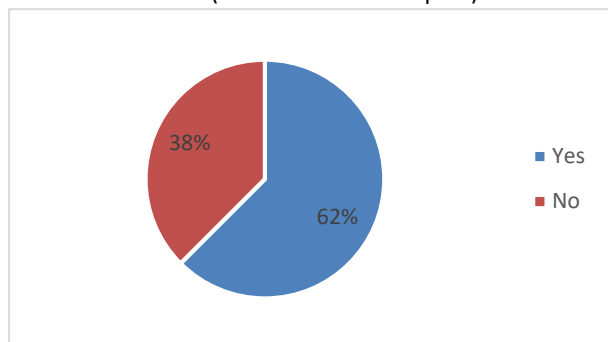
IP2: *A new micro fluidic sample preparation configuration to get a raw water sample ready for the photonic analysis especially in search for the existence of the bacterial cells.*

The WaterSpy system will apply a novel micro fluidics ATR configuration by ultrasound based sample pre-concentration mechanism. Beside WaterSpy system, this sample preparation configuration can also be integrated into other spectroscopy or colorimetry devices. The WaterSpy sample preparation configuration will be able to prepare both chlorinated water and environment water ready for the optical analysis.

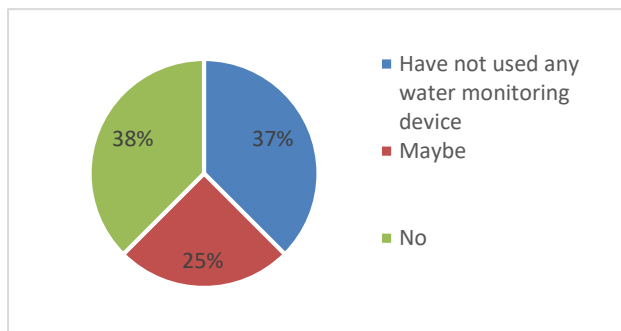
IP3: A new database of the detectable spectral signatures of

target bacterial beyond the 2 μ m range of the infrared spectrum.

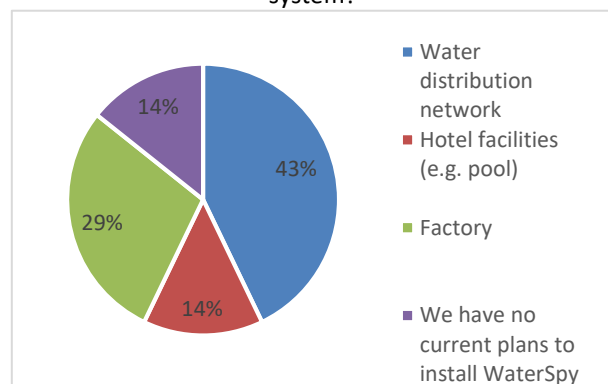
Do you make use of any other water quality monitoring device (now or in the near past)?



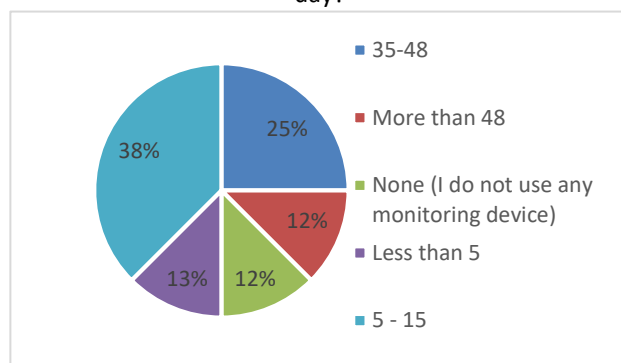
Did you face any problems while using the water analysis device?



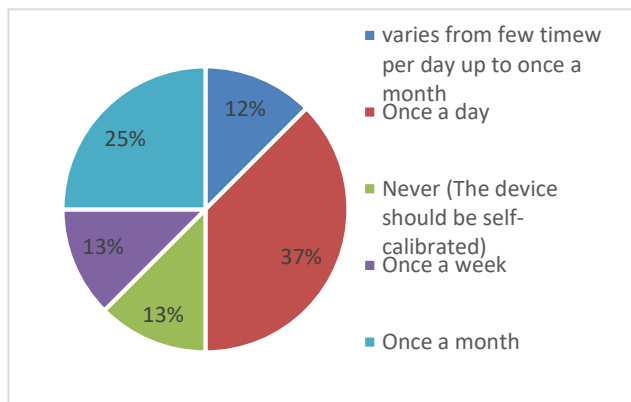
Where do you plan to install the WaterSpy monitoring system?



How many water samples do you currently analyze per day?



If the device requires calibration, how often can you be at the installation site?



In which of the following pollutant factors are you interested in?

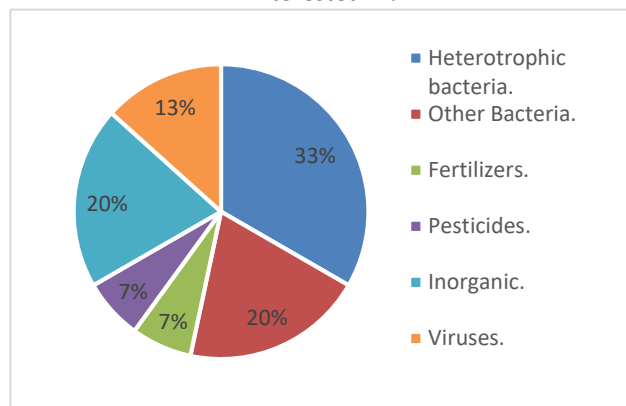


Figure 1. Survey results on operational characteristics.

The challenge is how to extract the signature spectral of the target bacterial with the interferences of the strong IR absorption of the water itself. Overall this database will provide a good reference to enforce the technology concept of the WaterSpy system.

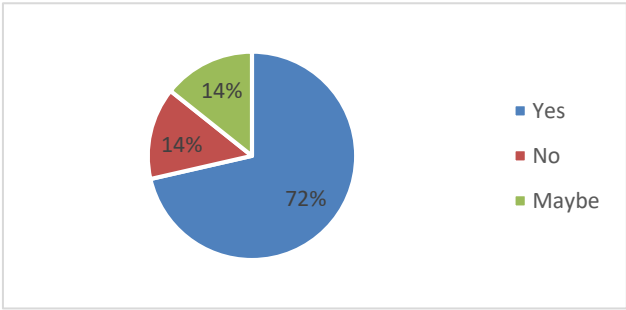
IP4: A new IR spectral analysis algorithm specifically developed to analyze beyond the 2 μ m range of the infrared spectrum and identify the existence of the target bacterial cells.

WaterSpy analyzer chooses to utilize the spectral information beyond the 2 μ m range of the infrared spectrum, which hasn't been

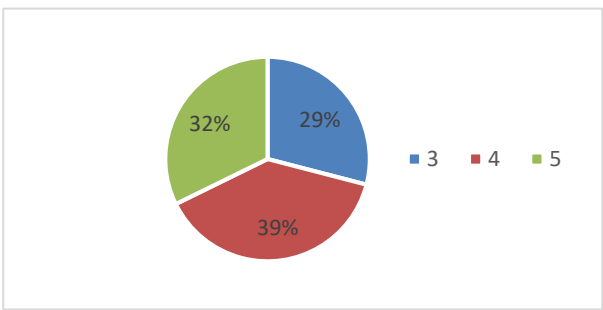
used elsewhere to detect the existence of bacterial cells in water sample, specifically as E. coli, Salmonella, and P. aeruginosa. The target detection limit of WaterSpy is no existence in 250mL water (European regulations for drinkable water).

The biggest challenge for IR spectral analysis of water samples is that the water itself absorbs strongly in IR region, which leads to significant background noise and much reduced detectable intensity in the IR region. Also, the WaterSpy system is targeting bacterial cells with zero tolerance in 250 mL drinkable water. The

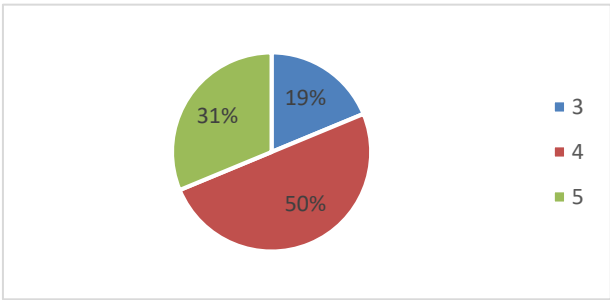
Would a self-diagnostics add-on be worthy of a higher price for you?



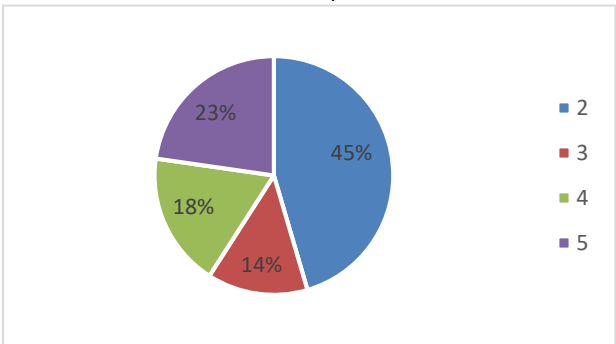
Electronics long lifetime is more important than upgradability (1: strongly disagree, 5: strongly agree)



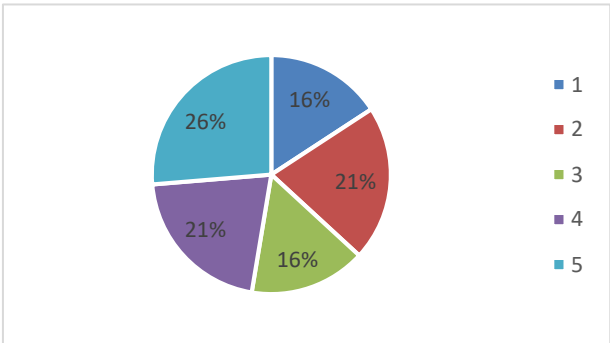
I would prefer a modular design.



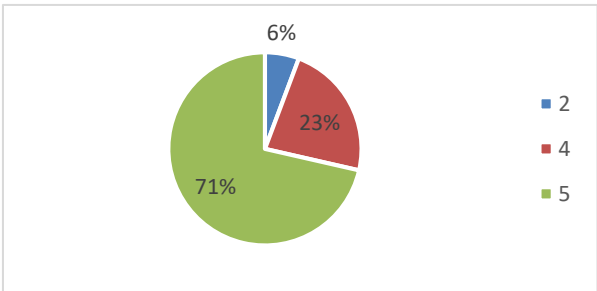
Low acquisition cost is more important than self-calibration capabilities.



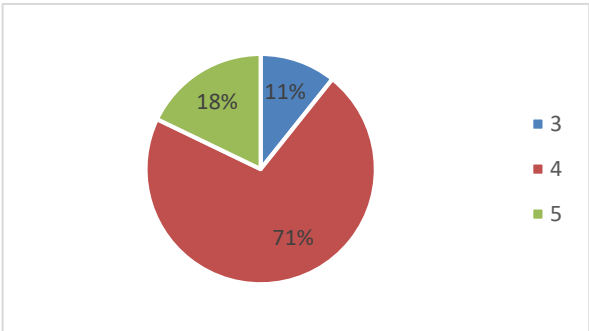
Computational times are more important than high detection accuracy.



Being able to repair the device myself is important.



Low acquisition cost is more important than maintenance cost.



Being able to move the device easily (portability) is important.

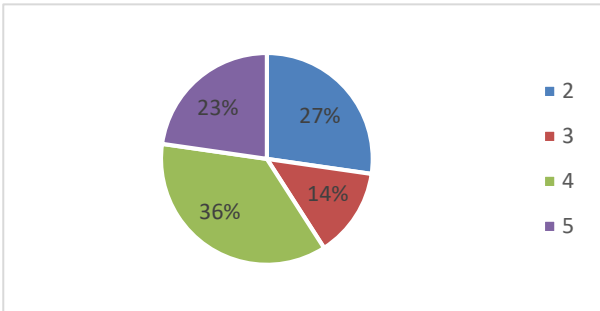


Figure 2. Survey results on user preferences

algorithms to be functional in the WaterSpy system will represent the top of this kind in spectral background subtraction, signal enhancement, classification and identification. The WaterSpy

Figure 3. Survey results on user preferences

algorithms will play a very important role to realize the system's high detection rate, sensitivity and low false alarm rate. These algorithms can also be tuned to analyze optical data in other spectral regions and other types of spectral data, such as x-ray, UV-Vis, Mass, Raman, Fluorescence and etc.

3. SURVEYING TARGET STAKEHOLDERS FOR REQUIREMENTS ELICITATION

The requirements elicitation process is driven by both an internal survey among the partners of the WaterSpy project as well as an external survey of users and stakeholders interested in water quality monitoring. Hereby we describe the different steps of this process starting from the identification of potential target users and stakeholders until the analysis of the survey's results.

3.1 Identification and categorization of target users and stakeholder

The most prominent target users of a water quality monitoring device are mainly governmental organizations and authorities responsible for water quality measurements, as well as water utilities and network managers. Important end-users also include research organizations in the fields of environment and water in particular. Additional stakeholders include NGOs, policy makers and private organizations developing water quality monitoring instrumentation. The different points of view for these and other possible categories will be examined, in order to group the WaterSpy stakeholders and collect their requirements.

A detailed search for potentially interested stakeholders has been made, followed by a clustering into groups according to their type (and therefore perspectives, needs and point of views). Three main groups are identified:

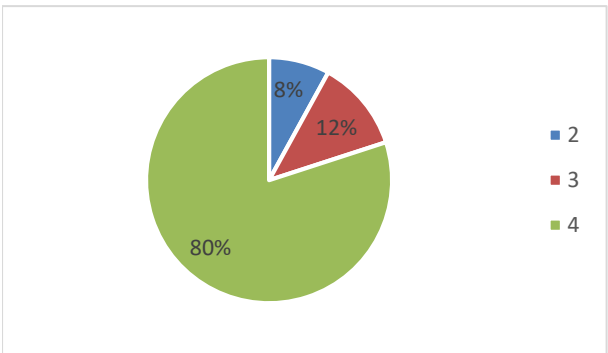
- i) Private companies that are interested in water quality, monitoring and management.
- ii) Non-profit organizations active in the area of water management. Charity organizations also fall under this umbrella.
- iii) Finally, the third group focuses on international organizations in water technologies.

3.2 Survey design and results

A twofold approach was followed with respect to gauging the needs and expectations of interested stakeholders, which included two different target groups: internal and external users:

1. WaterSpy project partners (internal users). In this case, a questionnaire was distributed. Partners were eligible to provide free text answers and further indications regarding the WaterSpy monitoring platform. The main goal was the identification of various factors that could affect the project's

The encryption of test results is important.



development and have not been identified in the proposal's related documents.

2. All possible users, except WaterSpy partners (external users). In this case a compact survey type form was distributed. The survey was based on the previously distributed questionnaire and the collected answers.

The user defined categories defined in Section 3.1 applied to both internal users' questionnaire and external users' survey.

In our surveys, gathered results were formatted appropriately in order to exploit pivot table processing techniques. In data processing, a pivot table is a data summarization tool found in data visualization programs such as spreadsheets or business intelligence software. Among other functions, a pivot table can automatically sort, count, total or average the data stored in one table or spreadsheet, displaying the results in a second table showing the summarized data. Pivot tables are also useful for quickly creating unweighted cross tabulations. The user sets up and changes the summary's structure by dragging and dropping fields graphically. This "rotation" or pivoting of the summary table gives the concept its name. Pivot tables can be seen as a simplification of the more complete and complex online analytical processing concepts (OLAP).

The external survey results are presented in detail in Figures 1-4.

4. REQUIREMENTS COLLECTION

Analyzing the results of the above described surveys and taking into consideration the innovation potential pinpointed after a review of the existing solutions for water quality monitoring, we have concluded to a basic set of requirements that will drive the design and developments in the WaterSpy project:

Req#1: The WaterSpy device should be portable

This requirement means that the WaterSpy device should be designed in a way to allow portability at different regions. Portability does not necessarily mean that the device should be handheld. Instead, it could be moved through other transportation means, such as vehicles. As a result, size and weight restrictions, regarding the WaterSpy device, are set. These constraints are in the line of the capacity of a vehicle to carry out the device.

Req#2: The WaterSpy device should analyze mainly organic pollutants

End users are mainly interested in detecting organic pollution.

WiFi would be more convenient than Ethernet

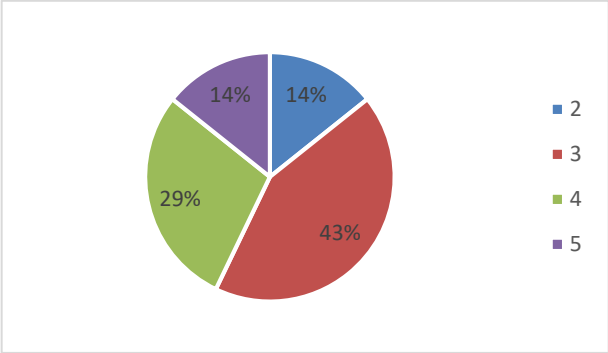


Figure 4. Survey results on connectivity and encryption preferences.

Organic pollution means different type of bacteria and especially enterococci bacteria and *E. coli* (*Escherichia coli*). Other type of organic pollution are also of interest to end users, such as detection of viruses into the water. The device also can detect other type of pollution, such as fertilizers and pesticides.

Req#3: The WaterSpy device should be reliable, reaching high detection accuracy rates, while computational efficiency is a less important demand

End users want a very reliable device of high detection accuracy. Smaller interest in computational efficiency does not mean that WaterSpy processing time should be excessively slow of course. Water samples should be processed within acceptable time frames and with high detection accuracy. Time intervals of half day are acceptable. State-of-the-art methods for detecting organic pollutants in the water need ~24 hours for culture and final detection.

Req#4: The cost of the WaterSpy device is an important factor of the project success, more so than device automation capabilities

There is a trade-off between the cost of a device and the respective automation capabilities. The more automated a device is, the more expensive it becomes. End-users first rank the device cost compared to automated capabilities. This means that configuration of some parameters of the device can be manually set and controlled so that the overall device cost is affordable. Automated procedures are welcome but not the expense of a significant increase of the price of a device.

Req#5: The WaterSpy device should be designed in a modular way, allowing additional plug-ins to be added to the system in an easy way

The WaterSpy device should be modularly designed to allow additional plug—ins to be added to the system. This configurable development stimulates the device to be active in future for other types of pollution such as virus, different density of organic materials, non-organic pollutants like fertilizers and pesticides. Modular and configurable design will greatly promote exploitation of the platform under different application domains and user demands regarding pollution detection.

Req#6: The WaterSpy device should allow networking capabilities

The device should be networked to support remote control from end-users. Among all the different networking capabilities, the WiFi is the most important. Remote control of the device allows easy manipulation in regions of hazardous natural conditions and difficulties in accessibility.

Req#7: The WaterSpy device should be equipped with signal processing and data analysis algorithms

These algorithms should be designed in a way to increase detection accuracy and increase the complexity of the system. Signal processing algorithms reduces possible noise in the detection and filters the results to improve device performance. The device should be able to store additional metadata information such as environmental data that are useful for end-users to better interpret the results of the analysis. Data encryption policies are also welcome as additional add-ons to the device.

Req#8: Simple configuration and maintenance procedures

The architecture of WaterSpy device should be designed in a way to allow simple configuration and maintenance procedures. This

way, end-users is capable of providing device configuration and maintenance without enforcing for subtracting. Most of the configuration and maintenance produces can be taken by the end users themselves.

Req#9: The WaterSpy device should be able to get data at a daily basis

The device should be able to capture many samples per day. Without a daily operation, water quality cannot be properly monitored and the outcomes derived may be less accurate.

Req#10: Compliance to existing standards are of great importance for the end users

The device should be compliant with existing standards. This is of great importance for the end-users in order to support a real exploitation of the final WaterSpy device.

5. CONCLUSIONS

In this paper we presented the requirements elicitation process for a pervasive water monitoring photonic device to be developed in the context of the EU WaterSpy project. At first possible target groups had to be defined. In total there three main groups were identified: companies, NPOs, and international organizations. Each of the suggested groups could have different requirements regarding operational standards. Questionnaire-based surveys were conducted both within and beyond the project partners. Various areas regarding the operational conditions, possible limitations, system's outputs and connectivity were investigated. The surveys, along with a careful review of the state of the art vis-à-vis the innovation potential of a new photonic water monitoring photonic device, like the one in WaterSpy, helped identify the basic user requirements which will, in turn, drive the design and development processes to follow.

6. ACKNOWLEDGMENTS

This work has been funded by the European Commission in the context of the WaterSpy project under Grant Agreement no. 731778. The authors would like to thank all the project partners for their collaboration and all external stakeholders who participated in the external survey.

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