BTO 2015.035 | May 2015

BTO report

Smartphone-Based Chemical and Microbiological Analyses for Citizen Science Applications in the Water Sector

Watercycle Research Institute

BTO

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BTO 2015.035 | May 2015

Project number
400695/042/003

Project manager
Jos Frijns

Client
BTO - Verkennend Onderzoek

Quality Assurance
Gertjan Medema

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Sent to
CO

Year of publishing
2015

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Keywords
Smartphones, Citizen Science, Chemical and Microbiological Analyses

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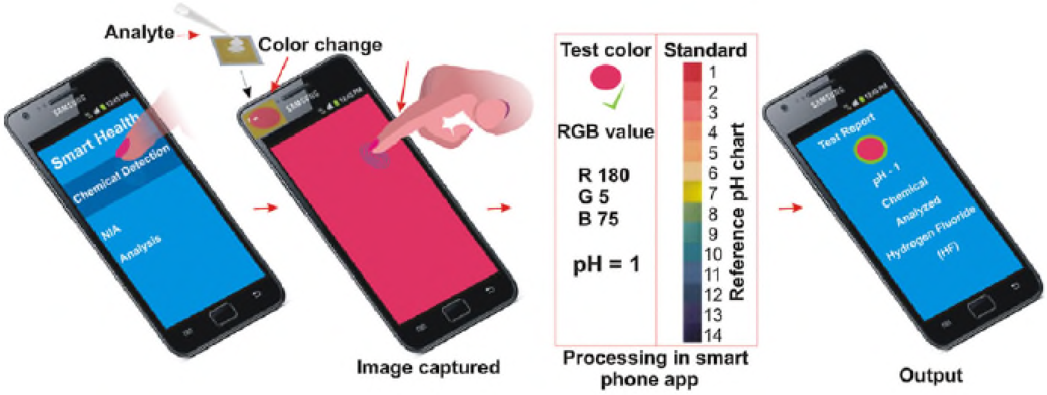
BTO *Managementsamenvatting*

Verkenning Citizen Science: overzicht van de mogelijkheden voor burgers om waterkwaliteitsgegevens te verzamelen met hun smartphone

Auteur(s) Dr. Auke Jisk Kronemeijer

In het afgelopen decennium zijn smartphones wijdverspreid geraakt in de samenleving. Recente ontwikkelingen bieden perspectief om burgers zelf met behulp van een smartphone chemische en microbiologische parameters in water te laten bepalen. De wetenschappelijke ontwikkelingen op dit gebied zijn samengevat: er blijkt een zeer grote hoeveelheid aan mogelijkheden in de literatuur te zijn beschreven waarmee burgers door middel van smartphones waterkwaliteit-gerelateerde informatie kunnen genereren. Op basis van deze snelle ontwikkelingen wordt de watersector aangespoord om de waarde en mogelijkheden om burgers te betrekken bij het verzamelen van informatie middels ‘citizen science’-arrangementen te onderzoeken. Door de potentieel voordelige én nadelige gevolgen van deze nieuwe vormen van kennisontwikkeling en participatie te inventariseren, kan de watersector zich goed voorbereiden op meer betrokken burgers / consumenten in de toekomst.



Colorimetrische detectie van de pH met gebruik van papierstrips en de camera van een smartphone

Belang: mogelijkheden voor Citizen Science en metingen door burgers groeien in de toekomst

Ook waterbedrijven merken dat “de burger” steeds meer een actieve burger is geworden die zich op tal van manieren inzet, meedoet of -denkt en/of - al dan niet via social media – van zich laat horen. In het Verkennend Onderzoek i-Water wordt daarom een conceptuele en methodologische verkenning gemaakt naar de betekenis van die veranderende houding van de burger en naar de mogelijkheden die drinkwaterbedrijven hebben om een verbinding met de burger te maken door deze te betrekken bij het vergaren, co-creëren en delen van kennis: citizen science. Een mogelijkheid is de optie om burgers met hun smartphones data te laten verzamelen, maar daarvoor is een beter beeld van de (on)mogelijkheden nodig.

Aanpak: samenvatting van wetenschappelijk literatuur

De tot nu toe bekende wetenschappelijke literatuur op het gebied van smartphone-gebaseerde waterkwaliteitsbepalingen is geanalyseerd en samengevat.

Resultaten: overzicht van de (on)mogelijkheden

Een voordeel van inzet van smartphones (eventueel met een toegevoegd apparaatje, een add-on) voor metingen door burgers is dat burgers op veel verschillende plekken kunnen meten en hun resultaten naar een centraal punt zenden. Tot de mogelijkheden behoren colorimetrische bepalingen, maar ook fluorescentie, lichtverstrooiing en elektrochemische bepalingen.

Op korte termijn is het bijvoorbeeld mogelijk dat burgers via een smartphone meetresultaten insturen van eenvoudige, met indicatorpapier uitgevoerde, chemische en microbiologische parameters, zoals pH, hardheid en de aanwezigheid van nutriënten. Toepassing voor detectie van specifieke stoffen of micro-organismen op deze manier wordt, net als andere detectiemethoden voor de drinkwatersector gehinderd door de behoefte heel lage concentraties te kunnen meten.

Het gebruik van add-ons, apparaatjes die worden gekoppeld aan de smartphone, behoort in de wat verdere toekomst tot de mogelijkheden. Het rapport geeft een overzicht van meer dan 20 toepassingsmogelijkheden. Daarvan zien we voor de colorimetrische bepalingen met de smartphone, bijvoorbeeld van hardheid, nu al potentiele toepassingen voor het betrekken van de burgers bij het waterbedrijf.

Implementatie: voorbereid zijn op de toekomst

Het rapport spoort waterbedrijven aan om voorbereid te zijn op de toekomst. Binnen het Verkennend Onderzoek van het BTO zal een citizen-science onderzoek met smartphone toepassing worden uitgewerkt (i-Water) om dit te verkennen, op basis van dit huidige literatuuroverzicht en andere activiteiten.

Rapport

Dit onderzoek is beschreven in rapport *Smartphone-Based Chemical and Microbiological Analyses for Citizen Science Applications in the Water Sector* (BTO-2015.035).

Jaar van publicatie
2015

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Contents

Contents 2

1 Introduction 3

2 Use of Intrinsic Smartphone Capabilities 4
2.1 Colorimetric Analyses 4
2.2 Potential for Paper-Analyses 5
2.3 Conclusions 6

3 Add-on Based Measurements 7
3.1 Colorimetric detection 7
3.2 Fluorescence 9
3.3 Light Scattering 10
3.4 Electrochemical 10
3.5 Conclusion 11

4 (Semi-)Commercial Water Quality-related Initiatives 12
4.1 La Motte Insta-Link App 12
4.2 KEM-TEK Water Tester App 12
4.3 Waterbot 13
4.4 Sensorex SAM-1 Aquameter + App 13
4.5 Sensorcon Sensordrone + App 13

5 Potential for a Pilot Concept in the Dutch Water Sector 14

6 References 16

1 Introduction

The scientific added value of engaging citizens to acquire data is the increased spatial coverage and temporal frequency of data that can be achieved. Successful citizen science-based monitoring campaigns have been demonstrated, e.g. numerous initiatives of natural biodiversity monitoring (resulting in subsequent policy making), as well as air quality monitoring and environmental algae bloom monitoring [1-3]. Other initiatives have been started to generate systems yielding distributed information using simple measurement equipment such as the CITCLOPS project aiming for seawater quality monitoring [4]. Citizen science projects will be most successful when they have a low threshold for citizens to join and perform measurements and that information that is generated by the citizens is of substantial interest for these citizens as well [5]. The possibility to connect these goals is closely related to the availability of (easy) measurement equipment at the disposal of citizens.

To this end cell-phones are becoming interesting instruments to use, as these days most citizen possess and use a (smart)phone. These instruments are currently technologically very advanced such that GPS, wireless connectivity, imaging functionalities and significant calculation power is at the easy disposal of citizens. With the (relatively simple) development of Apps for smartphones, the power of these phones is being explored for applications other than the originally intended purposes of these smartphones. It has therefore been of recent interest to start using smartphones for the analyses of chemical and microbiological parameters in aqueous media. Application areas that can be envisioned are very diverse with the determination of chemical contaminants, allergens, viruses and bacteria in for example water, food, blood or urine. For the water sector in general, applications in environmental surface water monitoring or produced drinking water can be envisioned.

Technological developments of the use of smartphones for the detection of chemical and microbiological contaminations in water can be divided in two categories by (i) the use of intrinsic functionalities of present-day smartphones or (ii) the use of compact, light-weight attachments to cell-phones to add specifically desired functionalities to the basic commercial platform (Add-ons) and utilizing the synergies of the add-on and the underlying smartphone platform functionalities.

2 Use of Intrinsic Smartphone Capabilities

The intrinsic capabilities of smartphones that can be employed for the analysis of chemical and microbiological contaminations in drinking water mainly concern (i) its computational power to perform chemometric analyses and (ii) the use of the built-in camera of the phones. External analyses are necessary to provide the chemical and microbiological sensitivity. These analyses can in principle be anything when using the citizen scientist as objective observer, with the smartphone providing computational power to convert the 'observations' into meaningful readings. (e.g. applied in available environmental monitoring application Creek Watch. The Creek Watch app uses four data inputs to make a rough estimate of the status of a water body: (i) Amount of water: empty, some, or full; (ii) Rate of flow: still, slow, fast; (iii) Amount of trash: none, some, a lot; (iv) A picture of the water). However, for more quantitative determination of more detailed chemical and microbiological water quality parameters, the sensitivity of this approach is generally not high enough. This could be alleviated by using specific on-line sensors and using the smartphone simply as an user-friendly platform for easy measurements, communication and computation. For quantitative readings the built-in camera can be used for optical readings. The necessary external analysis assay that can be employed in combination with smartphones would therefore need to be based on light emission or absorption upon the presence of the target analyte, e.g. by the analyte itself or a chemical reaction with an indicator.

2.1 Colorimetric Analyses

The most demonstrated application is the use of external colorimetric assays that are read with the camera of the smartphones. Colorimetry / spectrophotometry is a method to determine the concentration of a chemical by measuring the amount of light that is absorbed/reflected from a medium at specific wavelengths specific for the compounds of interest. The amount of light that is absorbed is directly related to the amount of molecules that are present, *i.e.* the concentration of the analyte in the medium. The concepts can be extended to more complex mixture of chemical determining a more complete absorption spectrum (over a wavelength range) providing a measurement of the 'colour' of the sample as e.g. perceived by the human eye.

Often analytical protocols to determine specific chemicals in media by colorimetry rely on indicator chemicals that significantly change colour upon binding to, or reaction with, the analyte of interest. By comparing the background absorption/reflection with the generated absorption upon addition of the indicator chemical, the concentration of the analyte of interest can be determined. With properly developed assays smartphones can easily be used for the detection of the colour change or change in light scattering of the analysis strips upon the presence of the analyte of interest. The camera, image analysis and computation capabilities are used to decipher the change in light intensities to meaningful measurement readings. In this adaptation of the use of smartphones, the larger part of the innovation of analyses is focused on the development and incorporation of new (colour) assay protocols for analytes of interest in mass-producible strips such that citizen scientist can be easily equipped with the analyses. The potential for the above-mentioned approach has received much attention for health diagnostics applications, as reviewed by Whitesides et al. [6].

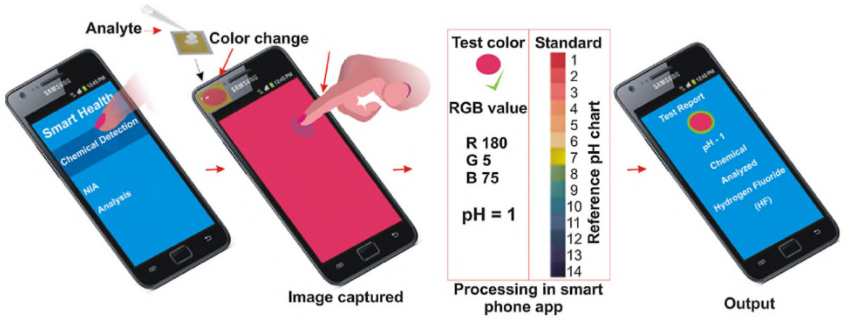


FIGURE 1: CONCEPT OF COLORIMETRIC DETECTION (OF PH) USING AN EXTERNAL PAPERSTRIP-BASED ANALYSIS IN COMBINATION WITH THE CAMERA OF AN SMARTPHONE [7].

For application in the water sector, the parameters pH and chlorine have been demonstrated by Devadhasan et al. and Shen et al. [7, 8] and Sumriddetchkajorn et al. [9], respectively, as demonstrated with add-on devices as well. The colour of analyte/indicator solutions or analyte/indicator-paperstrips are captured with smartphones, converted into colour patterns and compared with references. With this simple method, the smartphone can obtain a measurement reading. Images can either complete direct images of the samples of interest or can also contain reference materials / strips for self-referencing of the image analysis, increasing the effectiveness of the analysis. Sicard et al. have demonstrated the use of external assay, successive smartphone image-capturing and analysis into an actual citizen science concept, where the smartphone not only performs the analysis (of organophospate pesticides in this example) but also add the additional spatial information where the samples have been taken and analysed from GPS information [10].

As the described concept is universally applicable and only dependent on the availability of an proper assay for the target of interest, many different applications can be foreseen. Relevant for the water sector are developed applications for Cr(III) and Cr(VI) [11], Hg(II) [12] and metal ions /metallic salts, e.g. Fe(III), Cr(VI), Cu(II) and As(III) [13].

These types of smart-phone based analyses have been expanded into the realms of microbiological analyses as well. The potential to detect the presence of *Salmonella* has been demonstrated by Park et al. and Fronczek et al. based on antigen-binding and nucleic acid detection, respectively [14, 15]. The feasibility to detect *E. coli* in field water samples has been demonstrated by Tu et al. [16].

A very interesting opportunity within this approach is the potential for simultaneous ('multiplexed') detection of different parameters with a single analysis. This has been demonstrated by Lopez-Ruiz et al. with the simultaneous detection of pH and nitrite [17]. The development of a smartphone app for multi-analyte detection using smartphones has been described [18].

2.2 Potential for Paper-Analyses

The described concept is critically dependent on the availability of simple colorimetric assays for target analytes. In order to provide some insight in the possibilities, a limited (non-extensive) overview of possibilities from scientific literature is given in the table below, as well as an overview of a chemical analysis company (Macherey-Nagel). A broad range of (microfluidics- and/or paper-based) test-strip-based analyses are available, which has received large attention in the diagnostics community [19]. The potential to incorporate these type of assays with smart-phone based detection is very large. The potential for multiplexing is demonstrated by the availability of multiplexed analyses of water quality parameters, mostly developed for application in aquarium and pool environments.

TABLE 1: A SNAPSHOT OF PAPER-BASED ANALYSES DESCRIBED IN LITERATURE AND COMMERCIALLY AVAILABLE FROM A CHEMICAL ANALYSIS COMPANY (MACHEREY-NAGEL - [20]).

Parameter	Reference
Chemical	
Heavy Metals	[21-23]
Pesticides	[24]
Neurotoxins	[25]
Phenolic Compounds	[26]
Gold and Iron (Electrochemically Assisted)	[27]
Microbiological	
Tuberculosis Assays	[28, 29]
Multiplexed HIV -	[30]
Targets & 7 Pathogen	
Oligonucleotides	[31]
Blood Typing	

Commercially Available Analyses*
Combined pH, Total Hardness & Carbonate Hardness
Calcium
Chloride
Aluminium, Cobalt, Copper, Molybdenum, Potassium, Nickel, Silver, Tin, Total Iron, Zinc
Chromate
Arsenic
Cyanide
Ammonium
Phosphate
Nitrate, Nitrite
Sulphate, Sulphite
EDTA
Formaldehyde
Peracetic Acid
Peroxide
Quaternary NR_4^+ compounds

* MORE EXTENSIVE TEST-KITS ARE AVAILABLE FOR A TITRIMETRIC DETERMINATION OF VARIOUS WATER QUALITY PARAMETERS. MORE EXTENSIVE PROTOCOLS, CHEMICALS AND POTENTIALLY CHEMICAL ANALYTICAL EXPERTISE IS NECESSARY FOR APPLICATION IN CITIZEN SCIENCE.

2.3 Conclusions

The various different sub-components for the analysis of chemical parameters on location using an external (chemical of microbiological) assay have been demonstrated, either in separate single studies or combined within a single study. The concept opens up a plethora of possibilities, both academic and commercial, for the incorporation of colour reactions into paperstrip-based analyses. Especially, developments into multiplexed analyses seem promising. The extensive calculation power from smartphones can provide in-depth processing of multiplexed measurement readings into relevant (combined) information that otherwise would not be easy to obtain for users on location, providing an attractive perspective for citizen science initiatives in the not-too-distant future. By using the intrinsic capabilities of the smartphones – camera functionality and calculation power – the development of cross-platform apps might be more easily achievable. This will enlarge the pool of potential citizen scientists. With respect to relevance to both citizen scientists and drinking water utilities, a questions remain on the sensitivity of the available assays. Either very low concentrations or very small variations in parameters will need to be detected in order to be of relevance.

3 Add-on Based Measurements

With specific additions to standard commercially-available cell phones, interesting measurement devices have been created that can perform various measurements on-site. Progress has, for example, been made in creating generic microscopes based on smartphones [32-34]. While with microscopy generic conclusions on water quality issues and microbiological contamination might be possible, more elaborate determinations of specific water quality parameters need more specific detection principles. Additional development of apps on smartphones is of relevance to conduct more demanding calculations that can be performed based on the measurement results, an example of which can the determination of the calcification potential of water that, in itself, is a function of measurement parameters such as pH, hardness and temperature. In addition, the apps can increase the ease of use for citizens in order to render non-technical personnel capable of performing the relevant measurements. Complete concepts for citizen science based on the smartphone add-on measurement devices will generally involve various steps:

- Obtain the add-on and connect to the smartphone. Often these devices contain a sample container, possible light sources, filters, etc. In one study the add-on could be 3D-printed, which in the foreseeable future could facilitate the distribution of add-ons to citizens [35].
- Obtain and install software, an App, that will perform the necessary communication with the add-on device and perform any calculations necessary. The app will also lead the citizen through the measurement process which could involve calibration, the addition of chemicals, etc.
- Finally, the actual measurement of interest needs to be performed with the result being interpreted by the software, providing a feedback reading of interest to the person performing the measurement. In addition, the reading will need to be transmitted, via Wi-Fi or a mobile network, to a central server for additional interpretation of the (spatially-distributed) body of data generated by multiple citizen scientists. The results of the analyses will finally be communicated to relevant stakeholders that, amongst others, might be the citizen scientists once more.

For the specific measurements based on add-ons, various detection principles have been employed in order to make (quantitative) chemical and microbiological determinations.

3.1 Colorimetric detection

Smartphone-based devices that employ colorimetric detection for the analysis consist of a sample container / holder and either employ an external light source or use the (flash)light of the smartphones for illumination of the sample. The detection of the light of interest is performed by the (front or back) camera of the devices. Calibration is either to be performed just before the measurement or saved in the software. Based on the calibration the app will give the measurement reading after necessary computation.

With a specifically designed add-on in combination with various indicator chemicals (phenol red for pH, N,N-diethyl-p-phenylenediamine (DPD) for free chlorine, addition of I_2 to oxide chlorine-amines for total chlorine) Schaefer et al. demonstrated smartphone-based analysis of pH and chlorine in water [36]. In addition, based on a titration with strong acid to a specific pH end point the alkalinity of the water could be determined. Based on an identical technique, Oncescu et al. demonstrated the determination of pH in sweat and saliva for health monitoring applications, where the pH analysis has been incorporated in a miniature paper strip [37]. Another demonstration of a smartphone add-on developed for the determination of chlorine residue in water has been created by Sumriddetchkajorna et al. [38]. The analysis is based on a colour reaction with o-tolidine and subsequent image analysis of an obtained picture of a cuvette with the sample and a reference background for self-referencing the determined colour of the solution. The potential of mobile colorimetric analyses towards more specific chemical parameters is demonstrated by diagnostics applications such as e.g. the quantification of cholesterol in blood [39], and analysis of the presence of cortisol in saliva [40, 41].

More elaborate (health) diagnostic assays have been developed using add-on connected smartphones as well. Applications within this category have been driven by providing easy diagnostics for people in rural area with no easy access to hospital care. Mudanyali et al. have demonstrated lateral flow assays in connection with an appropriate app to sense the presence of target analytes in the sample for the diagnosis of diseases such as malaria and tuberculosis [42]. A second example has demonstrated the mobile analysis of enzyme-linked immunosorbent assay (ELISAs) with external light input from a second external device, *e.g.* an IPad or IPhone. Parameters that are measured are human C-reactive protein and horseradish peroxidase [43, 44]. Finally, Coskun et al. have demonstrated the feasibilty of personal allergen tests [45]. The examples demonstrate that colorimetric detection of relevant parameters in water is an application that can be foreseen in the (near-)future. Attempts have already expanded into the realms of metabolomics [46], a methodology that together with (meta)genomics is considered as promising for the efficient monitoring of water quality [47, 48].

FIGURE 2: ADD-ON SMARTPHONE-BASED MEASUREMENT DEVICES FOR THE DETERMINATION OF PH AND CHLORINE-RESIDUE IN WATER BY COLORIMETRY [36-38].

3.2 Fluorescence

Another measurement principle frequently employed in addition to colorimetric detection, is the detection of fluorescence from aqueous samples. Fluorescence is the emission of light from (chemical) compounds after these molecules have been excited by an external light source. The fluorescent emission is always at a lower energy (longer wavelength) than that is used for the excitation of the molecules. The specific intensity of fluorescence as well as the wavelength shift can be used for the identification of compounds. The general concept of smartphone-based fluorescence imaging and spectroscopy has been demonstrated by e.g. Zhu et al. and Yu et al. [49, 50]. The add-ons for measurements based on fluorescence detection are very similar to the devices developed for colorimetric detection. Critical components are the light source necessary to excite the molecules and a properly designed sample space. The camera of the phones is once more used for the detection. Some optical components such as filters or light diffusers are also applied to increase the sensitivity of the analyses.

Analyses based on fluorescence can once more be categorized in (i) imaging /counting based techniques and (ii) analyses based on fluorescent intensity correlations with the concentration of compounds. An application of (i) is the imaging of single nanoparticles and viruses by Wei et al., that, in combination with image analysis and counting algorithms, leads to quantitative determination of the presence of these entities [51]. In relation to applications in water, this type of analysis has been used by Koydemir et al. for the determination of *Giardia lamblia* cysts in water. An image is taken from a sample that is filtered and fluorescently labelled, and the amount of cysts present are counted by image analysis algorithms [52]. For category (ii) the use of a quantitative fluorescent assay for determination of the concentration of albumin analysis in urine by Coskun et. al. is an example [53]. Moreover, the quantitative determination of the presence of *E. coli* in liquid media has been realized with quantum dot-based sandwich assays by Zhu et al. [54], while *E. coli* and *Salmonella* spp. have been analysed via bio-functionalized fluorescent nanoparticles by Rajendran et al. [55]. Also, the dual detection of bacteria *E. coli* and *Salmonella* has been demonstrated by Nicolini et al. [56] Even the detection of specific DNA sequences, as mentioned becoming more and more relevant for the determination of water quality [48], has been realized using a smartphone add-on device by Lee et al., although detection is realized after extensive sample preparation amplifying the amount of DNA in the samples using convective polymerase chain reaction ((c)PCR) [57].

FIGURE 3: ADD-ON SMARTPHONE-BASED MEASUREMENT DEVICES FOR THE DETERMINATION OF MICROBIOLOGICAL PARAMETERS E. COLI, GIARDIA CYSTS AND DNA BY DETECTION OF FLUORESCENCE [52, 54, 57].

Another counting-based technique is fluorescent cytometry. (Flow) Cytometry is a methodology that is used in cell counting, cell sorting and biomarker or protein detection. By creating suspensions of objects of interest in a flow and passing these fluids along a detector the amount of objects can counted. More elaborate detection, e.g. fluorescent detection, can not only count the amount of particles but also the optical characteristics of the particles can be determined simultaneously. This will provide additional information for the potential identification of the particles. Flow cytometry is increasingly researched and implemented in the determination of water quality [58]. Zhu et al. have demonstrated the feasibility of general fluorescent optofluidic cytometry using a smartphone [59]. The technique has been applied for blood analysis, determining the amount of red and white blood cells and haemoglobin [60]. This application demonstrates that portable, on-site (flow) cytometry using smartphones for water quality applications might be feasible in the future as well.

3.3 Light Scattering

In addition to analysing the absorption or emission of light from samples, the scattering of light directed at the sample can be used for quantitative analysis of targets in aqueous media as well. Using the principle of light scattering for the detection of parameters generally implies that (spherical) particles are used as indirect indicator species, as light scattering from spherical objects is very well understood and quantifiable by the mathematical solution of Maxwell's equations of electromagnetism by Gustav Mie. This solution quantifies the amount of light scattering of electromagnetic plane waves by a homogeneous spherical particle. This light scattering from spherical particles is therefore called Mie scattering. From the amount of Mie scattering captured on a detector the amount of scattering particles can be deducted. As these particles are used in one way or another as an indicator of the parameter of interest, this amount of captured light quantifies the amount of the parameter of interest that is present. This detection principle has been applied in smartphone add-on detection devices determining the presence of thyroid stimulating hormone (TSH) by You et al. using lateral flow assays based on nanoparticles that ultimately scatter the incident light [61]. Additionally, the evaluation of pathogens in blood, tested for malaria targets, was demonstrated by Stemple et al. [62].

3.4 Electrochemical

Electrochemical reactions of specific chemical compounds at selective electrodes can be monitored via the measured potential of the electrodes or the amount of current drawn by the selective electrode. The chemical reaction rate is directly proportional to the concentration of the specific compounds that is monitored. Therefore, via proper calibration the concentration of analytes can be determined from the electrical readings from the electrodes. A module that performs generic electrochemical measurements (cyclic voltammetry) has been demonstrated by Sun et al. [63]. A more specific water-related electrochemical application (coined MoboSens) has been developed by Wang et al. [64]. Because this is an electrochemical add-on and detection is not performed by the built-in camera of the smartphone the device is connected to the smartphone using the audio jack. The attached sensor is capable of detecting nitrate concentrations in water. Although currently only demonstrated for nitrate, the developers have high ambitions with expansion plans towards contaminants such as e.g. arsenic, phosphate, heavy metal, carcinogens, and bacteria.

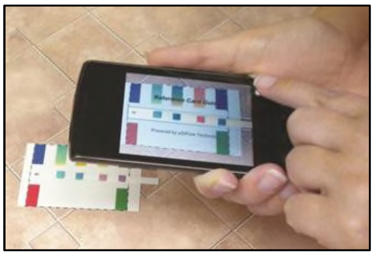
3.5 Conclusion

A relatively large body of research exists that demonstrates the feasibility of using smartphone add-ons to specifically detect various chemical and microbiological parameters for e.g. water quality, health diagnostics or other applications. Most detection principles rely on (more or less ingenious) assay protocols that convert the presence of the target analyte into a measurable optical signal. Difficult and extensive assay protocols make larger scale use in citizen science more problematic as it introduces barriers for citizens such as (i) obtaining / availability of the add-on, (ii) obtaining / availability of chemicals and (iii) ability and drive to follow the protocol precisely. Easier protocols and the adaptation of electrochemical detection might overcome these issues. However, based on what has currently been developed, parameters of relevance to both consumer and water utilities are limited, particularly at the sensitivity required to produce meaningful data. From the above overview, parameters as pH and chlorine seem most promising for citizen science projects, although specifically for the Netherlands chlorine is not too interesting as it is not used for disinfection of drinking water. However, as the overview demonstrates, there exists (increasing) potential for smartphone-based add-on devices for the determination of aqueous parameters and in the future these types of applications can be envisioned to become more sophisticated and more broadly applicable.

4 (Semi-)Commercial Water Quality-related Initiatives

A large body of research is available that demonstrates the (attractive) perspective of using smartphones for the analysis of water quality-related parameters. It is therefore not surprising that some commercial (start-up) initiatives have been undertaken to capitalize on this body of knowledge. Main drivers for commercial developments correspond with requirements from a citizen science viewpoint. The offered analyses need to be simple, robust, easy-to-use and provide relevant easy-to-interpret information. A small overview of a number of initiatives, selected with relevance to applications in the water sector, is described below .

4.1 La Motte Insta-Link App



A commercial effort in order to use external chemical analysis assays that are easily available to customers has been developed by LaMotte [65]. The app analyses test strip assays with a smartphone app/ The application has originated in the monitoring of spas en pools and the company sells dedicated test strips that analyse five parameters, *i.e.* free chlorine, pH, alkalinity, hardness and cyanuric acid. The app and test strips are coherently developed to '*maximize the photo-scanning technology*'. The current added value for customers is an independent read-out of the test strip and insight in the history of the data, showing e.g. trends. It can be foreseen that with minor adjustments, the app might be used for collecting spatially-distributed measurements for citizen science applications. To this end the incorporation of data communication protocols and GPS coordinate allocation is necessary.

4.2 KEM-TEK Water Tester App

The company KEM-TEK has developed a similar app for reading chemical test strips aimed at pool and spa care [66]. A combined test kit, with strips and access to the app, is on the market, with four-way test strips that analyse free chlorine/bromine, pH, alkalinity and hardness. As a demonstration of the added value of (somewhat) more detailed data evaluation, the KEM-TEK app provides specific advice to solve observed water quality problems (if any). As with the app from LaMotte, because the app is developed for quality control of designated discrete pools and remedy potential problems, distribution of data and location information is not of importance. For use of the app in these applications, these functionalities will need to be developed.

4.3 Waterbot

The Waterbot concept entails the deployment of a real-time conductivity sensor and data logger in a medium of interest. The conductivity reading is used as a secondary reading of the Total Dissolved Solids. The role of citizens and smartphones will be the reading of the data logger and submitting the acquired data to a centralized server for the analysis of the spatially-distributed data. As the developers of Waterbot claim: *'Collecting baseline data and setting up mobile sensor networks in areas impacted by water source contamination is essential for citizen science and civic monitoring projects*' [67].

4.4 Sensorex SAM-1 Aquameter + App

The company Sensorex has developed a product coined Smart Aqua Meter (SAM-1) [68]. The product consists of an add-on that connects into the audio jack of the smartphone (Apple and Android). Sensors are available for the parameters pH, Oxidation/Reduction Potential (ORP), conductivity and temperature. An app is available which communicates with the sensors and provides ease-of-use for users. The systems easily records the sensor readings, time and GPS coordinates. Readings can be submitted by email and/or exported to spreadsheets. A central database for analysis of spatial patterns in data will need to be based on these emails or spreadsheets currently. The company aims for an expansion of the available sensor types.

4.5 Sensorcon Sensordrone + App

A similar concept has been developed by Sensorcon named Sensordrone [69]. This add-on renders smartphones (Android) capable of performing a broad range of measurements such as the determination of various gases (air quality monitoring), detection of light in various ways, humidity and pressure. Relevant for the water sector is an available package with sensors for pH and dissolved oxygen. Two sensor probes for the two parameters, from Atlas Scientific, are connected to the Sensordrone that in turn communicates via Bluetooth connection with the smartphone. Sensorcon has developed an accompanying app. Although hardware for other (water quality) measurements is not available from Sensorcon and should be acquired from somewhere else, it provides an expansion connector to provide communication of external sensors with the app. The underlying code of the app is open source, providing opportunities to develop the concept further and adapt it to specific needs

5 Potential for a Pilot Concept in the Dutch Water Sector

A summary of applications that are relevant for the (drinking)water sector is presented in Table 2. The table offers a wide range of solutions that might be exploited in order to involve citizens in gathering (spatially-distributed) information of relevance for both these citizens themselves and drinking water utilities and/or water boards etc. Different timeframes are, however, of importance for the various implementations.

Solutions that are based on add-on devices are currently one-off prototypes for proof-of-principle studies. These solutions, their rapid development and the widespread application of instruments for the determination of chemical and microbiological parameters in a broad spectrum of areas other than the water sector will in the future no doubt present citizens with previously unseen capabilities to monitor relevant parameters within their personal environment. Currently however, distribution of a (relatively) large number of these add-on to citizen scientists is mainly limited by the possibility to fabricate prototypes in larger numbers, considering the final costs of such an add-on as well. Based on the rapid developments, also within the realms of 3D printing, the (international) drinking water sector would be well advised to proactively follow-up on these development and further explore the possibilities and implications of citizen science developments for their operation.

A shorter term foreseen application will thus be based on the described possibilities to use simple external chemical and microbiological (paper-based) analyses and use smartphones to analyse and transmit results to a centralized location. The described added value to perform multiplexed analyses of various parameters and use-extensive calculation power of smartphones to determine secondary indices can relatively quickly open up new information for citizens, together with spatially-distributed information for water utilities and boards. Various cheap paper-based water-quality related analyses are currently commercially available, determining parameters such a pH, alkalinity, (various forms of) hardness, calcium concentration, metallic ions and nutrients. For citizens, knowledge and minimization of the impact of these types of parameters on their health and/or household appliances will be of interest, while a more systems approach and insight in the variability of these parameters throughout (distribution) networks can yield improved understanding of its operation for drinking water utilities. Questions remain regarding the applicability of current analyses for the determination of species that are expected to be present in (very) low concentration, because the sensitivity of the analyses will very likely not be sufficient. However, a pilot-scale experiment monitoring parameters throughout the distribution network based on a citizen science approach using paper-based analyses in combination with smartphones is currently technologically feasible. Such an experiment would yield valuable information on the positive and negative effects of engaging citizens in the determination of (drinking) water quality and prepare drinking water utilities how to deal with increasingly engaged citizens in the future.

TABLE 2: SUMMARY OF WATER QUALITY-RELATED SMARTPHONE-BASED ANALYSES WITH POTENTIAL FOR CITIZEN SCIENCE APPLICATIONS IN THE WATER SECTOR.

Parameters	Add-on / External Analysis	Detection Principle	Data Platform	Commercially Available	Research group / Technology	Reference
pH	External Analysis	Colorimetry	External	No	Devadhasan et al.	[7]
pH	External Analysis	Colorimetry	Blackberry / HTC	No	Shen et al.	[8]
Chlorine	External Analysis	Colorimetry	Android App	No	Sumriddetchkajorn et al.	[9]
Organophosphates	External Analysis	Colorimetry	IPhone App	No	Sicard et al.	[10]
Cr(III) and Cr(VI)	External Analysis	Colorimetry	Unknown	No	Chen et al.	[11]
Hg(II)	External Analysis	Colorimetry	HTC / External	No	Chen et al.	[12]
Fe(III), Cr(VI), Cu(II), As(III)	External Analysis	Colorimetry	Nokia	No	Iqbal et al.	[13]
E. coli	External Analysis	Mie Scattering	IPhone App	No	Park et al.	[16]
Multiplexed pH, Nitrite	External Analysis	Colorimetry	Android App	No	Lopez-Ruiz et al.	[17]
pH, Chlorine (, Alkalinity)	Add-on	Colorimetry	IPhone App	No	Schaefer et al.	[36]
pH	Add-on	Colorimetry	IPhone App	No	Oncescu et al.	[37]
Chlorine	Add-on	Colorimetry	Android App	No	Sumriddetchkajorn et al.	[38]
Metabolomics	Add-on	Colorimetry	Android App	No	Kwon et al.	[46]
Nanoparticles, Viruses	Add-on	Fluorescence	Nokia / External	No	Wei et al.	[51]
Giardia Cysts	Add-on	Fluorescence	Windows / External	No	Koydemir et al.	[52]
E. coli	Add-on	Fluorescence	Sony-Ericsson / External	No	Zhu et al.	[54]
E. coli (, Salmonella)	Add-on	Fluorescence	Sony-Ericsson Android App	No	Rajendran et al.	[55]
Dual *E. coli*, Salmonella	Add-on	Fluorescence	Iphone App	No	Nicolini et al.	[56]
DNA	Add-on	Fluorescence	Various / External	No	Lee et al.	[57]
Nitrate	Add-on	Electrochemical	Windows, Android and IPhone App	No	Wang et al.	[64]
Free Chlorine, pH, Alkalinity, Hardness, Cyanuric Acid	External Analysis	Colorimetry	Android and IPhone App	Yes	Insta-Link	[65]
Free Chlorine/Bromine, pH, Alkalinity, Hardness	External Analysis	Colorimetry	Android and IPhone App	Yes	Water Tester App	[66]
Conductivity	Add-On	Electrochemical	Various / External	No	Waterbot	[67]
pH, ORP, Conductivity, Temp.	Add-On	Various	Android and IPhone App	Yes	Smart Aqua Meter	[68]
pH, Dissolved Oxygen	Add-On	Electrochemical	Android App	Yes	Sensordrone	[69]

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