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Working Paper

Digital Innovation in Citizen Science to Enhance Water Quality Monitoring in Developing Countries

Nicholas B. Pattinson, Jim Taylor, Chris W. S. Dickens and P. Mark Graham

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Nicholas B. Pattinson, Jim Taylor, Chris W. S. Dickens and P. Mark Graham

International Water Management Institute (IWMI)
P. O. Box 2075, Colombo, Sri Lanka

The authors:

Nicholas B. Pattinson is a Research Scientist at GroundTruth cc, Hilton, South Africa, as well as a PhD Biological Sciences candidate at the Fitzpatrick Institute of African Ornithology, University of Cape Town, Cape Town, South Africa.
Dr. Jim Taylor is a Research Fellow at the University of Kwa-Zulu Natal (UKZN), Pietermaritzburg, South Africa, and a Researcher within the United Nations University, KZN Regional Centre of Expertise (UNU-RCE), South Africa.
Dr. Chris Dickens is a Principal Researcher within Ecosystems at the International Water Management Institute (IWMI), Colombo, Sri Lanka.
Dr. Mark Graham is the Director of GroundTruth cc Environment and Engineering, a Research Fellow at UKZN and a Researcher within the UNU-RCE.

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Acronyms and Abbreviations

AI	Artificial intelligence
GPS	Global Positioning System
miniSASS	Stream assessment scoring system
ML	Machine learning
ODK	Open Data Kit
SDG	Sustainable Development Goal
TSS	Total suspended solids
WWQA	World Water Quality Alliance

Summary

Freshwater systems are adversely affected disproportionately by the ongoing, global environmental crisis. The effective and efficient water resource conservation and management necessary to mitigate the crisis requires monitoring data especially on water quality. This is recognized by Sustainable Development Goal (SDG) 6, particularly indicator 6.3.2., which requires all United Nations (UN) member states to measure and report the 'proportion of water bodies with good ambient water quality'. However, gathering sufficient data on water quality is reliant on data collection at spatial and temporal scales that are generally outside the capacity of institutions using conventional methods.

Digital technologies, such as wireless sensor networks and remote sensing, have come to the fore as promising avenues to increase the scope of data collection and reporting. Citizen science (which goes by many names, e.g., participatory science or community-based monitoring) has also been earmarked as a powerful mechanism to improve monitoring. However, both modern digital technologies and citizen science approaches have drawbacks and limitations. The synergy between the power of automated, verifiable data collection using modern technologies, and the power of citizen science to improve the spatial and temporal resolution of data collection while engaging and empowering communities, presents an opportunity to use the best features of each mechanism to mitigate the shortcomings of the other. Smartphones, sometimes in conjunction with other sensors, present such a nexus point, providing a method for citizen scientists to engage with and use sophisticated modern technology for water quality monitoring. Smartphones are widely accessible and equipped for objective, comprehensive and accurate data collection. The data can also be uploaded (via internet connections) to large cloud-based databases with cloud-based computing for data management and reporting. This paper presents a research synthesis of technological upgrades or innovations in citizen science water quality monitoring in developing countries, with a particular focus on exploring the current status of modern, smartphone-based, or smartphone-assisted citizen science tools, and how those tools can be validated or expanded for SDG reporting in developing countries. Essentially, the paper aims to briefly summarize the current standing, reiterate the urgent need for research and action in water resource monitoring and management, and urge further engagement with citizen science water quality monitoring using digital innovations; digital innovations for smartphones are being rapidly developed, but the scientific validation for their use in specific circumstances or regions, as well as their uptake and upscaling, are still widely lacking.

Globally, there are many options and developments relevant to citizen science smartphone-based or smartphone-assisted water quality monitoring. However, not all modern developments are suitable for deployment or testing across all socio-ecological environments. Innovations in smartphone water quality monitoring in low and middle-income country contexts need to be low-cost (requiring minimal input costs beyond having a smartphone), easy-to-use, easily scalable, commercially available, suited to use by minimally skilled people in rural and developing areas. Moreover, monitoring all the parameters (physical, chemical and biological) that contribute to water quality is highly complex and outside the scope of what is achievable by most people, organizations, or even governments. As a result, it is sensible that water resource monitoring and management efforts are primarily directed toward addressing the SDG indicators to align with global goals. The SDG water quality indicators were chosen as a result of extensive consultation and research. They are designed to provide a snapshot of water quality suitable for most regions and socioeconomic situations worldwide. The SDG 6.3.2. indicator method employs a water quality index that integrates basic core water quality parameters; oxygen, salinity, nitrogen, phosphorus and acidification. Monitoring algae, temperature and clarity also presents useful options since they are highly relevant to ambient water quality and can be monitored cheaply and easily by citizen scientists.

This paper summarizes a non-exhaustive list of examples of smartphone-based or smartphone-assisted applications (mobile apps) that are suggested or recommended for research and implementation in developing countries. Research and development regarding these options should aim to validate the accuracy of data collection, accessibility, ease of use, cost, and the feasibility of contributing to pathways from data collection to citizen mobilization and decision-making. Ultimately, once these options are validated, they can be used to design and implement monitoring networks around the globe. Well-designed citizen science water quality monitoring apps on smartphones can increase community engagement regarding environmental issues and policy, build awareness and scientific literacy, and generate large amounts of data, all at a greatly reduced cost compared to conventional and modern technological methods. It is suggested that smartphone-based or smartphone-assisted citizen science water quality monitoring has the potential to address critical data and knowledge gaps that contribute towards reporting on at least SDG 6.3.2 while fulfilling SDG 6b 'procedures for participation of local communities in water and sanitation management' – a potential which is still often not realized.

Digital Innovation in Citizen Science to Enhance Water Quality Monitoring in Developing Countries

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Introduction

GroundTruth, in conjunction with CGIAR, has engaged in a research-for-development project involving the incorporation of real-time natural resource monitoring data into decision-support systems as per the CGIAR Initiative on Digital Innovation (DI). The DI seeks to harness digital technologies for timely decision-making across food, land and water systems. The theory of change within DI is designed to address three challenge areas identified as key bottlenecks in the digital ecosystem: 1) the digital divide, 2) inadequate information, and 3) limited digital capabilities.

The project has multiple objectives. This paper presents the progress on one of the objectives: to conduct research into technological upgrades or innovations in citizen science water quality monitoring in developing countries, with a particular focus on exploring modern, smartphone-based, or smartphone-assisted citizen science tools.

The primary aims of this research are 1) to briefly contextualize the current status of freshwater globally, 2) to briefly overview why water resource monitoring is essential for improved water resource management and preservation of water resources, 3) to discuss some of the shortcomings of conventional monitoring methods and the need for increased worldwide engagement with citizen science, 4) to identify some of the potential for powerful synergies between modern technology and citizen science for water resource monitoring to help achieve Sustainable Development Goal (SDG) 6 among others, 5) to explore options (a non-exhaustive list) for integrating smartphones into citizen science water resource monitoring and 6) to provide recommendations for future research and implementation of smartphone-based or smartphone-assisted citizen science water resource monitoring which is, in many places, still not undertaken with the attention warranted.

Background

Freshwater in Crisis

Scientific and popular literature is growing rapidly in both abundance and urgency concerning the ongoing, global environmental crisis (Harrison et al. 2018; WWF 2020; Robinson 2023). The most recent update of the global Living Planet Index showed an average 68% decrease in population sizes of mammals, birds, amphibians, reptiles and fish between 1970 and 2016 (WWF 2020). Freshwater systems are disproportionately affected (Revenga and Mock 2000; Arthington et al. 2018; Flitcroft et al. 2019; Pastor et al. 2019; Tickner et al. 2020; Albert et al. 2021). Freshwater ecosystems are biodiversity hotspots, containing and supporting approximately 12% of all species on earth (including 30% of vertebrates) while comprising less than 2% of the earth's surface (Abramovitz 1995; Carrizo et al. 2017). Yet, there has traditionally been a poor representation of freshwater systems explicitly in policy or conservation landscapes (Carrizo et al. 2017; Darwall et al. 2018; Reid et al. 2019). At present, approximately 27% of all vertebrate species that are dependent on freshwater systems are threatened with extinction (IUCN 2023), with an average 84% decline in population of freshwater vertebrates worldwide since 1970 – a rate twice as high as those in terrestrial or marine systems (WWF 2016, 2020; Darwall et al. 2018; Harrison et al. 2018).

It is critical to understand that the problem is not simply one of biodiversity loss. Human well-being and sustainable futures are totally dependent on freshwater ecosystems (Abramovitz 1995; Vörösmarty et al. 2010; Lynch et al. 2023). The essential goods and services provided by freshwater systems include water treatment (freshwater systems are the primary receivers and treatment systems for waste and pollutants), clean drinking water (and its associated health benefits), fish, fiber, disaster mitigation (the resilience and adaptability of natural systems is crucial in the face of climate change), recreation and intrinsic 'quality of life' value (Dyson et al. 2008; Dudgeon 2010; Acreman 2016; Díaz et al. 2018; Lynch et al. 2023). As a result, the impact of the freshwater crisis is a catastrophic, direct threat to humans. The World Health Organization (WHO) estimated approximately 2.1 billion people do not have regular access to safe and sanitary water (WHO and UNICEF 2021), while water-borne diseases from consuming or using unsafe water results in 0.9 – 1.2 million deaths per year (WHO and UNICEF 2017; GBD 2017 Risk Factor Collaborators 2018). With the global population predicted to increase by 40 – 50% by 2070, the demand and pressures on freshwater are only set to increase (Jan et al. 2021). The World Economic Forum (WEF) Global Risks Report of the top ten biggest risks to society on Earth, over the next 10 years, identified

'Freshwater supply' as number 3 in 2016, 'Biodiversity loss and ecosystem collapse' and 'Natural resource crises' as 4 and 6, respectively in 2023 (WEF 2023). Risks to fresh water may be described as slow violence (Nixon 2011). Seemingly imperceptible, the sustained damage to freshwater rivers and streams will lead to future catastrophic events. For example, small amounts of nutrient load gradually accumulate over time, before reaching a crisis point (Romanelli et al. 2020).

The causes of the freshwater crisis were well-known since many of the problems today are the same as those identified over the past three decades, although they are worsening and being compounded by some emerging, increasingly complex anthropogenic pressures (Darwall et al. 2018; Dudgeon 2019; Albert et al. 2021). Reid et al. (2019), published a review reflecting on how the freshwater crisis has deepened since Dudgeon et al.'s (2006) landmark work listed 12 threats that have since intensified or emerged as new: (i) changing climates; (ii) e-commerce and invasions; (iii) infectious diseases; (iv) harmful algal blooms; (v) expanding hydropower; (vi) emerging contaminants; (vii) engineered nanomaterials; (viii) microplastic pollution; (ix) light and noise; (x) freshwater salinization; (xi) declining calcium; and (xii) cumulative stressors. A year after that review, Tickner et al. (2020) recognized that the freshwater crisis had grown so pervasive and intense, that they developed an 'Emergency Recovery Plan' to aid in addressing the critical state of freshwater brought about by the Anthropocene.

Approximately 82% of the world's human population gets its water from upstream areas that are under immediate and substantial threat of degradation (Green et al. 2015). Degradation of freshwater systems and the immense biodiversity they contain, reduces their capacity to deal with increasing human demand and threatens the essential goods and services that are naturally provided by functioning and healthy ecosystems (Forslund et al. 2009; Green et al. 2015; Abell et al. 2019; Cook et al. 2021). The financial value of the goods and services provided by natural systems is complex to quantify, but one global estimate puts this at over USD 4 trillion annually in a 'ballpark' attempt to emphasize the economic incentives for their conservation (Darwall et al. 2018). Though the exercise of assigning a monetary value to the often 'silent' goods and services is difficult and in some instances criticized, it is clear that in cases where water resources have been overexploited and cease to flow (e.g., Colorado or Indus River), or have become deeply polluted (e.g., the Ganges River), the loss, economic and otherwise, to downstream populations is almost immeasurable (Dudgeon 2010; Sharma et al. 2010). Further, the ecosystem collapses at the Aral Sea (Micklin 2007) and Azraq Oasis (Whitman 2019) provide grim examples of the disastrous consequences (e.g., loss of fisheries, water supply, biodiversity, tourism, and cultural heritage) of unabated exploitation and disregard for freshwater systems (Dudgeon 2019). The concept of how human societal and economic goals are embedded in a complex socio-ecological system (Njue et al. 2019; König et al. 2021) which is reliant on nature and functioning ecosystems was neatly illustrated by a recent depiction of the Sustainable Development Goals[1] (SDGs) by the Stockholm Resilience Centre (Figure 1).

Water Resource Monitoring: The First Step in Mitigating the Crisis

Over the period of the increasingly regular and urgent literature on the status of freshwater systems, various regulations, policies, and associated management and mitigation frameworks or concepts have been developed across the globe (Green et al. 2015; Albert et al. 2021). These include, for example, the landmark Water Framework Directive (WFD 2000) in Europe, the Clean Water Act in Canada (Government of Ontario 2006), the Water Act in Australia (Australian Government 2007), the Clean Water Act in the United States of America,[2] the Alliance for Freshwater Life[3] (Darwall et al. 2018), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Brondizio et al. 2019), United Nations Framework Convention on Climate Change (UNFCCC) Glasgow Climate Pact (UNFCCC 2021), United Nations Environment Programme (UNEP) World Water Quality Alliance[4] (WWQA), World Water Council,[5] Leaders Pledge for Nature,[6] the SOLUTIONS project[7] (Brack et al. 2015), and the Convention on Biological Diversity[8] (CBD). All of these have worked in some degree towards, or in concert with, the SDGs (Arthington 2021). Generally, global collaboration on freshwater management takes a particular focus on SDG6 'clean water and sanitation for all' (Capdevila et al. 2020; Quinlivan et al. 2020a, 2020b; White et al. 2020; Gemeda et al. 2021; Hegarty et al. 2021).

One key factor that emerges within these directives, frameworks, policy recommendations, and the SDGs concerning improved freshwater resource management and conservation is the need for monitoring data, including on water quality (Strobl and Robillard 2008; Behmel et al. 2016; McKinley et al. 2017; Harrison et al. 2018; Tickner et al. 2020). This focus arises because implementing efficient and targeted strategies for management and conservation requires large-scale and credible data, both to design the strategies and to assess

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[1] https://sustainabledevelopment.un.org/sdgs
[2] https://www.epa.gov/laws-regulations/summary-clean-water-act
[3] https://allianceforfreshwaterlife.org
[4] https://www.unep.org/explore-topics/water/what-we-do/improving-and-assessing-world-water-quality-partnership-effort
[5] https://www.worldwatercouncil.org/en
[6] https://www.leaderspledgefornature.org/
[7] http://www.solutions-project.eu/
[8] https://www.cbd.int/convention/guide/?id=web4

Figure 1. The Sustainable Development Goals (SDGs) 'wedding cake', developed by the Stockholm Resilience Centre. The diagram illustrates how human society and economic goals are embedded in, and reliant on, a foundation of a healthy and functioning biosphere, including SDGs 6, 13, 14, and 15.

Source: Azote for Stockholm Resilience Centre, Stockholm University Creative Commons License (CC BY-ND 3.0).

progress (Davids et al. 2019; Bishop et al. 2020; Poisson et al. 2020; Arthington 2021). Consequently, meeting SDG 6, especially indicator 6.3.2. which requires all UN member states to measure and report the 'proportion of water bodies with good ambient water quality' (UNEP and UN Water 2018), is heavily reliant on water monitoring data at fine spatial and temporal resolutions (Bonney et al. 2009; Buytaert et al. 2014; Trouille et al. 2019; Fraisl et al. 2020).

Current Systems are Coming Up Short: The Need for Nontraditional Monitoring Methods

The need for freshwater monitoring data is at odds with institutional capacities to collect and manage the required data (O'Grady et al. 2021). Governments and academic institutions, especially in developing nations, simply do not have the capacity to develop and implement data monitoring regimes at the spatial and temporal scale that are required to meet the SDGs (Freitag et al. 2016; Carlson and Cohen 2018; Paepae et al. 2021). Traditional or conventional water resource monitoring involves manually collecting samples, transporting them to laboratories (often via intermediary storage), technical laboratory analysis, reporting, and finally data analysis, uploading and visualization of data (Park et al. 2020). While this process is still valuable in many instances, it typically requires experts at every step, and becomes expensive and time-consuming, leading to it being done infrequently at low spatial resolution (Gholizadeh et al. 2016; Ahmed et al. 2020; Jan et al. 2021; Silva et al. 2022; Zainurin et al. 2022). Consequently, data collected institutionally are often outdated; uncoordinated in terms of data collection and handling protocols (thereby limiting comparability); not representative of fine-scale (especially of smaller water bodies and streams) or localized issues; may miss issues that are temporally distinct such as crop spraying or pollution spills; and can be slow to influence decision-making (Behmel et al. 2016; König et al. 2021; Manjakkal et al. 2021; Arndt et al. 2022; Wu et al. 2022). These drawbacks greatly detract from the ability to understand complex catchment- or fine-scale processes and significantly reduce the power of trend analysis (Ouma et al. 2018; O'Grady et al. 2021). In some instances, an institutional unwillingness to disclose monitoring information can also be prevalent. This diminishes the agency of independent interested or affected stakeholders to take appropriate action (Steyn 2022).

Digital Technology to Bridge Gaps in Monitoring

The power of digital technology to transform conventional monitoring frameworks has proven to be astounding. Technological advancements particularly in water quality monitoring have increased rapidly over the last two decades (Zulkifli et al. 2018; Park et al. 2020). These include a huge variety of developments, ranging from government-run, highly technical, catchment-scale monitoring networks, to simple, relatively low-cost, *in situ* monitoring apparatus (Adu-Manu et al. 2017; Jan et al. 2021). Promising avenues include advancements in, and connections between, portable laboratories (Silva et al. 2022; Thio et al. 2022), microfluidic techniques (Jaywant and Arif 2019), wireless sensor networks (Pule et al. 2017; Rahim et al. 2017; Kishore et al. 2022; Okpara et al. 2022), remote sensing (Gholizadeh et al. 2016; Leeuw and Boss 2018), microbial fuel cells (Olias and Di Lorenzo 2021), the internet of things (IoT) (Ullo and Sinha 2020; Ighalo et al. 2021a; Jan et al. 2021, Manjakkal et al. 2021; Singh and Ahmed 2021), artificial intelligence (AI) (Ighalo et al. 2021b; O'Grady et al. 2021), and even nanotechnology (Vikesland 2018; Hairom et al. 2021). New technologies for monitoring have a range of advantages over traditional monitoring methods including i) increased spatial and temporal coverage of basins, reduced sampling and data collection error (where potential for human error is minimized); ii) increased ease-of-use for data collection and handling; iii) reduced requirements for specialized personnel and facilities for sample collection and analysis; iv) potential for scalable, common standardized protocols for up-to-date data collection and management methods; v) reduced time and expense for sample transport; vi) reduced time between sampling and data reporting (including opportunities for real-time reporting); vii) in-field data collection and reporting; viii) improved data visualization, reporting and capacity; and ix) reduced cost (Behmel et al. 2016; Adu-Manu et al. 2017; Pule et al. 2017; Park et al. 2020; Jan et al. 2021; O'Grady et al. 2021; Arndt et al. 2022; Okpara et al. 2022).

Despite the benefits, new digital technologies are not without their drawbacks and issues that still need solving. For example, wireless sensor networks suffer drawbacks in terms of biofouling, limitations to use in remote areas in terms of both signal coverage for data transmission and power supply, sensor drift (incremental sensor data collection error over time without calibration), high maintenance costs, electronic waste generation, and data and physical security issues (Geetha and Gouthami 2016; Rahim et al. 2017; Manjakkal et al. 2021). Remote sensing (for example via satellite using Earth Observation[9]) is still overcoming issues in terms of spatial and temporal resolution, interference from plants or adverse weather and improving applicability outside of specifically validated use cases (Olias and Di Lorenzo 2021). Sensor networks are also generating enormous datasets which contribute to modern challenges associated with the age of 'big data' handling in terms of storage, hosting, quality assurance, control and analytical (human and software-related) capacities (Strobl and Robillard 2008; Hulbert et al. 2019; Ighalo et al. 2021a, 2021b; Arndt et al. 2022).

Addressing these challenges carries costs that often present a significant barrier to longevity, data utility and reporting (McKinley et al. 2017; Fraisl et al. 2020). Caution must also be taken not to fall prey to the "data-rich – information poor syndrome" (Ward et al. 1986), where the drive to capture 'big data' actually undermines or detracts from focusing on the information and the story data can provide (Behmel et al. 2016; O'Grady et al. 2021). In sum globally, especially in the context of developing countries, many new technologies are ruled out based on limitations regarding the accessibility, commercial availability, ease-of-use or technical capacity required for use, potential for vandalism or theft, and foremost, cost (Zulkifli et al. 2018; Kishore et al. 2022).

In addition to limitations regarding the uptake and use of modern, automated, or institutionally run monitoring technologies, there is also a growing recognition that top-down institutional monitoring and policy changes may not be effective, or gain momentum fast enough to bring about the emergency and drastic changes needed to monitor, manage, rehabilitate, and conserve freshwater resources and biodiversity for human and environmental purposes (Buytaert et al. 2014; Ouma et al. 2018; Paul et al. 2018; De Filippo et al. 2021; Jordan and Cassidy 2022). As such, there are widespread calls for integrated water resource management which involves and educates stakeholders at all levels throughout the process, from project conceptualization, through data collection, to management and reporting (Pahl-Wostl et al. 2013; Poff et al. 2017; Harrison et al. 2018; Pastor et al. 2019; De Filippo et al. 2021). This is well framed by Arthington et al. (2021) in a response to Tickner et al.'s (2020) 'Emergency Recovery Plan', who stated "solving complex conflicts about water use and management, especially in times of scarcity and uncertainty, requires collaboration and enduring partnerships among all stakeholders with indigenous, societal and scientific knowledge, technical expertise, and credentials at all levels of governance". Citizen science (which goes by many names, e.g., participatory science or community-based monitoring) provides a powerful mechanism to progress towards meeting these requirements, whilst contributing to filling critical data and knowledge gaps to work towards achieving the SDGs (McKinley et al. 2017; Irwin 2018; UNEP and UN Water 2018; Fritz et al. 2019; Trouille et al. 2019; UNEP 2019; Bishop et al. 2020; Capdevila et al. 2020; Fraisl et al. 2020; Poisson et al. 2020; Queiruga-Dios et al. 2020; Quinlivan et al. 2020a; Dörler et al. 2021; Hegarty et al. 2021; Moczek et al. 2021; Corburn 2022; Kirschke et al. 2022).

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[9] https://earthobservations.org/index.php

Citizen Science for Collaborative, Inclusive Water Resource Monitoring (and Management) to Meet SDG6

The general populace has huge potential to make large-scale changes and contributions to water quality monitoring and management, through collective alterations in behavior, inclusion in the scientific process, and engagement with policy creators and implementing agencies (Reid et al. 2019; Capdevila et al. 2020; Cook et al. 2021). The involvement of citizens in science comes in many forms, from simply collecting data, through to citizen-led science where citizens are engaged in research conceptualization, data collection, analysis, interpretation and reporting (Buytaert et al. 2014; Graham and Taylor 2018; Schölvinck et al. 2022). Whichever way the system is set up, citizen science offers data collection and scientific engagement that is dynamic, decentralized and more diverse (Hadj-Hammou et al. 2017; Dörler et al. 2021).

In a review of the current and potential contributions of citizen science to the SDGs, Fraisl et al. (2020) illustrated that citizen science is already making contributions towards 5 of the SDG indicators, with the potential to meaningfully contribute to 76 more (covering some aspects of all 17 SDGs). The authors highlighted that there is especially good potential for the inclusion of citizen science to be highly impactful for achieving SDG 6, with a range of literature identifying a strong potential for contributions particularly to SDG 6.3.2 and SDG 6b ‘procedures for participation of local communities in water and sanitation management’ (O’Donoghue et al. 2018; Capdevila et al. 2020; Quinlivan et al. 2020a, 2020b; Taylor et al. 2022; Wu et al. 2022). Well-designed citizen science can increase the efficiency of community engagement and awareness building, and generate large amounts of data which are essential in bridging current knowledge gaps at a greatly reduced cost compared to traditional methods (Hadj-Hammou et al. 2017; Fritz et al. 2019; Dörler et al. 2021). This potential is strongly evident in water quality monitoring, especially in the ability of citizen science to contribute fine spatial and temporal resolution data required for pollution management. For example, pollution has well-known albeit complex, direct and / or indirect negative consequences (Amoatey and Baawain 2019; Dudgeon 2019; Mushtaq et al. 2020). However, the sources of pollution are diverse, broadly categorized into point (e.g., single origin, ‘end-of-the-pipe’ sources), and secondary or diffuse (such as water run-off from cities or agricultural lands), which makes isolating sources of pollution without sufficient monitoring data extremely difficult (Behmel et al. 2016; Geetha and Gouthami 2016; Dudgeon 2019; Zolkefli et al. 2020; Silva et al. 2022). Through increased monitoring of water quality, facilitated by citizen science, both point and diffuse sources of various forms of pollution can be isolated, management actions can be implemented, and the efficacy of those actions can be tracked (Chapman 1996; Aitkenhead et al. 2013; Taylor et al. 2013; Altenburger et al. 2015; Forrest et al. 2019; Meyer et al. 2019; Lotz-Sisitka et al. 2022).

Beyond quantitative data generation, there is a range of other tangible and significant benefits to citizen science (Jalbert and Kinchy 2016; Jollymore et al. 2017; McKinley et al. 2017). In some instances, citizen science facilitates the gathering of valuable qualitative data, such as local insights into problems or patterns based on indigenous knowledge (Paul et al. 2018; Bishop et al. 2020; Hegarty et al. 2021; Lepheana et al. 2021). In this way, citizen science can give voice to individuals and communities, especially locals, minorities and those traditionally marginalized, in a manner that typical quantitative data-driven science usually does not facilitate (Conrad and Hilchey 2011; McKinley et al. 2017; Corburn 2022). This is especially pertinent in developing nations given the rapid growth of informal and semi-informal urban and peri-urban districts with limited sanitation and waste management infrastructure (Corcoran et al. 2010; Adu-Manu et al. 2017). Citizen science can also be a critical tool to increase public awareness, scientific literacy and accountability, mobilize members of the public, engage in involved education, and foster improved relationships between policymakers and the public (Bonney et al. 2009; Carlson and Cohen 2018; O’Donoghue et al. 2018; Graham and Taylor 2018; Capdevila et al. 2020; Queiruga-Dios et al. 2020; Taylor et al. 2022). As Alender (2016) puts it, “Citizen science projects generally have several overlapping goals that yield benefits in three major categories: outcomes for scientific research such as data collection; outcomes for participants including education and new skills; and outcomes for social-ecological systems such as conservation, stewardship, and policy”. Embedded in these benefits, citizen science can also lead to long-term investment in environmental ideologies, as well as research and policy interest (De Filippo et al. 2021; König et al. 2021). The quantitative value of these benefits is hard to estimate or measure, but there is a strong contention that under the right circumstances, they may be equally valuable to quantitative data generation (Conrad and Hilchey 2011; Jalbert and Kinchy 2016).

Citizen science, similar to modern technological techniques, can have some limitations compared to traditional monitoring by professionals and scientists (Hadj-Hammou et al. 2017; Njue et al. 2019). These include a potential lack of scientific understanding, inexperience with scientific protocols, a lack of objectivity and adequate training, unregulated or poor experimental design, biases in sampling interests and locations, risks to data collectors (especially at polluted, remote or otherwise dangerous sites), and irregularity in data collection, among others (Kolok et al. 2011; Hadj-Hammou et al. 2017). Cumulatively, these contribute to the largest barrier to citizen science: a lack of trust from the scientific community and policymakers (Balázs et al. 2021). Despite the evidence that citizen science data can be sufficiently precise and accurate (especially when collected in large volumes), and are comparable to data collected by trained professionals and scientists (Holt et al. 2013; Lewandowski and Specht 2015; Alender 2016; Swanson et al. 2016;

Poisson et al. 2020), citizen science is still broadly viewed with skepticism regarding its validity (Cohn 2008; Bonney et al. 2009, 2014; Kolok et al. 2011; Cook et al. 2021). For example, one review found that less than half of citizen science monitoring programs reported that their data were being used for decision-making, as they were largely viewed as being unreliable due to inconsistent protocols, insufficient funding and poor communication (Carlson and Cohen 2018). These findings were also supported by another recent review that a significant percentage of citizen science projects in Europe (19%) reported that data were not passed on to any agencies or authorities (Moczek et al. 2021). The reality is that for the data generated by citizen science to be useful in decision-making (both in research and policy), it must be considered high quality, trustworthy and legitimate (Buytaert et al. 2014; Hulbert et al. 2019; Arndt et al. 2022).

Another major barrier to citizen science is built-in; citizen science generally relies on volunteers (Thornhill et al. 2019; Schölvinck et al. 2022). Consequently, citizen science needs to factor in volunteer motivation when designing monitoring projects or research, ensuring that volunteers find the involvement to be engaging, accessible and worthy of repetition (Alender 2016; Carlson and Cohen 2018). The motivation to partake in citizen science, as well as the type of benefit garnered, will vary according to region and economic status, among other factors (Buytaert et al. 2014; Jollymore et al. 2017). For example, wealthy people or regions might generally engage for the benefit of learning, scientific or natural enrichment, or contributing to scientific knowledge, while in developing regions / poorer people might generally engage to enhance their well-being, uplift the community, alleviate pressing issues, or for benefits such as financial rewards or the promise of remediation interventions based on the data (Paul et al. 2018; Quinlivan et al. 2020a; Walker et al. 2020). In many instances funding may prove essential, given that financial support (e.g., reimbursement for any costs accrued, such as travel or equipment, for participation) or reward (e.g., payment for services, gifts) may be a critical component of sustained and constructive involvement (Capdevila et al. 2020; Lepheana et al. 2021). For rural, poverty-stricken, or developing areas, this may be especially important. Even relatively minor expenses such as the cost of mobile data required to upload data may be a bottleneck in data collection, management, feedback and participation (Weingart and Meyer 2021). However, compared to the costs of conventional monitoring funding citizen science may provide a far more cost-effective approach to monitoring for governments. For example, providing financial incentives for citizen science monitoring river water clarity, using a cheap citizen science technique such as the clarity tube (Dahlgren et al. 2004) could provide high spatial and temporal resolution data at a fraction of the cost of grab-sampling and laboratory analysis of suspended solids.

Some of the requirements to get people to engage in sustained citizen science work are more universal. For example, participation needs to be as easy as possible; people will more often volunteer their time and efforts if the citizen science they are engaging with is as painless and streamlined as possible (Alender 2016; Scott and Frost 2017). People also require feedback, which is a powerful form of reward (Scott and Frost 2017). There is ample evidence showing that citizen scientists quickly become demotivated when they cannot see how their work has an influence at some higher level (e.g., use in institutional databases, contributing toward decision-making) or do not receive constructive or positive feedback of some kind (Conrad and Hilchey 2011; Capdevila et al. 2020; Dörler et al. 2021). The combination of these requirements was emphasized by Hulbert et al. (2019), “Simply, a gap often exists between intention and behavior. Citizen scientists who initially struggle to participate in a project are unlikely to try again in the future. This challenge underscores how critical it is to tailor an experience that firstly captures the interest of a potential citizen scientist and then creates a participatory environment that is both intuitive and rewarding”.

Integrating Technology and Citizen Science

Clearly, a potential nexus exists between the need for monitoring data to meet SDG 6, among other global needs, as well as the strengths and drawbacks of modern technology and citizen science. Synergy between the power for automated, verifiable data collection using modern technologies and the power of citizen science to improve the spatial and temporal resolution of data collection, along with associated benefits, presents an opportunity to use the best features of each to mitigate the shortcomings of the other.

Citizen science is no stranger to the augmentations proffered by technological advancement, as Baker (2016) expresses, “Low-cost, user-friendly technology allows people across the globe to participate in the scientific endeavor, and this trend is expected to mushroom far into the future. Technology is indeed driving citizen science in ways unimaginable even a decade ago”. Interaction and integration between citizen science and technology has already given rise to multiple platforms dedicated to the coordination, management and dissemination of information about citizen science over the last two decades. Well-known examples include the Global Biodiversity Information Facility[10] (GBIF) (Lane and Edwards 2007), Earthwatch Institute,[11] Zooniverse[12]

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[10] https://www.gbif.org/
[11] https://earthwatch.org
[12] https://www.zooniverse.org/

(Trouille et al. 2019), SciStarter[13] (Hoffman et al. 2017), CitiSci,[14] iNaturalist[15] (Nugent 2018), and eBird[16] (Sullivan et al. 2009) – all of which have been associated with exemplary and encouraging successes. It is also encouraging that many of these initiatives provide open access to online data free of charge as a cause for the common good. Engaging with modern technologies for citizen science is essential to meet the SDGs and broadly address many societal and ecological issues, particularly given the large volume of credible, high-resolution data required alongside the need for wider involvement and education in science (Paul et al. 2018; Njue et al. 2019; Trouille et al. 2019; König et al. 2021). Indeed, Lukyanenko et al. (2020) stated, "Conducting research in citizen science also heeds the call within the information science discipline to conduct research that promotes or supports environmental sustainability through innovative information technologies".

Alignment between the objectives of the DI and SDG 6 (among others) creates a large scope for the integration of modern, accessible, low-cost, real-time tools with citizen science and initiatives for use in water monitoring and management. Alignment between SDG 6.3.2 and SDG 6b in particular, present excellent synergistic opportunities for technologically upgraded and equipped citizen science involvement in water quality monitoring and water resource management (Capdevila et al. 2020; Hegarty et al. 2021). This is epitomized by the WWQA principle pillar 'Citizen Engagement', with the dedicated workstream 'Citizen Science for SDG 6.3.2'.[17]

Smartphones and Citizen Science

Smartphones, sometimes in conjunction with other sensors, present tools to engage with citizen scientists since they are widely accessible, powerfully equipped for data collection and have large scope for upscaling to many users (Graham et al. 2011; Kolok et al. 2011; Buytaert et al. 2016; Rahim et al. 2017; Ouma et al. 2018; Davids et al. 2019). The concept is relatively recent, following the rapid pace at which mobile technologies develop, which now includes extended battery life, internet connectivity, Wi-Fi, local and cloud-based data storage, Bluetooth, Global Positioning System (GPS), accelerometers, gyroscopes, temperature, humidity, ambient light, fingerprint and heart rate sensors, as well as powerful cameras, all mediated through simple touchscreen interfaces (Aitkenhead et al. 2014; Kwon and Park 2017; Dutta 2019; Kishore et al. 2022). However, Graham et al. (2011) noted that the potential of mobile phones in data collection was recognized over a decade ago, "Mobile phone–based tools have the potential to revolutionize the way citizen scientists are recruited and retained, facilitating a new type of 'connected' citizen scientist—one who collects scientifically relevant data as part of his or her daily routine."

Smartphones enable the collection of large amounts of potentially more objective, comprehensive (including metadata such as time, date, identity, location), and accurate data that can be uploaded (via internet connections) to large cloud-based databases with cloud-based computing for initial data management (McKinley et al. 2017; Njue et al. 2019; Park et al. 2020). Creating a data acquisition – database and creating a curation pathway in this manner potentially allows for more automated and streamlined data management, verification, visualization and reporting processes (Adu-Manu et al. 2017; Paul et al. 2018; Poisson et al. 2020; O'Grady et al. 2021). This is a vital process to minimize the collection of data that either never reaches a database because it is collected manually on paper and never uploaded to a digital platform, or the data is stagnant with decreasing relevance in a database which is not managed or is continually used for real-time reporting (Strobl and Robillard 2008; Dong et al. 2015). 'Gamification' (the process of using game-like elements in a nongaming context) and AI machine-learning (ML) technology presents especially exciting avenues of exploration in this regard (Lowry et al. 2019; Lukyanenko et al. 2020; Ighalo et al. 2021b; Khakpour and Colomo-Palacios 2021). However, simple auto-verification protocols that flag submissions outside of expected boundaries for manual checking can be simple and effective tools to substantially increase data credibility while reducing manual time and effort (Njue et al. 2019). This system has already been employed to a great effect in citizen science projects such as eBird[18] or the Southern African Bird Atlas Project 2[19] in conjunction with BirdLasser,[20] where submissions have automated protocols for checking and flagging potential mistakes. Through enabling more objective, accurate and auto-verified data collection, smartphones have the potential to mitigate the concerns (at least partially) about the credibility of citizen science data (McKinley et al. 2017; König et al. 2021). For example, smartphones allow the collection and submission of GPS data, photos and videos to support and help verify data collection. Much of the data are recorded automatically as well, which reduces the chance for human error in writing down and later transcribing information such as the time, date and location of data collection. Smartphones can also perform a wealth of other functions related to improving data quality, such as providing access to training media, real-time support from project managers or internet connectivity to seek help. Collectively, these functions might allow improved, easier, and faster integration and acceptance of citizen science data into the framework of knowledge generation, and dissemination involved in publication-policy pathways (Buytaert et al. 2014; Fritz et al. 2019; Arndt et al. 2022).

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[13] https://scistarter.org/
[14] https://www.citsci.org/
[15] https://www.inaturalist.org/
[16] https://ebird.org/home
[17] https://www.unep.org/explore-topics/water/what-we-do/world-water-quality-alliance-wwqa-partnership-effort/world-water
[18] https://ebird.org/home
[19] https://sabap2.birdmap.africa/
[20] https://www.birdlasser.com/

Another key feature of the interactive nature of internet connectivity and powerful computing associated with smartphones is that they enable faster (potentially real time), easily comprehensible feedback (e.g., through communication, data visualization, or 'game-like' points or credits) to the user based on potentially large cloud-hosted datasets (Graham et al. 2011; Geetha and Gouthami 2016). Feedback can serve to empower citizens on the ground, often as stewards of their environments, with understanding and agency to take action directly or via commentary on policy or research structure (McKinley et al. 2017; Scott and Frost 2017; Carlson and Cohen 2018). Mobilizing citizen scientists with actionable, real time data collection and feedback via smartphones may then work towards two of the most important motivators of citizen scientists, which are to help the community and environment and to get outside into protected, healthy nature (Alender 2016; Jollymore et al. 2017) "People who are passionate about a subject can quickly locate a relevant citizen science project, follow its instructions, submit data directly to online databases, and join a community of peers" – (Bonney et al. 2014). As a corollary, internet connectivity on smartphones also enables quick and easy sharing of information via social media or similar channels. Therefore, smartphones also present good potential as a platform for information and data sharing within communities to boost awareness and scalability (Bonney et al. 2014). This may facilitate broadscale data collection that uses common, standardized protocols, maximizing comparability and usefulness in trend analyses (Strobl and Robillard 2008; Behmel et al. 2016). It is important that feedback can be two-way as well; feedback can also be from data collection frontline users to project management or end users of the data. This form of feedback from frontline users is useful to refine data collection protocols, maintain participation and perspective, and enable project management monitoring to ensure that the project goals and requirements align realistically with the goals, capabilities and motivations of the participants (Walker et al. 2020; Weingart and Meyer 2021). In this way, citizen science may prove critical to speeding up positive environmental action and meeting the SDGs (Njue et al. 2019).

Connectivity facilitated by smartphones can also make a significant contribution to disaster risk management, both via citizen-driven communication, and access to timely intervention information for and from authorities (Paul et al. 2018). For example, the Minister of Environmental Affairs in South Africa, Barbara Creecy, opened her 2022/2023 National Assembly budget speech lauding the efforts of citizen scientists / activists, the Enviro-Champs, for saving lives during flooding in Durban, South Africa, "Using information from the satellite linked, Flood Early Warning System she [Mrs Thembisa Nomlala an Enviro-Champ] and fellow Enviro-Champs were able to save all but one life, as the Palmiet River washed away 450 homes in her community" (brackets added by authors) - (DFFE 2022).[21] Geetha and Gouthami (2016) also demonstrated an example of how real-time connection via the internet can be used to create a real-time, customizable 'dashboard', inclusive of alerts sent via short messaging service (SMS), or alternative instant messaging platforms, on imminent water quality threats.

It is worth noting that caution must be taken when integrating technology with citizen science (Jalbert and Kinchy 2016). There are examples where attempts to integrate technology can be exclusionary, actually reduced understanding and decreased willingness to engage (Jalbert and Kinchy 2016; Trouille et al. 2019). For example, using ML to prescreen images and remove uninteresting or unimportant images from a camera trap database actually reduced volunteer engagement with processing (Bowyer et al. 2015). There is already a lack of diversity in citizen science; often wealthier people more familiar with science have the time and resources to participate, while the most vulnerable and disaffected people most in need of a voice and citizen science involvement are excluded (Lepheana et al. 2021; Pateman et al. 2021; Harrisberg 2021). As Walker et al. (2020) stated, "Participants [are] most likely to live in an advanced economy and be in the middle class, thus having the education, technical skills, access to resources and infrastructure and the free time or the particular leisure pursuits that facilitate participation. This results in a geographic bias as majority of the projects are located in North America and Europe". Technology can also make data collection technical or complex in some instances, rendering it too complicated for broader or sustained involvement "Simplicity is one key to the success of mass participation citizen science projects. As the complexity of the protocol increases then the number of participants is likely to decrease, even though the value of the data may increase (e.g. because the dataset is more detailed)." - (Pocock et al. 2014). The lack of representation of poorer communities may be aggravated by citizen science that is focused on expensive or highly technical systems, especially where scientific literacy can be severely limited (Walker et al. 2020; Weingart and Meyer 2021). Common examples include devices such as personal weather stations (e.g., Davis Instruments or NetAtmo) used to collect precipitation data worldwide for upload and management in centralized databases such as NetAtmo,[22] Weatherlink,[23] or Weather Underground,[24] or 'pocket water quality meters' such as the Horiba LAQUAtwin range[25] for easy measurement of various water quality parameters. These personal weather stations cost upwards of USD 500 (ZAR 9,000), while a LAQUAtwin kit (including 4 pocket meters) costs USD 2,080 (ZAR 38,000). As a result, these devices are not accessible to aspiring citizen scientists who cannot afford them. Naturally, at the extreme end of the spectrum, machine-automated data collection cuts people out completely.

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[21] https://www.dffe.gov.za/speech/creecy_2022.2023budgetvote

[22] https://weathermap.netatmo.com/

[23] https://www.weatherlink.com/

[24] https://www.wunderground.com/

[25] https://www.horiba.com/fra/water-quality/pocket-meters/

An interesting twist on the integration of technology with developing regions is the notion of innovation 'leapfrogging', which can actually advance rural and semi-developed economies more rapidly than developed regions. Leapfrogging occurs when innovations are picked up without going through a traditional developmental path (James 2014). For example, mobile phones spread far more quickly in some developing countries (e.g., Myanmar, Kenya, and Uganda) compared to developed nations where landline connectivity seemed adequate (Cilliers 2021). Another prime example is in underprivileged townships in Southern Africa, where the use of innovative citizen science water quality biomonitoring techniques is often more extensive and complete than in other more affluent regions (Taylor and Taylor 2016; Taylor et al. 2022).

Smartphones can assist in combating participation biases as well as any potential exclusionary practices that would involve more complicated or expensive technologies, in at least three ways: first, many modern smartphones are relatively affordable, accessible and understandable to most people even in rural and impoverished areas (Aitkenhead et al. 2014); an estimated more than 6 billion people (estimates indicate 80 – 90% of the global population) are in possession of a smartphone (Kishore et al. 2022; Fabio et al. 2022). Second, smartphones facilitate connection to the internet, a rich platform for information sharing and learning to assist and facilitate citizen science in multiple languages (Quinlivan et al. 2020a). Third, smartphones undergo thorough, constant modification to make them evermore user friendly, easy to understand, and robust yet malleable in terms of the software and computing they can support (Aitkenhead et al. 2014). In that vein, smartphones facilitates potential gamification of data collection and interaction (Scott and Frost 2017). Citizen science platforms can be designed to be more engaging and 'game-like', to enhance, rather than detract from the data collection and feedback process, especially among young people (Morschheuser et al. 2017; Lowry et al. 2019).

The value of smartphones in facilitating, rather than degrading, involved education (sometimes termed 'action-learning') in citizen science is worth highlighting. Involving people in the scientific process, as opposed to traditional top-down teaching, has been recognized as a potent mechanism for increasing environmental understanding, building trust and fostering further participation or sustainable practices (Conrad and Hilchey 2011; Hulbert 2016; Fraisl et al. 2020). For example, Holmes et al. (2019) and De Filippo et al. (2021) emphasized the distinction between public *involvement* (i.e., actively involving people in research) and public *engagement* (i.e., raising awareness of research). The distinction challenges the common notion (which is usually a misconception) that awareness translates to action and tangible benefits downstream, and emphasizes that involvement is correlated with more rapid, sustained and noticeable effects (Jalbert and Kinchy 2016; Jordan and Cassidy 2022; Taylor et al. 2022).

Through their combined benefits and capabilities, smartphones may also motivate more citizen scientists to engage continuously for longer periods (McKinley et al. 2017). Overall, smartphones (often in conjunction with other technologies or data collection protocols) help make data collection easier and more interactive, improve training, create a sense of agency, facilitate feedback, and increase diversity of participation in citizen science to bridge poverty and geographic divides. In this way, smartphones may contribute towards more citizens collecting data regularly for longer periods at the fine spatial and temporal scales necessary to meet the SDGs (Buytaert et al. 2016; Thornhill et al. 2019; Silva et al. 2022).

Future Research, Development and Implementation Directions for Smartphone Water Quality Monitoring

Globally, there are many options and developments relevant to citizen science smartphone-based or smartphone-assisted water quality monitoring. However, not all modern developments are suitable for deployment or testing across all socio-ecological environments. For example, some smartphone-based or smartphone-assisted technologies require expensive, or difficult to operate without training, auxiliary components (Njue et al. 2019). Many of these are by no doubt powerful, but presents prohibitive costs to most citizen scientists and projects in developing regions (Abegaz et al. 2018). Also, various smartphone-based or smartphone-assisted developments have only ever reached prototype level (Kishore et al. 2022). These include among others the Secchi3000 for measuring turbidity and Secchi depth (Toivanen et al. 2013), the Mobile Water Kit for determining total coliform and *Escherichia coli* in water (Gunda et al. 2014), a spectrometer for measurement of water pH (Dutta et al. 2015), an approach to measure turbidity (Hussain et al. 2016), two approaches to measure water salinity (Hussain et al. 2017), and a device (SmartFluo) to measure chlorophyll a fluorescence (Friedrichs et al. 2017). Exploring these prototype technologies, especially where they are developed to become relatively low-cost, might be a promising avenue for future research. However, most never became commercially available or easy and affordable to deploy at a local scale.

Essentially, innovations in smartphone water quality monitoring in the context of developing countries need to be low-cost (requiring minimal input costs beyond having a smartphone), easy-to-use, easily scalable, commercially available, suitable to be used by minimally skilled people in rural and developing areas. Considering that developing countries also have limited resources, it is also important that the efforts in research, development and implementation are strategic and efficient. Monitoring all the parameters (physical, chemical and biological) that contribute to water quality is highly complex and outside the scope of what is achievable by most people, organizations or even governments (Kruse 2018; Zolkefli et al. 2020; Paepae et al. 2021; Okpara et al. 2022). As a result, it makes sense that efforts are primarily directed towards addressing water resource monitoring and management aimed at achieving the SDG indicators to align with at least the minimum requirements for global water quality monitoring. This also provides a good starting point to standardize collection and reporting worldwide. The SDG 6.3.2. indicator method employs a water quality index that integrates basic core water quality parameters; oxygen, salinity, nitrogen, phosphorus and acidification (UN Water 2018; Quinlivan et al. 2020b; Wu et al. 2022). These SDG water quality indicators were chosen as a result of extensive consultation and research. They are designed to provide a snapshot of water quality suitable for most regions and socioeconomic situations worldwide. However, they acknowledge that where they indicate problems, further, more in-depth analyses will be required; they should not and do not replace the need for monitoring a much wider range of water quality metrics. Monitoring algae (via chlorophyll or algal cells), temperature and clarity, also present useful options since they are highly relevant to ambient water quality and can be monitored cheaply and easily by citizen scientists (Dahlgren et al. 2004; Castilla et al. 2015; Ho et al. 2020).

The relevance of each of these parameters to monitoring ambient water quality is summarised briefly below:

- Acidification: The pH of water specifies how acidic or alkaline it is. Generally, water is acidic if the pH is less than 6, and alkaline if pH is more than 8. The acceptable range for environmental or ambient water is between 6.5 – 8.5 pH units. The pH of water usually correlates to electrical conductivity, hardness (the total calcium and magnesium ion concentration), sulfates, total dissolved solids and chemical oxygen demand (Kruse 2018; Ahmed et al. 2020). Monitoring pH is important since it has various effects on infrastructure (e.g., corrosion potential of water for pipes), disinfection efficiency, humans and freshwater ecosystems (Tibby et al. 2003; Banna et al. 2014; Jan et al. 2021). Particularly, acidification can have severe consequences for biota through facilitating changes to the mobility and toxicity of elements in water, though any changes in pH can affect ecosystems in complex ways since the pH tolerance range of species vary substantially (Tibby et al. 2003).

- Algae: Anaerobic explosive algal blooms causing, for example, severe depletions of dissolved oxygen and reductions in visibility and photosynthetic potential, are a major threat to freshwater systems worldwide (Sellner et al. 2003). Algal concentration broadly correlates with the color of water, making the measurement of chlorophyll-a or the 'greenness' of water a proxy for algal concentration (Ouma et al. 2018; Malthus et al. 2020).

- Clarity and turbidity: The measurement of visual water clarity, in centimeters (cm), has a strong inverse relationship to total suspended solids (TSS), thereby providing a powerful proxy for the measurement of TSS (Davies-Colley and Smith 2001; Kilroy and Biggs 2002; Ankcorn 2003; Anderson and Davie 2004; Dahlgren et al. 2004; Ellison et al. 2010; Ballantine et al. 2015; West and Scott 2016; Johnson et al. 2018). The TSS content of water is recognized as one of the most important water quality traits to monitor (Packman et al. 1999; Rügner et al. 2013; Mucha and Kułakowski 2016; Sader 2017); high TSS above naturally occurring levels, is responsible for, or is directly associated with some of the most prominent negative impacts of low-quality water (for reviews, see Cordone and Kelley 1961; Kirk 1985; Ryan 1991; Wood and Armitage 1997; Henley et al. 2000; Dallas and Day 2004; Bilotta and Brazier 2008; Kjelland et al. 2015; Schumann and Brinker 2020). Measurement of visual clarity has been suggested as preferable to turbidity (Davies-Colley and Smith 2001), since clarity relates intuitively to humans and directly relates to biological consequences for fish and birds which perceive relative clarity similarly to humans (Kilroy and Biggs 2002; Newcombe 2003). Moreover, clarity is measured in the International System of Units (SI) as opposed to the more arbitrary units of turbidity measurement (Davies-Colley et al. 2014). However, turbidity, a measurement of the deflection of light, can also be a useful proxy for TSS in water where light deflection is closely correlated to TSS (Ankcorn 2003; Sader 2017).

- Nitrogen: Nitrogen comprises 78% of the earth's atmosphere. In water, nitrogen is usually fixed as nitrates (NO_3-), nitrites (NO_2-), ammonia (NH_3), or ammonium (NH_4+), stemming primarily from atmospheric deposition, agricultural fertilizer runoff, or industrial waste (Kruse 2018; Jaywant and Arif 2019). Monitoring would ideally delineate the specific form of nitrogen present to offer increased information about sources and impacts. Nitrogen pollution can contribute towards nutrient loading and the exponential proliferation of plankton and algae, leading to eutrophication (Romanelli et al. 2020). High nitrogen in drinking water can also directly harm young animals and humans through restricting the transportation of oxygen in the blood (Majumdar 2003; Ozmen et al. 2005).

- Oxygen: Dissolved oxygen is a measure of the oxygen content of water. Dissolved oxygen is critical for aquatic biota; declining dissolved oxygen affects biota along a spectrum, from reduced activity and growth, through reductions in breeding success and stress, to mortality at low levels for sustained periods (Ahmed et al. 2020; Jan et al. 2021; Silva et al. 2022). Dissolved oxygen is influenced by a range of factors but is highly susceptible to anthropogenic influence via pollution especially with organic waste and sewage (Gholizadeh et al. 2016; Kruse 2018).

- Phosphorous: Phosphorous is an essential nutrient used by plants and microorganisms. It therefore forms a base for the primary production of animals and plants. In water, phosphorous is typically in dissolved forms such as orthophosphates. Similar to nitrogen, unnaturally high concentrations of phosphorous in water (usually related to agricultural runoff from fertilizers) can contribute to nutrient loading and can cause eutrophication where the 'nuisance value' of water is elevated (Park et al. 2020; Silva et al. 2022). Total phosphorous generally correlates to chlorophyll-a and in some circumstances to water clarity (Gholizadeh et al. 2016).

- Salinity: Salinity is the concentration of dissolved salts in soils and water. Unnaturally high or low salinity can severely, negatively affect aquatic environments because aquatic organisms generally have delicate osmotic balances and can only tolerate specific ranges of salinity (Velasco et al. 2019; Paepae et al. 2021). In some instances, even relatively small changes in salinity can have dramatic effects on organisms if the rate of change in salinity is faster than their ability to adjust. Salinity is also important since water desalination is a highly costly process both financially and in terms of time, energy and human capital (Jan et al. 2021), while saline irrigation water is highly detrimental to soil condition, and the longevity of agricultural lands.

- Temperature: Water temperature is an important component of water quality since temperature affects the physicochemical parameters of water (such as dissolved oxygen potential, electrical conductivity, and the toxicity of ammonia), and has direct and indirect effects on aquatic biota (Gholizadeh et al. 2016; Ahmed et al. 2020; Silva et al. 2022).

Examples of Smartphone Applications for Exploration in Developing Countries

Various smartphone-based or smartphone-assisted technologies are available which may prove to be useful in the context of developing countries once validated for local use. Below, a summarized, non-exhaustive list of examples that are suggested for research and implementation in developing countries. These are low-cost, commercially available, continually supported, accessible, easy to use and have requirements limited to functionalities common to almost all smartphones (such as powerful camera modules). Given the fact that there is potential for variation in the chemico-physical parameters and app functionality depending on geographic location, weather, and operators, it is wise to make sure that each of the options are locally validated before being implemented for use in citizen science monitoring networks:

- The **Hydrocolor** (Leeuw 2014; Leeuw and Boss 2018) and **EyeOnWater**[26] (formerly Citclops) apps for measurement of water color, reflectance, and turbidity. Both apps have been tested for use in various water systems in several countries with mixed but promising results (Mahama 2016; Leeuw and Boss 2018; Ouma et al. 2018; Yang et al. 2018; Jovanovic et al. 2019; Ayeni and Odume 2020; Malthus et al. 2020; Al-Ghifari et al. 2021; Burggraaff et al. 2022). Some studies have shown that data collection should be cognisant of potentially confounding environmental variables such as cloud cover and wind speed (Ouma et al. 2018). The most recent version of both apps have been upgraded to use RAW images instead of JPEG, aiming to increase data collection accuracy (Burggraaff et al. 2022).

- **Deltares Aquality App**[27] (formerly Deltares Nitrate App) in combination with Hach© nitrate test strips. The Nitrate App allows for automated determination of nitrate levels based on nitrate test strip results. The data generated are automatically synced with the Delta Data Viewer[28] to contribute to a global database of nitrate concentrations in water. One study has indicated that volunteers using visual methods produce more accurate results than the Nitrate app (Topping and Kolok 2021). The Agricultural Research Council (ARC) and Water Research Commission (WRC) in South Africa are currently engaged in a joint project exploring the use of this app in a Southern African citizen science framework. The app is also undergoing development at Deltares to increase its functionality to be able to measure a proxy of electrical conductivity.

- **The Nutrient App** (Push Interactions, Inc., developed by the University of Saskatchewan and Global Water Futures Project [GWF] with the support of Environment and Climate Change Canada[29]) determines nitrate and phosphate concentrations in water based on automated analysis of *in situ* test nitrate (Hach©) and phosphate (API Phosphate

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[26] https://www.eyeonwater.org/

[27] https://www.deltares.nl/en/software/nitrate-app/

[28] https://v-web002.deltares.nl/fewsprojectviewer/projectviewer/

[29] https://gwf.usask.ca/projects-facilities/nutrient-app.php#Overview

Test Kit) test strips (Costa et al. 2020). The Nutrient App measurements are geo-referenced and are uploaded to a server managed by GWF at the University of Saskatchewan. Similar to the Nitrate App, results form part of a global database available for visualization on a map interface in the app or on the website.

- Data collection for citizen science projects such as the Enviro-Champs (Taylor and Taylor 2016; Lepheana et al. 2021) can take place via customizable form-based data collection tools such as the **Open Data Kit**[30] (ODK), **Cybertracker**,[31] or **Ushahidi**[32] (formerly Crowdmap). These use a mobile app (such as ODK Collect or the Cybertracker app) that can be custom-built to help citizen science projects record geo-referenced data (including photos, video and voice recordings among other things) on a range of water quality-related topics. As a result, there is the possibility to explore simple, low-cost in situ water quality test kit data, such as those measuring pH, temperature, nitrate, phosphate and even *Escherichia coli* (*E. coli*; e.g., Praecautio *E. coli* water test developed by Microfoodlab), and recording the results using these apps.

- The **Crowdwater**[33] initiative and app developed at the University of Zurich gathers citizen science data on water level, soil moisture, dynamics of temporary streams, plastic pollution, and other qualitative data, via a form-based platform.

- The stream assessment scoring system (**miniSASS**[34]) (Graham et al. 2004) citizen science biomonitoring tool traditionally functions with a pen and paper survey. However, an app is being developed to aid in completing a miniSASS survey by providing AI camera recognition capability to identify freshwater invertebrates, compute a river health score based on their tolerance to pollution, and geo-locate the data. The development is taking place as part of parallel work in DI.

- The **Freshwater Watch** program[35] (a division of Earthwatch Europe) is a global initiative to monitor water quality to aid in SDG indicator reporting. The Freshwater Watch protocol collects similar data to those proposed here; data collection uses a water testing kit (Hach© nitrate and phosphate strips) to test water chemistry parameters and a small clarity tube to measure water clarity. Anecdotal, qualitative data can also be collected regarding any other visual observations (e.g., waste dumping, observations of algal blooms). Data are uploaded via the ArcGIS Survey123 app, which is freely available to use for Freshwater Watch. The data are automatically available to, managed and curated by the Freshwater Watch program based in Europe. Through collaboration with Freshwater Watch, the data can be made available to local authorities or agencies to become locally actionable and useful, in addition to automatically becoming part of the global Freshwater Watch database on water quality.[36]

- Apps such as TurbAqua (Meridian IT Solutions, developed by the Central Marine Fisheries Research Institute (CMFRI), iQwtr (BlueLeg Monitor), or Secchi (developed by Richard Kirby) require Secchi disks, clarity tubes, or other associated devices for actual data collection. Therefore, they are redundant to the use of one of the form-based apps (e.g., ODK, Cybertracker) listed above; these can also be designed to record data from clarity tubes etc., as part of the data input forms. The bloomWatch,[37] Bloomin' Algae[38] (UK Centre for Ecology and Hydrology), and Levävahti (Algae Watch; VTT Technical Research Centre of Finland, only available in Finland) (Kotovirta et al. 2014) apps help citizen scientists record qualitative data about the presence / absence, and relative scale of algal blooms in local waters. The information captured by these apps would be redundant with the use of the form-based apps listed above, which can be custom-designed to collect similar data (including photos) on the presence and extent of algal blooms.

- The Algal estimator mobile application (Ayeni and Odume 2020) estimates total and cyano-chlorophyll, ultimately estimating the likelihood of algal bloom. However, the app requires input of various river parameters only attainable via measurements using other, precise and often expensive in-field analysis, such as determination of brightness (lux), water temperature at the surface and bottom of the water, water phosphate concentration, and chlorophyll a, or dissolved oxygen and turbidity (Ayeni and Odume 2020). As a result, this app is unlikely suitable in the context of citizen science in developing countries.

The apps identified in this report are summarized in Table 1, with information on their cost, their use, and what platform they exist on.

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[30] https://getodk.org/
[31] https://cybertracker.org/
[32] https://www.ushahidi.com/
[33] https://crowdwater.ch/en/start/
[34] https://minisass.org/en/
[35] https://www.freshwaterwatch.org/
[36] https://www.freshwaterwatch.org/pages/community-groups
[37] https://cyanos.org/bloomwatch/
[38] https://www.ceh.ac.uk/our-science/projects/bloomin-algae

Table 1. Summary information on a non-exhaustive selection of smartphone apps available for investigation into their ability to assist in citizen science water quality monitoring.

App	Function	Requirements	Cost	Platform	Reference
Hydrocolor	Determines the reflectance of natural water bodies. Uses reflectance to estimate water turbidity, the concentration of total suspended solids (TSS), and the backscattering coefficient in the red-light spectrum. The data are saved on the device and can be accessed via the HydroColor app or downloaded. Data are saved as a text file containing additional information about the measurement including: latitude, longitude, date, time, sun zenith, sun azimuth, phone heading, phone pitch, exposure values, red-green-blue (RGB) reflectance, and turbidity.	Smartphone with a camera, GPS, gyroscope,andcompass. Also requires an 18% photographers' grey card as a reference. Instructions for use are provided by the app.	Free	Android and iOS. Can function offline.	Leeuw and Boss 2018
EyeOnWater	Determines the color of water based on the Forel-Ule scale. The measurements are sent to a central server, validated, stored and visible via the EyeOnWater website.[a] Results are available to the user as well.	Smartphone with a camera and GPS.	Free	Android and iOS. Can function offline.	Ouma et al. 2018; Ayeni and Odume 2020
Deltares Aquality App	Assists in determination of nitrate levels based on Hach© nitrate test strip results. The data generated are automatically synced with the Delta Data Viewer[b] to contribute to a global database of nitrate concentrations in water. Results are available to the user as well.	Smartphone with a camera and GPS. A Hach© nitrate test strip.	Free	Android and iOS. Can function offline.	Topping and Kolok 2021
The Nutrient App	Determines nitrate and phosphate concentrations in water based on automated analysis of in situ test nitrate (Hach©) and phosphate (API Phosphate Test Kit) test strips. Geo-referenced data are uploaded to a server managed by the Global Water Futures (GWF) Project at the University of Saskatchewan and form part of a global database available for visualization on a map interface in the app or on the website.[c]	Smartphone with a camera and GPS. Hach© and API Phosphate Test Kit test strips.	Free	Android and iOS. Can function offline.	Costa et al. 2020
Open Data Kit (ODK)	Customizable form-based data capture tool via the ODK Collect app. Data collection can be designed to include photos, videos, voice recording, detailed location or tracking data, or any text or picture-based question options. Data are uploaded to the ODK cloud server where they can be managed or downloaded.	Smartphone with a camera and GPS. Requires auxiliary equipment where necessary based on the desired data. For example, the form can record clarity as measured by a clarity tube, or a miniSASS score from a miniSASS survey.	USD 169 – USD 429 per month.	Android and iOS. Can function offline.	https://getodk.org/

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Table 1. Summary information on a non-exhaustive selection of smartphone apps available for investigation into their ability to assist in citizen science water quality monitoring. (continued)

App	Function	Requirements	Cost	Platform	Reference
Cyber tracker	Customizable form-based data capture tool via the Cybertracker app. Data collection can be designed to include photos, videos, voice recording, or any text or picture-based question options. Data can be uploaded to the Cybertracker cloud server where they can be managed, visualized or downloaded.	Smartphone with a camera and GPS. Similar to ODK Collect in requirement for auxiliary data collection equipment.	Free	Android and iOS. Can function offline.	https://cybertracker.org/
Ushahidi	Customizable crowdsourcing tool. A user can create a 'deployment' for other users to contribute data to or contribute data to a preexisting deployment. Ushahidi sources data from multiple outlets (e.g., SMS, Twitter, email) and collates them into a geo-referenced database.	Smartphone. Requires auxiliary equipment where necessary based on the desired data.	Free for small-scale users. USD 5,000 for enterprise level.	Android and iOS. Can function offline.	https://www.ushahidi.com/
Crowdwater	Collects data on water levels in streams or canals using a virtual staff gauge and qualitative data on soil moisture, stream flow, and plastic pollution with an allowance for additional anecdotal notes. The data are uploaded and publicly available for viewing online on the website.	Smartphone with a camera and GPS.	Free	Android and iOS. Can function offline.	https://crowdwater.ch/en/start/
miniSASS	Currently in development. Performs all data capture tasks of a miniSASS survey. Additionally, uses artificial intelligence (AI) to identify aquatic macroinvertebrates to improve identification. Auto-generates a miniSASS score. Data are stored locally, or uploaded to the miniSASS website, where they are available for visualization and downloading.	Smartphone with a camera and GPS.	Free	Android and iOS. Can function offline.	miniSASS.org (under construction) Graham et al. 2004
Freshwater Watch	Data collection uses water testing strips (Hach© nitrate and phosphate strips) and a small clarity tube to measure water clarity. Anecdotal, qualitative data can also be collected regarding any other visual observations (e.g., waste dumping, observations of algal blooms). Data are uploaded via the ArcGIS Survey123 app. The data are automatically available to, managed and curated by the Freshwater Watch program based in Europe where they form part of the global Freshwater Watch database on water quality.	Smartphone with a camera and GPS. To use Freshwater Watch, one must register a local group and receive training from a Freshwater Water representative.	Free	Android and iOS. Can function offline.	https://www.freshwaterwatch.org/

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Table 1. Summary information on a non-exhaustive selection of smartphone apps available for investigation into their ability to assist in citizen science water quality monitoring. (continued)

App	Function	Requirements	Cost	Platform	Reference
TurbAqua	Captures data as measured by the user using visual assessment or Secchi disk depth. Data recorded includes water color code (based on the Forel-Ule scale) and Secchi depth, location of measurement and color images of the water body being sampled.	Smartphone with a camera and GPS. Also requires a 3D-printed miniature Secchi Disk and measuring tape.	Free	Android and iOS. Can function offline.	Menon et al. 2021
iQwtr	Measures the Secchi depth and turbidity of water. Photographic data are uploaded to a centralized server and the Secchi depth and turbidity are calculated on the server-side. Results are available to the user.	Smartphone with a camera and GPS. Requires a specific container/device that needs to be filled with the target water. App may no longer be supported.	Free	Android and iOS. Only functions online.	https://d3pcsg2wjq9izr.cloudfront.net/files/84433/download/620713/3.pdf
Secchi	Records the geolocated measurement of Secchi disk depth. Data are uploaded to a server.	Smartphone with a camera and GPS. Requires a Secchi disk. Designed for use at sea. Instructions are given in the app.	Free	Android and iOS. Only functions online.	Kirby et al. 2021
Bloom Watch	Records geo-referenced photos of algal blooms. Data are uploaded and can be visualized on the website.	Smartphone with a camera and GPS.	Free	Android and iOS. Only functions online.	https://cyanos.org/bloomwatch/
Bloomin' Algae	Records geo-referenced photos of algal blooms. Data are uploaded, where they go through a verification process before becoming available for visualization on a global map.	Smartphone with a camera and GPS.	Free	Android and iOS. Only functions online.	https://www.ceh.ac.uk/our-science/projects/bloomin-algae
Leväväahti	Records geo-referenced photos of algal blooms, water temperature, ice, water depth, invasive water plants, jellyfish, and rubbish. Data are uploaded, where they go are available for visualization on a global map.	Smartphone with a camera and GPS. Only available in Finland.	Free	Android and iOS. Only functions online.	https://www-jarviwiki-fi.translate.goog/wiki/Etusivu?_x_tr_sl=fi&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc

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Table 1. Summary information on a non-exhaustive selection of smartphone apps available for investigation into their ability to assist in citizen science water quality monitoring. (continued)

App	Function	Requirements	Cost	Platform	Reference
Algal estimator	Estimates the likelihood of harmful algal bloom events.	Requires input brightness (lux), water temperature at the surface and bottom of the water, water phosphate concentration, and chlorophyll a, or dissolved oxygen and turbidity to estimate chlorophyll a. Instructions are provided in the app. App may no longer be supported.	Free	Android and iOS. Only functions online.	Ayeni and Odume 2020

Source: Author's creation.

Notes:

[a] www.eyeonwater.org

[b] https://v-web002.deltares.nl/fewsprojectviewer/projectviewer/

[c] https://gwf.usask.ca/projects-facilities/nutrient-app.php#ViewYourMeasurements

Conclusions

Bridging gaps in data and knowledge, especially in terms of water quality, has been identified as a necessity in informing policy and interventions, as well as managing water for a sustainable future as encapsulated by SDG indicators/targets (Buytaert et al. 2016; UNEP and UN Water 2018; UN Habitat and WHO 2018; Flitcroft et al. 2019; Bishop et al. 2020). So far, monitoring data on water have primarily come from developed countries and regions, since less developed areas often lack the resources required to gather, analyze and manage data (Capdevila et al. 2020; Quinlivan et al. 2020a, 2020b; Paepae et al. 2021). Southern Africa provides a good example of these obstacles (Graham and Taylor 2018; Hulbert et al. 2019). Southern Africa's freshwater security is at risk due to scarcity, compounded by poor and aging infrastructure, a growing population and increasing demands. These issues are compounded by pollution pressure, corruption, vandalism and theft, lack of skilled personnel, as well as climate change (Edokpayi et al. 2017; Boni et al. 2021). Moreover, Southern Africa has a widespread lack of institutional, financial and human resources to undertake thorough water quality monitoring regimes to aid in mitigating the water scarcity and quality problems (Heyns 2003; Hulbert et al. 2019; Weingart and Meyer 2021; Mukuyu et al. 2023). The result is that the most disadvantaged people are at the highest risk, and often lowest priority, regarding the global freshwater crisis (Paul et al. 2018; Corburn 2022).

Using modern, low-cost, easy-to-use technologies to co-create and communicate the knowledge, understanding, and policy at all levels is a good approach for helping developing countries recognize, monitor, and preserve vital freshwater ecosystems (McKinley et al. 2017; Reid et al. 2019; Arthington 2021; Jordan and Cassidy 2022; Lynch et al. 2023). While many technologies have been developed, and the number of publications showing the power and potential of smartphones and citizen science have increased, uptake and critical validation are still scarce. Going forward, we recommend exploration of the apps above, or others that are suitable, in the context of developing countries with a focus on scientific validation and upscaling implementation for water resource monitoring and SDG reporting. Validation should aim to assess data collection accuracy, accessibility, ease of use, cost, and the feasibility to contribute to pathways from data collection to citizen mobilization and decision-making (Jollymore et al. 2017; Fritz et al. 2019).

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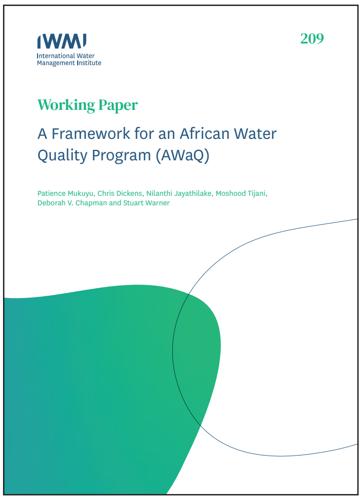

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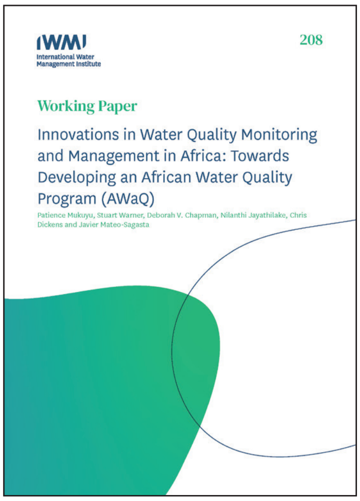

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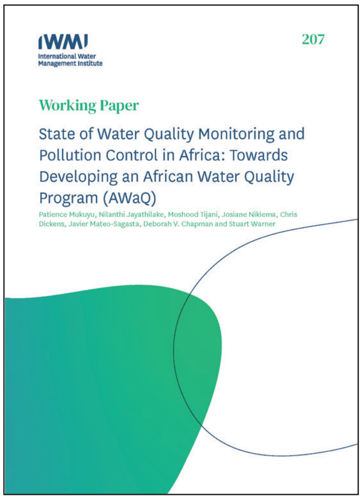

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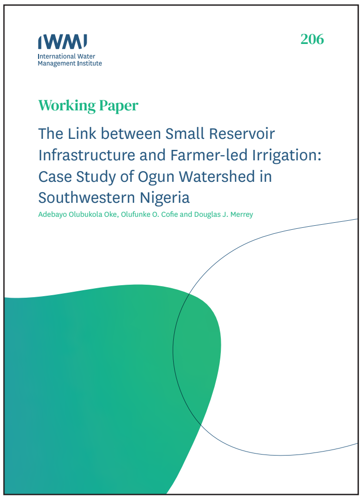

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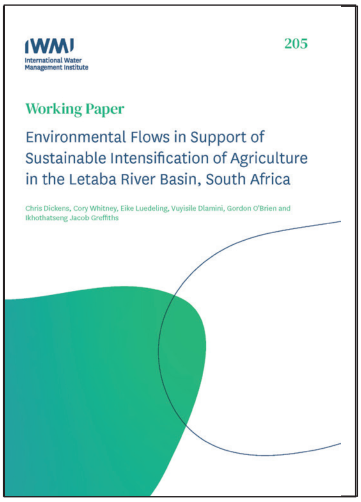

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Headquarters
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Mailing address
P. O. Box 2075
Colombo
Sri Lanka

Telephone
+94 11 2880000

Fax
+94 11 2786854

Email
iwmi@cgiar.org

Website
www.iwmi.org

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