

Working Paper

Innovations in Water Quality Monitoring and Management in Africa: Towards Developing an African Water Quality Program (AWaQ)

Patience Mukuyu, Stuart Warner, Deborah V. Chapman, Nilanthi Jayathilake, Chris Dickens and Javier Mateo-Sagasta



Working Papers

The publications in this series record the work and thinking of IWMI researchers, and knowledge that the Institute's scientific management feels is worthy of documenting. This series will ensure that scientific data and other information gathered or prepared as a part of the research work of the Institute are recorded and referenced. Working Papers could include project reports, case studies, conference or workshop proceedings, discussion papers or reports on progress of research, country-specific research reports, monographs, etc. Working Papers may be copublished, by IWMI and partner organizations. Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

The International Water Management Institute (IWMI) is an international, research-for-development organization that works with governments, civil society and the private sector to solve water problems in developing countries and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a CGIAR Research Center with offices in 15 countries and a global network of scientists operating in more than 55 countries.

IWMI Working Paper 208

Innovations in Water Quality Monitoring and Management in Africa: Towards Developing an African Water Quality Program (AWaQ)

Patience Mukuyu, Stuart Warner, Deborah V. Chapman, Nilanthi Jayathilake, Chris Dickens and Javier Mateo-Sagasta

The authors:

Patience Mukuyu was a Researcher – Transboundary Water Management at the International Water Management Institute (IWMI), Pretoria, South Africa, at the time this study was conducted; Stuart Warner and Deborah V. Chapman are independent consultants based in Ireland; Nilanthi Jayathilake is Researcher – Septage Management and Reuse at IWMI, Colombo, Sri Lanka; Chris Dickens is Principal Researcher - Ecosystems at IWMI, Colombo, Sri Lanka; and Javier Mateo-Sagasta is Senior Researcher and Coordinator – Water Quality at IWMI, Colombo, Sri Lanka.

Mukuyu, P.; Warner, S.; Chapman, D. V.; Jayathilake, N.; Dickens, C.; Mateo-Sagasta, J. 2024. *Innovations in water quality monitoring and management in Africa: towards developing an African Water Quality Program (AWaQ)*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 52p. (IWMI Working Paper 208).
doi: <https://doi.org/10.5337/2023.217>

/ water quality / monitoring / innovations / technology / policies / regulations / guidelines / standards / laboratory techniques / instrumentation / analytical methods / testing / water resources / catchment areas / transboundary waters / groundwater / contaminants / water pollution / pollution control / parameters / bio-assays / human health / awareness-raising / data management / wastewater treatment / water reuse / nature-based solutions / intervention / community involvement / citizen science / capacity development / training / best practices / Sustainable Development Goals / Goal 6 Clean water and sanitation / earth observation satellites / sensors / Africa /

ISSN 2012-5763
e-ISSN 2478-1134
ISBN 978-92-9090-954-5

Copyright © 2024, by IWMI. All rights reserved. IWMI encourages the use of its material provided that the organization is acknowledged and kept informed in all such instances. The boundaries and names shown and the designations used on maps do not imply official endorsement or acceptance by IWMI.

Please send inquiries and comments to IWMI-Publications@cgiar.org

A free copy of this publication can be downloaded at:
<https://www.iwmi.org/publications/iwmi-working-papers/>

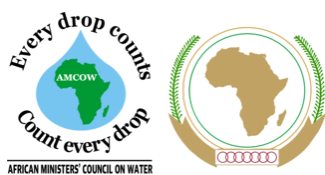
Acknowledgments

The authors acknowledge funding from the CGIAR Initiative on NEXUS Gains for conducting this study. Additional funding came from the World Water Quality Alliance (WWQA) of the United Nations Environment Programme (UNEP), which oversees the periodic World Water Quality Assessment and contributes to an understanding of the emerging water quality issues around the world. Importantly, the authors would like to thank Moshood Tijani of the African Ministers' Council on Water (AMCOW) for representing the interests of AMCOW in the design of the framework for the African Water Quality Program (AWaQ).

Collaborators



International Water Management Institute (IWM)



African Ministers' Council on Water (AMCOW), Abuja, Nigeria

Donors



This work was carried out under the CGIAR Research Program on Water, Land and Ecosystems (WLE) and finalized under the CGIAR Initiative on NEXUS Gains, which is grateful for the support of CGIAR Trust Fund contributors (<https://www.cgiar.org/funders/>).



World Water Quality Alliance (WWQA) of the United Nations Environment Programme (UNEP)

Contents

| | |
|--|------------|
| Acronyms and Abbreviations | vi |
| Summary | vii |
| Introduction | 1 |
| Objectives | 2 |
| Water Quality Monitoring | 2 |
| Introduction | 2 |
| Limitations of Conventional Approaches and Practices in Africa | 2 |
| Capacity Gaps | 2 |
| Data Gaps | 2 |
| Information Gaps | 4 |
| Monitoring Innovations Being Tested and Used Globally | 5 |
| Design of Monitoring Programs | 5 |
| Field and Laboratory Techniques and Associated Instrumentation | 8 |
| Deployment of Instrumentation | 8 |
| Satellite-based Earth Observation | 10 |
| Citizen Science | 11 |
| Biological Monitoring | 13 |
| Monitoring Innovations Applicable to Africa | 15 |
| Innovations in Water Quality Management | 19 |
| Introduction | 19 |
| Limitations of Conventional Water Quality Management Approaches and Practices in Africa | 19 |
| Environmental Water Quality Guidelines, Standards and Objectives | 19 |
| Data Management and Sharing | 19 |
| Pollution Control | 20 |
| Organizational Disconnect | 20 |
| Awareness | 21 |
| Management Innovations Being Tested and Used Globally | 21 |
| Policy and Regulation | 21 |
| Catchment-based Management | 22 |
| Data Management and Sharing | 22 |
| Wastewater Treatment and Reuse | 23 |
| Nature-based Solutions | 24 |
| Pollution Source Identification | 25 |
| Community and Citizen Engagement | 25 |
| Management Innovations Applicable to Africa | 26 |
| Conclusion | 30 |
| Key Messages | 30 |
| References | 32 |
| Annex 1. Examples of Standard Methods for Water Quality Analysis | 40 |
| Annex 2. Examples for Online Water Quality Monitoring Sensors Available in the Market | 43 |
| Annex 3. Links to Additional Resources | 44 |

Acronyms and Abbreviations

| | |
|------------|--|
| AAS | Atomic Absorption Spectrophotometry |
| AMCOW | African Ministers' Council on Water |
| ASTM | American Society for Testing and Materials |
| AWaQ | African Water Quality Program |
| DIN | German Institute for Standardization |
| eDNA | Environmental DNA |
| EN | European Norm |
| EO | Earth Observation |
| EP | Emerging Pollutant |
| EPA | United States Environmental Protection Agency |
| GC-MS | Gas Chromatography-Mass Spectrometry |
| GEMS/Water | Global Environment Monitoring System for Freshwater |
| HAB | Harmful Algal Bloom |
| ICT | Information and communications technology |
| IoT | Internet of Things |
| ISO | International Organization for Standardization |
| IWMI | International Water Management Institute |
| IWRM | Integrated Water Resources Management |
| ML | Machine Learning |
| Nbs | Nature-based Solutions |
| NCCOS | National Centers for Coastal Ocean Science |
| NGO | Nongovernmental Organization |
| NOAA | National Oceanic and Atmospheric Administration |
| NWRMA | National Water Resources Management Agency |
| OECD | Organisation for Economic Co-operation and Development |
| OGC | Open Geospatial Consortium |
| RBO | River Basin Organization |
| REMP | River Eco-status Monitoring Programme |
| ROV | Remotely Operated Vehicle |
| SASS | South African Scoring System |
| SCA | Standing Committee of Analysts (Blue Books) |
| SDG | Sustainable Development Goal |
| SLMB | Swiss Book for the Analysis of Food |
| SST | Solar Septic Tank |
| UAV | Unmanned Aerial Vehicle |
| UNEP | United Nations Environment Programme |
| USP | United States Pharmacopeia |
| WARMA | Water Resources Management Authority |
| WASP | Water Quality Analysis Simulation Program |
| WHO | World Health Organization |
| WWQA | World Water Quality Alliance |

Summary

Water quality deterioration is a growing concern for Africa's water resources. Monitoring and management of water quality are essential to identify the causes of poor water quality and inform the design of corrective measures to restore it. The current state of water quality monitoring coverage and effectiveness is inconsistent across the 50-plus countries that make up the continent. Nonetheless, commonalities associated with inadequate technical and human capacity as well as resource constraints have been identified.

In this paper, a detailed analysis of innovations in water quality monitoring and management is undertaken to propose interventions to strengthen Africa's current water quality monitoring and management efforts. Innovations related to monitoring program design, analytical techniques and instruments, deployment of instrumentation and approaches to water quality monitoring are presented together with their applicability and suitability for implementation in Africa. Similarly, water quality management interventions — policy and regulatory mechanisms, catchment-based management, data management and sharing, wastewater reuse and nature-based solutions, among others — are examined. The most suitable interventions are proposed for African contexts. These criteria consider important innovation features including affordability, scalability and flexibility.

Key findings of this paper highlight the following:

- There are numerous innovations within water quality monitoring and management. However, not all of them may be suitable for implementation in resource-constrained environments characteristic of many parts of Africa. For example, statistical analysis and modelling may require large amounts of existing monitoring data currently unavailable in most African countries. Nonetheless, other interventions such as the priority monitoring approach can be beneficial in optimizing resource utilization. Similarly, technological interventions such as multi-parameter sensors for basic water quality variables are now widely available

and affordable in the provision of in situ results and lessening the need for laboratory analysis.

- Available and existing traditional methods of water quality monitoring and management offer a good starting point to further strengthen and streamline efforts for increasing efficiency and effectiveness. Currently available laboratory facilities may benefit from instrumentation upgrades and continuous staff training.
- There is scope for community and citizen engagement in the various processes of water resources monitoring and management. There is evidence that this enables success where governments do not have the monitoring capacity or adequate resources.

Effectively managing water quality is still a challenge in most African countries, and even more so at the national and transboundary scales. By undertaking suitable investment and targeted capacity development, existing monitoring programs could be expanded to increase the monitoring station density and ameliorate the subsequent data flows. However, a substantial data gap which proves challenging is that of historical data to indicate the reference or baseline conditions and to define the natural state of a water body.

Innovations pertaining to monitoring program design, analytical techniques and instruments, deployment of instrumentation and approaches to water quality monitoring have been presented together with their applicability and suitability for implementation in Africa. Similarly, water quality management interventions are considered, with the most suitable of these proposed for African contexts based on a set of defined criteria. These criteria examine important innovation features such as affordability, scalability and flexibility, among others. The African Water Quality Program (AWaQ), therefore, offers the opportunity to ensure that best practices are established and scaled up rather than being merely imitated from the past.

Innovations in Water Quality Monitoring and Management in Africa: Towards Developing an African Water Quality Program (AWaQ)

Patience Mukuyu, Stuart Warner, Deborah V. Chapman, Nilanthi Jayathilake, Chris Dickens and Javier Mateo-Sagasta

Introduction

Responding to a request made by the African Ministers' Council on Water (AMCOW), the International Water Management Institute (IWMI) is supporting the design of an African Water Quality Program to accelerate the water security agenda in Africa. The AMCOW Secretariat committed to design and implement an African Water Quality Program (AWaQ) in its Strategic Operational Plan (2020–2024) considering the guiding frameworks it uses such as the Africa Water Vision 2025, United Nations Sustainable Development Goals (SDGs) and the African Union Agenda 2063: The Africa We Want. Additionally, AWaQ will form part of a broader program on water quality in Africa being promoted by the work-streams of the World Water Quality Alliance (WWQA), coordinated by the Global Environment Monitoring Unit in the Science Division of the United Nations Environment Programme (UNEP). Ultimately, the added value of AWaQ is its regional reach, for instance, in terms of shared basin systems across multiple countries.

The work carried out under AWaQ has been conceptualized in five phases (Figure 1). The first two phases (Mukuyu et al. 2024a) assess past and existing initiatives and capacity for

water quality monitoring and management. Phases 3 and 4 (this paper) analyze potential innovations in ambient water quality monitoring and management that AWaQ should consider. Finally, a framework for AWaQ is developed in phase 5 (Mukuyu et al. 2024b).

The key output of this research effort is the development of a framework to guide the design of the African Water Quality Program (AWaQ). This framework will enable the establishment of a working program that can be adopted by all AMCOW Member States for monitoring and managing water quality. AWaQ will also promote Africa's ability to participate meaningfully in the WWQA and SDGs, and allow further scrutiny of a multitude of water quality issues. It also sets in motion a continent-wide initiative to collect and provide data to larger repositories including UNEP's Global Environment Monitoring System for Freshwater (GEMS/Water). The design and implementation of AWaQ will, therefore, be informed by the framework developed during this research effort, resulting in the establishment of an African program to monitor and manage water quality that will benefit the environment and all of its inhabitants.

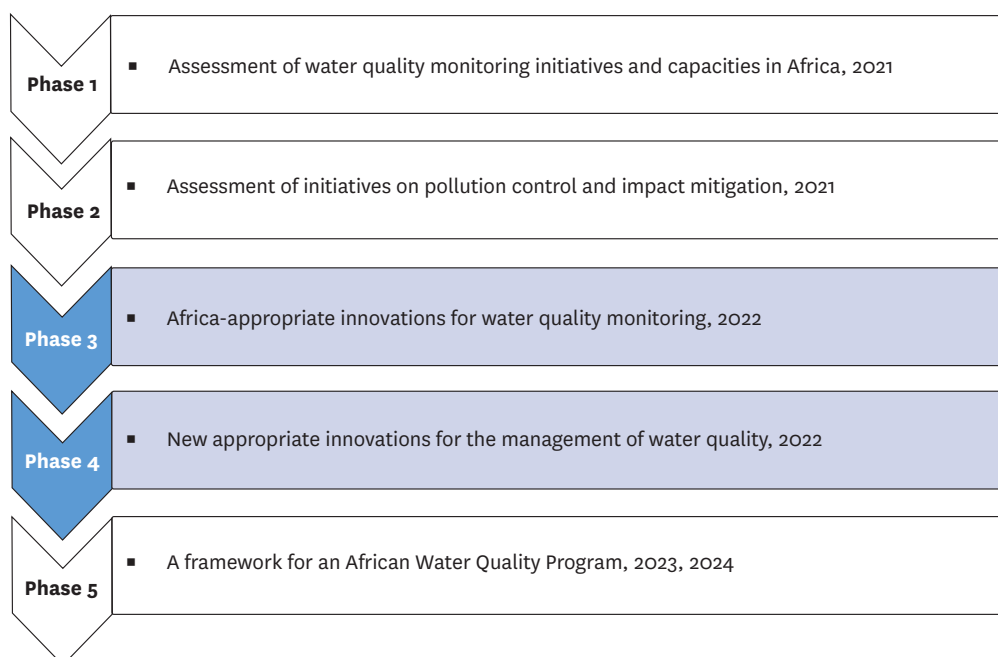


Figure 1. Five phases in the development of a framework for the African Water Quality Program.

Objectives

The objective of this paper is to contribute to the formulation of a new AMCOW African Water Quality Program with a focus on innovation designed to advance water quality monitoring and management

in the continent. This objective, informed by phases 1 and 2 of AWaQ (see Figure 1 and Mukuyu et al. 2024a), will focus on innovations in water quality monitoring and management that are already being tested, implemented or developed and which would be suitable for application in Africa.

Water Quality Monitoring

Introduction

Water quality monitoring in Africa was established in the first two phases of this study to be largely marked by inconsistencies and capacity gaps (Mukuyu et al. 2024a). The need for training in best practices among laboratory personnel as well as inadequate instrumentation and infrastructure were revealed as limiting factors in water quality monitoring and management. The use of traditional methods of water quality monitoring and management could benefit from the adoption of new and cost-effective methods and approaches that may better serve the needs of African countries. The following sections will discuss, in depth, the limitations of conventional approaches as well as innovations in water quality monitoring with the aim of highlighting their applicability within the African context.

Limitations of Conventional Approaches and Practices in Africa

Phases 1 and 2 of this project (Mukuyu et al. 2024a) illustrated the inconsistent implementation of water quality monitoring practices across Africa. While some countries operate extensive and advanced programs, others struggle with implementing even basic monitoring (UNEP GEMS/Water 2020a). Creating a continent-wide picture of the water quality in rivers, lakes and aquifers, along with an understanding of how this picture is changing over time is currently not possible due to multiple challenges associated with variable monitoring and regulatory standards. The issues faced in developing and delivering effective water quality monitoring in Africa are significant. Each country is unique and faces a specific set of challenges. However, many of these challenges are shared, with enormous potential for peer-to-peer learning to be engrained within the AWaQ framework. As efforts to monitor water quality in Africa are constrained by numerous factors, this section discusses these limitations in the context of current and recent water quality monitoring practices.

Capacity Gaps

The dedicated personnel working to monitor and assess their country's freshwater often perform their roles in challenging circumstances. Significant constraints include insufficient staff numbers, inadequate staff training, inconsistent revenue streams that are needed to provide a constant supply of consumables and replace basic equipment, and also a lack of capital investment to build laboratories and purchase key pieces of equipment.

Conventional approaches to monitoring could provide good water quality information if suitably financed, but this is rarely the case across Africa. The observed inadequacies of active monitoring programs can be directly linked to the capacity gaps listed above. The type of training required to address technical capacity gaps includes field sampling techniques, laboratory procedures, quality assurance, data management as well as data analysis and reporting. An understanding of how water bodies function and how this knowledge can be used to support effective monitoring program design as well as to interpret results is also observed to be lacking (UNEP GEMS/Water 2020a).

To enable effective monitoring programs, there is a need to extend beyond the technical capacity development of personnel, and to include supportive institutional arrangements based on sound policy and institutional coherence. This can be aided by raising awareness of the importance of water quality monitoring in addition to the resultant impacts of poor water quality on human health, agriculture, environment and tourism and the subsequent economic consequences (Damania et al. 2019).

Data Gaps

Water quality data are less consistently collected in Africa as compared to other world regions, with limited availability of information on the current state of water bodies and how they are transforming over time.

These changes may be in response to widespread human activities such as agriculture, but they may be also relevant at a more local scale such as the site of a wastewater effluent or associated with a specific activity such as mining. This data gap is pronounced for basic parameters that help provide an overall picture of a water body's health and the health of the freshwater ecosystem. Additionally, there is limited data on specific pollutants that may harm human health if present in water used for drinking, irrigation or recreation.

This data gap is highlighted by the UNEP Global Freshwater Quality database GEMStat,¹ which is the most comprehensive global database of in situ data currently available. GEMStat comprises of voluntary submissions provided mainly by national governmental organizations in the spirit of data sharing and openness.

Another example that demonstrates the relative lack of data from Africa is shown by the SDG indicator 6.3.2 progress report (UNEP 2021). It requires countries to submit information on water quality every 3 years and, currently, data from 31 African countries are available (Figure 2). This indicator provides a useful snapshot of water quality at the continental scale. This map is useful, but it does not clearly represent the amount of data being used in each country. As part of the same data request,

countries are asked to include information about their monitoring networks such as the number of monitoring values and monitoring stations used in their assessment. This additional information can be used to generate a useful metric of a country's monitoring capacity. Of the countries that provided this information in 2020, the global average density of surface water monitoring stations was 7.5 per 1,000 km². For Africa,² however, the density was much lower at 0.82 km², i.e., one monitoring station for every 1,220 km². This suggests that, in Africa, significantly fewer monitoring stations are being utilized to collect data than on a global scale.

With suitable investment and targeted capacity development, existing monitoring programs can be expanded to increase the monitoring station density and improve the subsequent data flows. However, historical data that can be used to define reference or baseline conditions and used to define the natural state of a water body prove to be a more critical data gap.

Establishing a reference condition is a fundamental prerequisite for certain management objectives; for example, to restore an impacted water body to a natural or near-natural condition. However, in many African countries, there is insufficient information on the condition of most water bodies prior to significant

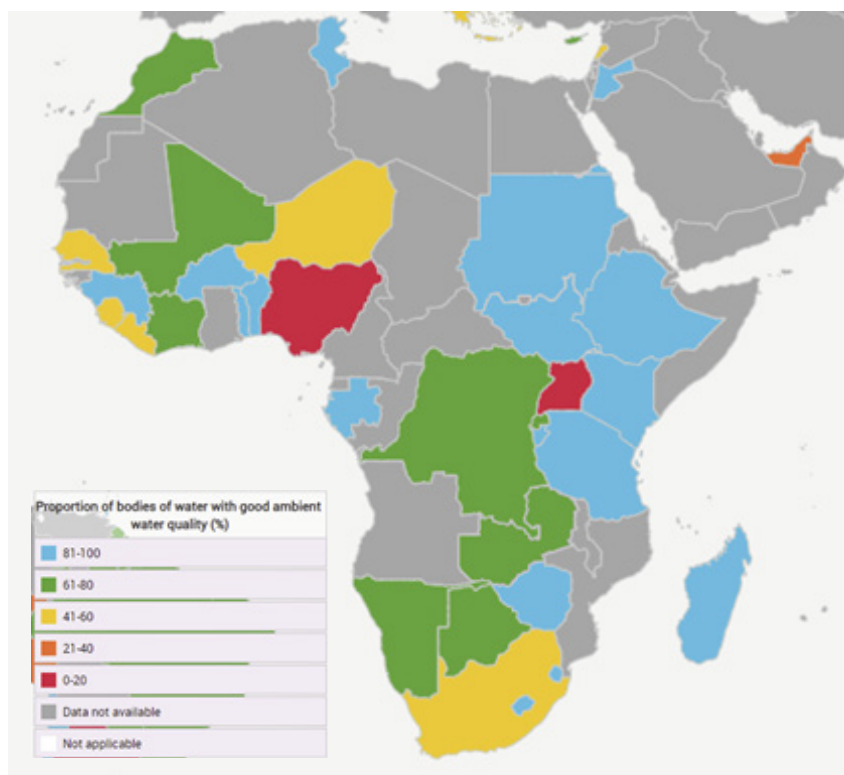


Figure 2. SDG Indicator 6.3.2 (ambient water quality) showing the available data for the period 2017-2020.

Source: Adapted from UNEP 2021.

¹ <https://gemstat.org/>

² Personal communication with an official from the UNEP GEMS/Water program on October 4, 2021.

human influence. This lack of historical water quality data makes it difficult to know how far removed from a natural condition a measured status is, making the completion of a reliable assessment more difficult to achieve. While it is possible to estimate this condition based on other water bodies that may have similar geological, climatic and hydrological characteristics, this undertaking requires a detailed assessment, often reliant on expert opinion.

Groundwaters are the least monitored of the three freshwater body types (rivers, lakes and groundwater), not merely in Africa, but across all world regions (IAH 2017). This is in part due to the relative complexity of monitoring groundwaters when compared with surface waters. This is also a factor of a lack of hydrogeological knowledge in many countries which undermines the initial monitoring program design and the interpretation of any outputs (Chilton 2020).

Biological monitoring, or biomonitoring, forms an essential component of many monitoring programs globally in provisioning a comprehensive indication of water quality and/or ecosystem health (see section *Biological Monitoring*). Biomonitoring is overall less commonly undertaken in African countries despite the presence of some advanced programs such as the River Eco-status Monitoring Programme (REMP) in South Africa.³ An assessment of ecosystem health offers information on the integrity of aquatic ecosystems and their ability to continue to provide ecosystem services such as water for drinking, food for eating and recreational activities.

In addition to those listed above, there are considerable data gaps concerning specific pollutants. Pathogenic pollution is widespread in Africa and endangers human health and causes avoidable deaths. Monitoring at the point of use is common, although not universal, with many people using water directly without any information on its suitability or safety for particular uses. Apart from simply increasing the monitoring, this situation could be ameliorated with better information on the sources of pollution, the pathways by which pollution is transported and information regarding the receptor's capacity to ameliorate the pollution. This is applicable from the very local up to the catchment scale, and supports the concept of river-basin scale monitoring and management.

There are many water quality parameters that are only rarely monitored in Africa; information on their concentration and distribution is almost entirely unknown. Emerging and less commonly recognized chemical contaminants, more commonly called emerging pollutants (EPs), are often associated with domestic and industrial wastewater effluents (Necibi et al. 2021). Monitoring programs that struggle to collect data and assess the impacts of basic physicochemical parameters, such as nutrients, are ill-equipped to accurately monitor

concentrations of EPs which are often found at very low concentrations in the environment. Given the unknown consequences of the cumulative effects of these compounds that may originate from disparate sources yet have a combined impact on human and/or ecosystem health (Stasinakis and Gatidou 2010), efforts to address this data gap should be pursued.

Quantity and quality of sediment in African rivers is scant. While activities such as industrial or artisanal mining, deforestation and agriculture are capable of mobilizing huge quantities of sediment from land to surface waters, not all activities result in an increase in sediment transport. Dams retain sediment causing a downstream sediment deficit; sand mining can lead to huge quantities of sediment being removed (Leal Filho et al. 2021). This interplay of pressures on natural sediment flow can have catastrophic socioeconomic as well as environmental impacts that extend beyond rivers and lakes to deltas and coastal zones. Data on both natural sediment dynamics and the cumulative impacts of activities at the catchment scale are largely unavailable.

In summary, there are significant water quality data gaps in Africa due to limited monitoring activities, both currently and historically. Although groundwaters usually require less frequent monitoring than surface waters, information on these water bodies is relatively scarce. Biomonitoring is less commonly practiced compared to physicochemical monitoring but provides critical information on the health of freshwater ecosystems. There is a data gap on numerous specific pollutants such as pathogens and geogenic pollutants, but one of the greatest unknowns are EPs and their potential health concerns. Lastly, sediment plays an important role in the health of Africa's surface waters, but natural sediment dynamics are being impacted by various human activities with insufficient understanding of the consequences.

Information Gaps

The significant capacity and data gaps listed above manifest as information gaps for decision-makers and policy makers. In the absence of appropriate data generation, identifying patterns and trends in water quality over space and time is daunting. This in turn leads to an information deficit about the current impacts on water quality. Generating estimations on future scenarios is also rendered more difficult given the predicted population growth and climate change. Water resources cannot be managed without information generated from credible and reliable monitoring programs notwithstanding the increasing importance of citizen science data.

SDG indicator 6.3.2 is an example of a simple water quality indicator that classifies water quality by comparing the measurements of five basic core parameters with relevant

³ https://www.dws.gov.za/iwqs/rhp/rhp_background.aspx

target values (water quality standards in some cases); it then applies an 80% compliance rate to classify a water body as either 'good' quality or not. There are many other indicators (Uddin et al. 2021) that are more sensitive to specific pressures on water quality that can provide additional targeted information such as those pertaining to particular activities, or that focus on certain aspects of water quality such as eutrophication or sediment load. New indicators designed to fill specific information gaps are necessary at regional and continental scales.

Information can be created by combining existing data from different sources. Coordination between organizations responsible for monitoring within each country is often weak (UNEP GEMS/Water 2020a). In certain countries, one organization may monitor surface water quality, another groundwater, and yet another which collects hydrometeorological data (including water quantity). If coordination between these organizations is weak, potential information remains hidden or is unavailable for assessment. For information gaps to be filled, better coordination mechanisms are necessary to make the best use of any available data.

Monitoring Innovations Being Tested and Used Globally

This section considers global innovations in water quality monitoring with respect to their suitability for African conditions.

Design of Monitoring Programs

Monitoring programs are a vital aspect of managing water quality — they enable the current situation to be determined, spatial and temporal differences in water quality to be observed, and progress with management actions to be evaluated. In order to ensure that a monitoring program can meet expectations and provide the essential information and data for the anticipated management purposes, it must have defined objectives that are precise and realistic (practically as well as financially). Many monitoring programs are mandated to determine trends in water quality and/or whether water quality meets the set criteria (targets, quality objectives, guidelines, quality criteria, etc.). The objectives should enable the appropriate selection of the approaches needed to gather the data, the water quality parameters to be monitored, and the appropriate spatial and temporal coverage required. The anticipated use of the data generated and thus the required levels of accuracy, precision and comparability should further be indicated. Appropriate selection of all of these aspects is essential to ensure the monitoring program supports water quality management in the most economical and cost-effective way.

There are different approaches to monitoring water quality (physical, chemical and biological), many of which have been tried and tested at national and international scales for decades, to generate information for management. In addition, however, there are also many new developments

in monitoring approaches and methods that have not yet been harnessed at the national or international scale and for which the relevant cost-benefits are difficult to assess. Therefore, in the consideration of new innovations for inclusion in a monitoring program, it is necessary to examine whether they can make a beneficial contribution and meet the needs of the objectives of the monitoring program. Such innovations may, for instance, enable better data gathering over greater spatial areas or at greater frequency, or with a higher or lower level of accuracy and precision.

When designing a monitoring program, it is essential to consider potential natural influences on the water quality of the freshwater system(s), i.e., geographical, climatological and biological. A good understanding of how the water bodies function enables the appropriate selection of the temporal and spatial needs of the water quality monitoring program. Subsequently, natural causes of variability can be anticipated and factored into the measurement program and the resultant data assessment.

There are seven key steps in the process of designing a monitoring program:

- Reviewing available information on the water bodies, existing monitoring programs, methods and data, and any potential constraints on field and laboratory activities, such as access to sampling sites, equipment, and human and financial resources.
- Setting monitoring program objectives, including expected outputs for management purposes.
- Selection of monitoring approaches, specific parameters and methods to be used in the field and laboratory.
- Development of a monitoring network, which involves the selection of sampling locations while considering any potential natural and anthropogenic influences on water quality at the locations.
- Selection of frequency of measurements for each parameter, accounting for any natural variations, such as seasonal influences, on the parameters being monitored, as well as any anticipated variability, such as periodic effluent discharges or seasonal use of agricultural chemicals.
- Deciding how monitoring data will be recorded, stored and shared. This may involve the creation of a new database, or expanding/modifying an existing data handling system.
- Preparing a quality assurance plan specifying the accuracy, precision and quality checks required in the field and laboratory, and for the management of data.

Management of freshwater resources should be undertaken at catchment scale and thus many monitoring programs are tailored to individual catchments — particularly in terms of the intensity of monitoring and the range of parameters included. Catchments and sub-catchments can be delineated according to variability within the catchment, e.g., intensity of urbanization or agriculture; very large catchments may involve international collaboration for the monitoring of transboundary water bodies. In order to describe catchments, sub-catchments and transboundary systems, a global database of river basins, HydroBASINS,⁴ is available online to assist with planning monitoring networks. A recent advancement of this project, HydroATLAS,⁵ includes many hydrological and environmental characteristics for each defined basin unit that can be used to inform monitoring program design. These basin units, ranging in scale from approximately 10 km wide up to continental size, are appropriate for monitoring programs of various scales. Ideally, an integrated monitoring approach should include surface water and groundwater. The associated monitoring program(s) and networks should include hydrological and water quality measurements, taking into consideration the point and diffuse sources of pollution, as well as water abstraction and hydromorphological modifications within the catchment (dams and their associated reservoirs).

Traditional approaches to monitoring water quality rely on physical and chemical measurements, which are then sometimes compiled into a water quality index that is more easily understood by non-experts. In recent decades, the drive to protect and restore freshwater ecosystems — not merely for the ecosystems themselves but also for their social benefits — has resulted in a growth in monitoring approaches that include the biological components of the ecosystem. Where human health may be affected by water quality, microbiological and contaminant monitoring are important. Microbiological monitoring has often been overlooked as a means of identifying sources of fecal pollution and their (human or animal) origin (Hagedorn et al. 2011).

As an innovative approach to monitoring water quality, the use of reflectance data from satellites, planes and drones, is still limited to certain types of water body (mainly large lakes) and relatively few parameters (e.g., chlorophyll) but examples of its inclusion in monitoring programs are increasing rapidly.

Selection of monitoring parameters

Some water quality monitoring programs have very specific objectives, such as checking compliance with criteria for drinking or irrigation, or monitoring the impacts of a wastewater discharge. These objectives have associated, specific monitoring parameters. However, in order to comprehensively recognize the observed changes

in water quality, monitoring programs should include basic parameters such as pH, major ions, temperature and oxygen concentrations. These characterize the water, aid in interpretation of other measurements and can influence other water quality parameters. Understanding the natural ambient water quality based on these basic parameters allows for an assessment of the state of the water quality. Such basic parameters now have many new corresponding sensors and field kits to be deployed for different monitoring scenarios, such as early warning of change, high frequency measurements, and for use with citizen monitoring programs (see section *Citizen Science*), for intensive surveys or for greater spatial coverage. Additional parameters to be included depend on the objectives of the monitoring program and are typically selected from the following groups: nutrients which drive the productivity of the freshwater ecosystem (i.e., forms of nitrogen (N), phosphorus (P) and silicon), contaminants (including an increasing number of newly emerging contaminants such as pharmaceutical residues), and pathogens, such as fecal coliforms. Specific innovations for monitoring are elaborated in the section *Monitoring Innovations Being Tested and Used Globally*.

Monitoring for many diverse contaminants, or for all potential pathogens, is usually not feasible due to economic and resource constraints. Consequently, there is a constant search for cheaper and easier surrogate measurements, and for methods to assist in selection of the most appropriate parameters. An example is the use of rapid test kits for identifying the simple presence or absence of *Escherichia coli* (*E. coli*) as an indicator of fecal material. The presence of fecal material indicates a potential risk to human health from many different pathogens transmissible through the fecal-oral route, yet is difficult or expensive to monitor. Contaminants, including those that may be toxic for people and animals, often occur at very low concentrations in surface water and groundwater and may be difficult to detect or measure without highly advanced sample preparation and analysis techniques. Inclusion in a monitoring program should only be considered if the objective is to confirm their presence or to quantify their potential risk. Some alternatives to complex sampling and analysis are: (i) measuring the contaminants in the media that concentrate them, such as biological tissues; (ii) focusing on specific forms that may have implications for transport or distribution in the catchment, e.g., particulate matter; and (iii) modelling concentrations and distribution in water bodies based on known emissions.

Modelling can be done at different scales from local to global for a wide range of potential water quality issues. For example, a modelling approach recommended by the Organisation for Economic Co-operation and Development (OECD) (OECD 2019) can aid in better policy and management for pharmaceutical residues. Modelling concentrations in water bodies can be based on

⁴ <https://hydrosheds.org/page/hydrobasins>

⁵ <https://www.hydrosheds.org/page/hydroatlas>

measurements from actual discharges, discharge volumes and mixing in the water body; these may be a suitable alternative to expensive sampling and analysis techniques. The modelled results can be validated with selected samples and analyses from the water bodies receiving the discharge. However, modelling is more complex when there are many sources of the same contaminants in the catchment or water body.

Modelling can be a useful approach to predict concentrations when a risk-based approach is taken to select priority pollutants or compounds likely to present the greatest environmental or human health risk in water bodies (Oosterhuis et al. 2013; Wajsman and Rudén 2006), particularly in smaller water basins (Kugathas et al. 2012). A recent innovation, for microbiological monitoring of *E. Coli*, has been to apply machine learning to enhance predicted concentrations (Naloufi et al. 2021).

Modelling has also been shown to be useful for predicting the development of harmful algal blooms (HABs) which are of particular concern in drinking water sources, especially reservoirs. It can reduce the need for frequent or continuous monitoring for the specific HAB species, or suitable surrogate parameters, e.g., phycocyanins. For management purposes, the modelling needs to be site-specific (Rousso et al. 2020).

The European Union has adopted a priority pollutant approach that prescribes a list of compounds that must be included in monitoring programs. The list includes pesticides and herbicides, some metals, and organic compounds such as polyaromatic hydrocarbons and polybrominated biphenylethers (EU 2013). It is periodically revised as new pollutants or new information about toxicity emerges. In addition, this list does not preclude countries from including additional compounds that are important nationally or in specific locations. Similarly, in South Africa, the Resource Quality Objectives approach has been adopted to focus only on important variables at each site, thus enabling cost reduction in monitoring (DWA 2011).

Sampling design and monitoring locations

In general, the greater the number of monitoring locations throughout a water body or in a monitoring network, the more likely it is that the measurements accurately represent the water quality status at the time of sampling. However, a large number of monitoring locations requires considerable human and financial resources, necessitating a balance between the resources available and an acceptable representation of the water quality. Ideally, water quality monitoring locations should be close to water quantity gauging stations to facilitate an understanding of the relative influence of point and diffuse discharges to the water body as well as to enable direct comparison of water quality data over spatial and temporal scales by calculating loadings. However, the locations of gauging stations may not be suitable to meet

the objective of a water quality monitoring program and hence additional monitoring locations may need to be included. A means of determining discharge should always be included in the data collection at these locations, such as water level or velocity, which will allow the loading of pollutants to be estimated.

Within a river catchment, it is usually recommended that, at the very minimum, there should be at least one monitoring location:

- in the headwaters to indicate relatively 'pristine' water quality,
- at the point where the catchment discharges to the sea or a lake (often called a flux station), and
- where tributaries join the main river or where major impacts are anticipated, such as immediately downstream of an urban area or a wastewater discharge.

For lakes, the monitoring network should include the major inputs and outputs, with at least one location in the open water body. Large lakes, or those containing several basins, benefit from several monitoring locations, ideally including sampling at depth.

In the past, selection of monitoring locations was often based on scientific judgement and local knowledge about factors such as possible sources of impacts on water quality, ease of access, etc. High resolution, freely available, satellite imagery such as Google Earth has considerably assisted the identification of potential locations. In recent years, there has also been notable advancement in the use of statistical modelling techniques to aid in refining sampling networks and reducing the number of sampling locations. However, many of these approaches rely on the usage of existing long-term data sets (O'Hare et al. 2020) and are therefore more suitable for refining existing monitoring programs. Examples using Combined Cluster and Discriminant Analysis (CCDA) for rivers have been provided by Kovács et al. (2014, 2015a, 2015b) and Tanos et al. (2015), for ungauged river basins by Lee et al. (2014a) and for optimizing lake and reservoir sampling locations using information theory by Lee et al. (2014b). Filik Iscen et al. (2008) give examples of dimension reduction methods, such as principal component-, factor-, or redundancy analysis. Canonical correspondence analysis and artificial neural networks have been applied for groundwater by Khader and McKee (2014) and self-organized maps by Khalil et al. (2011) have also been deployed to explore the spatial or temporal structure of the data.

Monitoring frequency

The frequency of monitoring at the same locations is usually a compromise between resource availability and the need to capture the impacts of specific influences on water quality. Traditionally, grab samples have been taken at specific times to indicate the water quality at that given

time, but new techniques enabling rapid or continuous monitoring are now becoming widely available, including the potential to trigger sampling events remotely using mobile data networks and fixed samplers. Where the objective is to protect human health, measurements may need to be taken frequently, i.e., weekly, daily or even continuously. On the other hand, seasonal impacts (e.g., rainfall causing runoff, population increases due to tourism, agricultural use of fertilizer and pesticides) may only require three or four samples a year. Robust growth in urbanization and climate change may only require annual samples over multiple years. Where monitoring occurs on an annual basis, it is important that the same sampling and analysis protocols are followed from year to year to ensure the comparability of data. Ecosystem change is usually quite slow, so monitoring may only be needed annually or even every few years. As with optimizing monitoring locations, computational techniques can also be used to optimize sampling frequency (both temporally and spatially).

Field and Laboratory Techniques and Associated Instrumentation

There are comprehensive international guidelines and standards available on the traditional water quality monitoring analytical techniques, such as the International Organization for Standardization (ISO) guidelines. In addition, other standard methods developed by countries such as USA, Switzerland, Germany and Australia have also been widely adapted by other countries. Annex 1 indicates standard methods that are available for water quality analysis based on different water quality parameters.

Water quality monitoring techniques are continuously being advanced. Major improvements for broader applicability include tailored sampling techniques, screening and identification techniques for a broader and more diverse set of chemicals, higher detection sensitivity, and standardized protocols for chemical, toxicological and ecological assessments combined with systematic evidence evaluation techniques (Altenburger et al. 2019).

Potential risks from a wide variety of emerging pollutants in the water ecosystem also demand the development of continuously evolving monitoring technology (Zolkefli et al. 2020). Consequently, many analytical methodologies have been developed for specific monitoring purposes. Among the instrumental techniques applied, gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are the most commonly used (EMCO, CSIC and TMF 2007).

In situ sensors

Evolutions in water quality monitoring have responded to the current needs to understand and manage water quality more effectively. This need is driven by various factors including the protection of domestic water

supplies, regulatory compliance, climate change, emerging pollutants, ecosystem protection and increasing spatial coverage. Rapid water quality assessments are particularly desired in the face of life-threatening situations such as drinking water contamination. Similarly, real-time water quality monitoring enables efficient water management to protect ecological integrity of aquatic ecosystems (de Lima et al. 2020).

Innovative water quality monitoring techniques attempt to address conventional limitations by allowing the operator to monitor water continuously for deviations from defined standards and to be able to report them as real-time data (see Table 1). Real-time sensor monitoring is an innovative technique increasingly applied for efficient data collection in recent times. The availability of different sensors in the market allows for application basis the location and/or the different and changing guidelines in a given country (see Annex 2).

As the technology in sensors continues to advance, the number of parameters that can be monitored also rises. However, each sensor may have unique deployment requirements, with each requiring specific deployment and maintenance considerations. Common sensors currently measure the following:

- Temperature
- Electrical conductivity
- pH
- Dissolved oxygen
- Turbidity
- Nitrate
- Chlorophyll

Traditional in situ monitoring techniques have evolved to use wireless sensor networks and to undertake smart monitoring with information and communications technology (ICT) applications. The utilization of ICT with sensor technology shows great potential for the monitoring, transmission and management of in situ water quality data and enables efficient and real-time monitoring of water quality, the prediction of future trends in water quality, and rapid responses to toxic events (e.g., HABs) in water resources (Park et al. 2020).

Deployment of Instrumentation

Traditional water quality monitoring methods largely depend on field personnel travelling to specific sites for monitoring. On-site tests are conducted for physical parameters and rapid ecological assessments while for other measurements, samples are sent to laboratories for testing. While laboratory tests are more accurate, this traditional approach is generally associated with higher costs (O'Flynn et al. 2010), such as travelling costs to sites that are distant or difficult to access which hinders monitoring. In addition, sample preservation is also a challenge within some contexts. In resource-constrained environments such as those in

Table 1. Evolution of water quality monitoring techniques related to in situ sensors.

| Water quality monitoring scheme | Description | Pros and cons |
|--|--|--|
| Enhanced traditional water quality monitoring | Measuring some water quality parameters on-site using portable sensors. | Still unable to offer real-time feedback about water quality, with limited spatial resolution due to data still being collected manually, transport delays, etc. |
| WSN (wireless sensor network)-based water quality monitoring | An embedded microprocessor-based gadget (also called node) reads specific water properties using portable sensors (e.g., pH) installed on-site which process the acquired data locally if required. The data are transferred to a main station (e.g., server computer) using wireless communication media (e.g., Zigbee, Wi-Fi and LoRaWAN), where all required processing and analysis are carried out. | Used for monitoring of big natural water systems. Ability for real-time detection of massive data with relatively low costs. |
| WSN and Machine Learning (ML) techniques-based water quality monitoring | Can be used to assess water quality using a small number of water quality monitoring parameters and predict future trends. | High energy requirements, compromised security, low communication speed, storage issues and high installation/maintenance costs. |
| Smart water quality monitoring (Internet of Things [IoT]-based monitoring) | Water can be monitored in real time from any location of the world using a combination of portable sensors, digital computing devices, communication media (e.g., Transmission Control Protocol/Internet Protocol [TCP/IP]), and internet services. | Low cost, increased spatial resolution, low computational cost, low energy requirements, provision of real-time feedback, developers can easily integrate analytical tools (e.g., ML techniques) in a cloud server to infer some water quality monitoring parameters based on measured values of these parameters using sensors and can predict future water trends. |

Source: Jan et al. 2021.

Africa, this has resulted in the collapse of monitoring programs due to the high associated costs coupled with the lack of a regular monitoring schedule. In this section, some of the innovations in the deployment of instrumentation that counter the challenges experienced in traditional water quality monitoring are discussed.

Deployment of instruments is fundamental to procuring quality data and varies across different types of water bodies, e.g., shallow lakes, rivers and streams. When instruments are deployed inappropriately, it may result in instrument fouling which leads to a reduction in data quality. This is observed particularly in instruments deployed and left in situ while data are transmitted remotely. Different deployment methods allow for access in different environments. Examples of traditional deployment include instruments deployed from a bridge tied within a polyvinyl chloride (PVC) casing or tied to a buoy (Webber 2020).

Progress in different deployment methods has been observed across the globe, most notably in the developed countries, yet less so in the Global South (Sibanda et al. 2021). This review provides a broad overview of innovations in deployment methods using emerging technologies.

Remotely operated and unmanned vehicles

Technological advancements in the development of remotely operated vehicles (ROVs), also known as underwater drones, have led to opportunities in exploring deep aquatic environments. They help in reducing costs that would otherwise be associated with deploying divers to carry out underwater monitoring (de Lima et al. 2020). ROVs are tethered to the boat and controlled by an operator. While testing these gadgets for water quality monitoring, de Lima et al. (2020) noted challenges with maneuvering the drone and with visibility in turbid waters. Delay in transmission of the video is also a hindrance

which resulted in difficulties in maneuvering the drone accurately.

Lally et al. (2019) reviewed the applicability of drone technology in sampling and collecting hydro-chemical data and observed certain challenges with large-scale implementation of the technology despite the notable advancements. These challenges include the accuracy of data obtained through drones and the limited volumes of water that can be collected. Nonetheless, refinements may result in better applicability. In addition, ROV technologies have been widely commercialized and it is important to select the most appropriate product with applicable features.

The use of unmanned aerial vehicles (UAVs) has its roots in military operations and is more than 40 years old. UAVs or drones are gaining attention for their application in various sectors where a visual understanding of the sources of pollution is of concern, including the identification of irrigation water quality and quantity (Sibanda et al. 2021). Drones are also being used to observe/identify pollution incidents, check sampling location access and deploy optical measurement instruments.

Koparan et al. (2018) tested an unmanned aerial vehicle for in situ water quality measurement where a custom hexacopter equipped with an electronic sensors platform to measure the temperature, electrical conductivity, dissolved oxygen, and pH was built. Several variables that impact the data collection process were observed using the testing (Table 2). While the cost of using a drone to collect samples may seem high, the technology may become cost-effective in specialized situations, especially where access is difficult.

The disadvantages of using drone technology in water quality monitoring in Africa are associated with regulations around the usage and operation of such unmanned aerial vehicles, including the height at which they should be operated. A drone operating licence is also needed, which may be prohibitive for most African contexts (Sibanda et al. 2021). Such challenges have limited the scale of their use in African countries and their potential benefit in water quality monitoring.

Satellite-based Earth Observation

This section looks at satellite-based Earth observation (EO). Solar radiation that hits a water body is either reflected by the surface or is absorbed and interacts with material in the water column. The light that emerges from the water body surface is termed the emerging flux, and it is this signal that can be captured by the cameras and sensors mounted on orbiting satellites. The ‘fingerprint’

of the emerging flux is specific to the concentrations of constituents such as chlorophyll-a or the turbidity present in the water column.

Deployment of satellites equipped with multispectral sensors for EO began in 1972 with the launch of the National Aeronautics and Space Administration’s (NASA’s) Landsat 1⁶ (Tatem et al. 2008). More recent programs — the European Space Agency’s Sentinel 3 satellites⁷ and NASA’s Landsat 8⁸ — are capable of data collection at improved spatial resolution scales and at much narrower bandwidths (improved spectral resolution).

Advantages of using EO to monitor water quality include data capture over large areas at high temporal resolution compared with in situ data collection. EO satellites are constantly collecting data and frequently overpass the same water body, with a revisit rate measured in days depending on the altitude and orbit of the satellite, thereby ensuring a constant and regular data flow. Furthermore, a single EO image often captures the entire lake surface at a particular moment in time. Achieving comparable coverage from an in situ program is practically impossible. Furthermore, EO images do not recognize geopolitical boundaries and capture comparable data from both sides of international borders.

Although the cost of launching and operating EO satellites and managing the massive quantities of data generated may run into multi-million dollar figures, many EO products are made freely available to the end-user, such as those from Landsat and Sentinel programs. In addition, there are several commercial companies offering processed products at high spatial resolution that may focus on specific parameters or monitoring objectives such as EOMAP.⁹

Despite the many advantages of applying EO technology in monitoring water quality, there are significant limitations for potential users. Primarily, the range of parameters that can be detected is limited to those that are optically active such as turbidity, chlorophyll-a, suspended solids and colored dissolved organic matter. Monitoring parameters such as pH or electrical conductivity is not possible because there is no optical ‘fingerprint’ associated with them.

Efforts to improve the spatial resolution of EO approaches have been successful, with the spatial resolution continually improving. However, this approach is at present only suitable for certain water body types. First, they must be large such as large lakes, large rivers, estuaries or coastal waters. For smaller water bodies, the resolution of the sensors may not be sufficiently sensitive to discern between the water’s surface and vegetation

⁶ <https://landsat.gsfc.nasa.gov/satellites/landsat-1/>

⁷ <https://sentinel.esa.int/web/sentinel/missions/sentinel-3>

⁸ <https://landsat.gsfc.nasa.gov/satellites/landsat-8/>

⁹ <https://www.eomap.com/>

Table 2. Advantages and disadvantages of UAVs and ROVs as instrument deployment methods.

| Unmanned Aerial Vehicles/Remotely Operated Vehicles | |
|---|---|
| Advantages | Can be deployed in difficult to access locations and terrains Can be used in hazardous environments, such as contaminated areas, for sample collection Faster data collection Autonomous in situ water quality measurement |
| Disadvantages | Accuracy of maneuvering and positioning Low battery life — differences across several commercial products Mounted sensors are still required to be accurate In-flight wind interference Payload capabilities |

Source: Adapted from Koparan et al. 2018.

along the shoreline. Second, shallow clear lakes can cause problems because the emerging flux may be affected by the presence of material on the lake bottom rather than that suspended in the water column.

Lakes are complex systems with biological, chemical and physical processes ongoing throughout the water column. However, EO approaches can only gather information from the surface or near-surface with little or no information from the depths. This is especially relevant when defining trophic status of lakes. For this type of assessment, information from multiple depths is required, particularly if the lake stratifies during periods of the year. This is not possible using EO alone, which can only provide partial information for this kind of assessment.

Once an image has been captured, certain factors must be accounted for to ensure the reliability of information. When high concentrations of multiple parameters, such as high turbidity and chlorophyll are simultaneously present in the water column, it can be difficult to distinguish between them accurately. Atmospheric pollution too, such as smoke or smog, can influence the emerging flux signal, making corrections necessary. Cloud cover is the biggest issue because the wavelengths used are all within the visible electromagnetic radiation wavelengths, unable to penetrate clouds.

Concentrations of parameters generated from EO imagery are based on algorithms that relate the intensity and bandwidth of the reflectance signal captured at the sensor to provide a modelled estimation of water quality. One of the most important considerations when using EO approaches for water quality assessment is to ensure in situ validation for ensuring that the estimated concentration reflects the real-world measured concentration. This requires simultaneous sample collection timed to coincide with the satellite overpass.

Efforts to apply EO to support water resources management are broad and constantly improving. These

include the identification of harmful algal blooms, assessments of water clarity and turbidity, measurement of algal biomass and trophic status, concentrations of suspended sediments, colored dissolved organic matter, surface temperature and surface oil slicks (IOCCG 2018).

Examples of ongoing EO initiatives to monitor water quality include the following:

- Copernicus Global Land Service: Lake Water Quality: <https://land.copernicus.eu/global/products/lwq>
- UNEP's Freshwater Ecosystems Explorer for SDG 6.6.1: <https://www.sdg661.app/>
- National Oceanic and Atmospheric Administration (NOAA) Lake Erie Harmful Algal Bloom Forecast Products: https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/bulletin.html
- The Earth Observation National Eutrophication Monitoring Programme (EONEMP) developed by Cyanolakes: <http://www.cyanolakes.com/>
- Water clarity in the United States Great Lakes: Binding et al. 2015
- Early warning systems of harmful algal blooms in reservoirs (Example from South Africa: <https://www.ocims.gov.za/water-quality-theme/>)

Citizen Science

Citizen science involves individuals and communities assisting scientists and resource managers to understand and address environmental problems. Citizen monitoring has been highly successful in generating data at national and even international levels for biodiversity and air quality, for which the techniques and tools needed to record data are fairly straightforward or mainly observational (e.g., recording observations of a number of different species). Many citizens have a close relationship with their local water bodies, e.g., they use them for drinking water for themselves and their livestock, for crop irrigation, and for fishing as a source of food or recreation. Therefore, citizen engagement in monitoring

local water bodies can provide them with the knowledge and information to actively participate in preserving water quality at community level, with the provision of additional data and information that can support policy and management at the national and regional levels (Thornhill et al. 2019). For a successful citizen water quality monitoring program, it is necessary to have environmentally aware, well-trained and motivated citizens, along with consistency of funding and support from appropriate organizations, and good communication and feedback between citizens and supporting organizations (Capdevila et al. 2020).

Organizing a citizen water quality monitoring program involves the selection of participants who can access water bodies of interest on a regular basis, training them in the use of the monitoring kits or equipment, reaching a consensus on time and locations for taking measurements, providing a means for storing and accessing the data collected and engaging with them regularly for feedback. Compared with the technical and financial resources required by a national or local agency to collect data at equivalent spatial and temporal scales, citizen science can be a cost-effective option, most notably in areas where in situ monitoring is very limited (Alfonso et al. 2022). Nevertheless, despite being an innovative means of monitoring ambient water quality, local and national water agencies can be reluctant to use citizen networks for the collection of data. This is often due to perceived difficulties with assuring the quality of the data collected and with continuity of data collection. Citizen data can be useful, however, as a supplemental data source for national and international monitoring activities and is encouraged as a data source for Sustainable Development Goal 6 for water (UNEP 2021), including indicator 6.3.2 for ambient water quality. Recent pilot studies have shown the potential for citizen monitoring for water quality data for this SDG indicator (Bishop et al. 2020; Quinliven et al. 2020a, 2020b) based on simple and cheap monitoring equipment.

Great progress has been made in the development of new tools that are suitable for citizen monitoring of freshwater quality, and in understanding the most successful modes of implementing citizen science. In the last decade or so, three significant developments have made it more feasible for citizens to contribute to national and international water quality data collection: new simpler equipment with improved accuracy and ranges of detection; the development of online databases that can share and visualize the data with the citizens collecting it; and the proliferation of smartphones and the development of easy-to-use apps. A hindrance to the wider use of citizen science for water quality monitoring in the past has been the technical expertise and training needed

for citizens to use monitoring equipment for freshwater quality. Where resources permit, highly trained citizens can use the same monitoring equipment as professional water authority personnel, as is the case for some citizen programs in the USA such as the Chesapeake Monitoring Cooperative.¹⁰ A broad range of water quality parameters — temperature, bacteria - Coliscan Easygel, pH, dissolved O₂ (sensor and winkler kit), Secchi disc, transparency tube, depth, alkalinity (Hannah kit, LaMotte kit), nitrate (Hach, LaMotte), phosphate (Hannah kit, Hach ortho kit), turbidity (LaMotte kit)), as well as biological data (macroinvertebrates) — are collected by citizens to be used in the management of the water quality of Chesapeake Bay and watershed.

By contrast, some citizen water quality monitoring programs organized by nongovernmental organizations (NGOs) that are successful internationally rely on the use of simple and cheap instruments and methods. Freshwater Watch has evaluated the value of their citizen data to supplement monitoring done by the national Environment Agency in the UK (Hadj-Hammou et al. 2017). It was observed that the data can provide valuable information for water bodies that are not within the scope of the Agency for regular monitoring (i.e., those considered too small). The additional data were also useful to fill gaps in temporal and spatial coverage. Current growth in research relating to the use of citizen science and citizen monitoring in recent decades will enable more effective citizen participation in water quality monitoring at national scale (Capdevila et al. 2020; Thornhill et al. 2019; August et al. 2019) and in the development of a greater range of appropriate monitoring methods and instruments.

Examples of methods and instruments used for citizen monitoring

A citizen monitoring program for lakes in operation since 1994 is the Great Secchi Dip-In.¹¹ The Secchi disc is cheap, easily constructed, and simple to use. It provides an indication of transparency in surface water by lowering it into the water on a calibrated cord, and is used as a surrogate measure for phytoplankton concentrations or levels of dissolved organic and inorganic compounds and as a proxy for eutrophication. The European Union-funded project titled Multiscale Observation Networks for Optical monitoring of Coastal waters, Lakes and Estuaries (MONOCLE),¹² along with its partners, has developed a 3D printable mini-Secchi disk¹³ for measuring transparency (Brewin et al. 2019). They are also developing low-cost optical sensors to support water quality monitoring by regional and national agencies, including instruments that can be used by citizen groups for validation of satellite data, such as add-ons for smartphones with a corresponding app for measuring surface water

¹⁰ <https://www.chesapeakemonitoringcoop.org/>

¹¹ <https://www.nalms.org/secchidipin/>

¹² <https://monocle-h2o2o.eu/>

¹³ https://monocle-h2o2o.eu/Sensors_and_services/Mini-secchi_disk

reflectance (iSPEX;¹⁴ Burggraaff et al. 2020). In South Africa, GroundTruth sell a 'clarity tube' that is used to measure water clarity in a tube rather than at depth.¹⁵

There are many simple kits available for measuring basic water quality parameters in ambient freshwaters, but the most common parameters included in citizen monitoring programs are nutrients (N and P), turbidity, pH and electrical conductivity. Kits that have been tested and are widely used globally for citizen science efforts include those used by Freshwater Watch¹⁶ and Drinkable Rivers.¹⁷ Where drinking water is directly sourced from ambient water bodies, health-related parameters, particularly fecal bacteria, are important and should be included in citizen monitoring. Simple kits have been developed to determine the presence or absence of fecal bacteria or more specifically, *E. coli*. There are several commercial monitoring kits¹⁸ but many of these kits are beyond the budget of typical citizen monitoring programs.

One of the most successful uses of citizen monitoring is in the early detection of pollution incidents or hotspots and of the onset of blooms of potentially harmful algae, such as cyanobacteria. This can be done by simple observation and reporting using a smartphone application, such as bloomWatch¹⁹ in the USA and Bloomin' Algae²⁰ in the UK. Data from such applications are usually shared openly through an associated online data hub and can be used by regulatory bodies and other water-related organizations for management purposes. More advanced citizen science programs designed to collect long-term data for research and management of algal blooms in lakes require the collection of water samples for pigment analysis, as in the United States Environmental Protection Agency (EPA) Cyanomonitoring program.²¹

Citizens benefiting from good quality water bodies, such as fishermen, can be successfully engaged to assist with monitoring water quality using biological monitoring approaches, such as collection and identification of benthic macroinvertebrate species or recording morphometric data of fish (as in the Lake Tyers program in Australia).²² A nationwide citizen network in the UK with over 2,000 volunteers is the Anglers' Riverfly Monitoring Initiative (ARMI). The numbers of pollution-sensitive species in river samples are used in the identification of possible incidents, which are subsequently investigated

by the national regulatory authority.²³ The value of using biological communities for water quality monitoring is discussed in the section *Biological Monitoring*. While the approach itself is not novel, there have been nascent developments in adapting such methods for use in citizen monitoring programs, largely stimulated by widespread access to the internet for storing and sharing the data. One such example is miniSASS (Graham et al. 2004; Taylor et al. 2022), based on the South African Scoring System (SASS), a biomonitoring method for evaluating river health. Citizen monitoring reliant on smartphone cameras to record species lends itself to the use of machine learning for species identification, which will further simplify citizen biomonitoring (Wälchen and Mäder 2018).

A recent approach in facilitating citizens to make decisions about whether the quality of their drinking water well is a potential risk to their health does not involve taking samples. Instead, a risk score is calculated from the well user's observations of criteria that are likely to have an impact on the well water quality, such as capping of the well, human and livestock access to the well, and geology. This approach is easily facilitated through a smartphone app and can be tailored to national and local situations and conditions (Hynds et al. 2018). This risk-based approach has the potential to be expanded to other aspects of water quality and has already been proposed by the World Health Organization (WHO) for drinking water surveillance (WHO 2019).

Biological Monitoring

Human populations rely on ecosystem services provided by freshwaters, such as fish for food, and their ability to assimilate wastewaters. Therefore, sustainable management of ambient freshwater should address the entire aquatic environment, including the ecosystem and the organisms within it. Aquatic organisms are exposed, for all or part of their life cycle, to multiple impacts arising from human activities within the water body. Consequently, their responses can be used to provide information on the overall status of water quality in the locations monitored, and on any changes in status over time. Biological monitoring as a means of determining water quality has been proposed since 1902 (Kolkwitz and Marsson 1902). While it is not a new approach, innovations in its implementation are constantly being tried and tested. This section assesses the methods that have been found

¹⁴ <https://ispex.pocket.science/>

¹⁵ <http://www.groundtruth.co.za/our-products>

¹⁶ <https://www.freshwaterwatch.org/>

¹⁷ <https://drinkablerivers.org/>

¹⁸ <https://www.simplexhealth.co.uk/product/simplexhealth-water-bacteria-test-with-e-coli-detection/>; <https://www.alloratestkits.com.au/shop/e-coli-water-test-kit/>; https://www.3mireland.ie/3M/en_IE/p/c/b/petrifilm/; <https://www.idexx.com/en/water/water-products-services/colilert/>

¹⁹ <https://cyanos.org/bloomwatch/>

²⁰ <https://www.ceh.ac.uk/our-science/projects/bloomin-algae>

²¹ <https://cyanos.org/cyanomonitoring/>

²² <https://vfa.vic.gov.au/science-in-fisheries/fisheries-research-findings/community-science/angler-diary-program/diary-anglers-monitoring-lake-tyers>

²³ <https://www.riverflies.org>

to be useful or displaying potential for monitoring water quality at national or regional scales, or that can be easily adapted for local use without much additional investment in research and development.

There are four biological approaches beneficial for national and international monitoring programs:

- Identification and quantification of species and communities
- Analyzing contaminants in the tissues of biota (especially useful for potential human health impacts)
- In situ or laboratory-based bioassays
- Observation of morphological and histopathological changes

Species and community monitoring

There are many examples globally of monitoring water quality at the national level using species and communities. Most of these are based on the principle that individual species, or groups of species, have environmental preferences. Hence the presence or absence, or a change in abundance, of these species can suggest a difference from their preferred water quality. Presence, absence and abundance of species can be scored to produce a biotic index for which the index value indicates the severity of water quality deterioration. Such methods require some national or local understanding of the species associated with specific aquatic habitats and water quality. Knowledge of their tolerance of environmental disturbance, such as low oxygen levels, high turbidity (reduce light levels), excess siltation, inadequate food resources, etc., is also important. Most biological monitoring methods for water quality use benthic macroinvertebrates in rivers, with such methods now being used globally. A widely used example in Africa is the SASS (Dickens and Graham 2002). Benthic diatoms have also proved useful at the catchment level, such as in the River Danube in Europe (Liska et al. 2015), and have been proposed for use in Africa (Dalu and Froneman 2016). Some well-established methods have been accredited by ISO and have associated quality assurance protocols.²⁴

Recent innovations attempt to minimize the amount of taxonomic expertise required by focusing on a very limited number of keystone species or groups with very restricted tolerance to different aspects of water quality. Minimizing the level of identification required, such as using family level identification rather than species level, also makes it possible for citizen scientists to use such methods (see section *Citizen Science*) and facilitates rapid bioassessment protocols (see for example Barbour et al. 1999). Such methods are useful in detecting quite

severe pollution but are not very sensitive to more gradual deterioration (e.g., from diffuse pollution sources), for which detailed species identification is usually required. In order to simplify species identification, molecular methods are being developed. Often referred to as environmental DNA (eDNA) metabarcoding, they display potential to be included in routine biomonitoring programs (Pawlowski et al. 2018). A review of the use of macroinvertebrate monitoring of water quality in relation to its use for regulation and policy and for the monitoring of restoration activities is offered by Kenney et al. (2009).

Monitoring of microbiological species in ambient water quality monitoring programs is much less common than benthic invertebrates. It is, however, extremely important when water is used directly for drinking and is often the only form of monitoring carried out on groundwaters from domestic or community wells. Microbiological monitoring can be useful for locating and managing diffuse and point sources of fecal contamination. With recent innovations, it can assist in determining whether sources are of human or animal origin (Hagedorn et al. 2011). New molecular and enumeration techniques²⁵ may also make it possible to use microbiological species for regulatory monitoring, although the associated cost may be high (Oliver et al. 2010, 2014).

Contaminants in the tissues of biota

Water-soluble contaminants may be absorbed directly into the cells of aquatic organisms, and these cells may bioaccumulate the contaminants until they reach the toxic threshold for the organism. This threshold concentration can sometimes exceed the concentrations in the water in which the organisms live by several orders of magnitude. Contaminants that are insoluble in water (principally organic contaminants), but are soluble in lipid, may accumulate in the fatty tissues of living organisms. Once a contaminant moves from abiotic forms such as water or sediment into living organisms, the contaminants can then move through the food chain, with concentrations increasing in organisms higher up the food chain. This 'bioaccumulation' of contaminants can be useful for monitoring contaminants in water bodies. In particular, it is useful for the following:

- Determining transport and distribution of contaminants within a water body
- Protecting human health by measuring the concentrations of contaminants in aquatic organisms that are used as a food source, e.g., fish and shellfish
- Establishing the presence of contaminants where the concentrations in water samples may be below the limits of detection for the analytical methods available

²⁴ <https://www.iso.org/standards.html>

²⁵ For example <https://www.veracet.com/>

There are many examples of monitoring heavy metals in fish tissues, especially where the fish species are used for human consumption and may pose a risk to human health, like mercury (Hanna et al. 2015). Regular sampling of contaminants in biota can be used to examine trends and to locate contamination hotspots. In the USA, for instance, NOAA's National Centers for Coastal Ocean Science (NCCOS) have extended their National Mussel Watch Program using freshwater mussels to monitor contaminants of emerging concern in the Great Lakes of North America.²⁶ In the European Union, monitoring contaminants in biota has been embodied in the Environmental Quality Standards Directive 2008/105/EC for use in relation to the Water Framework Directive (Carere et al. 2012a, 2012b). Metal analysis in biota requires the acid digestion of the biological tissues, whereas organic solvent extraction is used for organic contaminant analysis. This is followed by standard analytical techniques such as Atomic Absorption Spectrophotometry (AAS) with flame or graphite furnace for metals and Gas Chromatography-Mass Spectrometry (GC-MS) for organic micropollutants.

Bioassays

Bioassays look for specific reactions in selected organisms, based on the principles of toxicology where a response is measured as a proportion of the population of organisms used in the test that demonstrate an effect. They are used to indicate poor water quality, usually resulting from the presence of toxins affecting specific cellular, metabolic or life cycle features of the selected organisms, such as behavior, growth, reproduction or respiration. Standardized methods utilize commercially available cultures of aquatic organisms, such as *Lemna* sp, *Daphnia magna*, *Danio rerio*, and *Vibrio fischeri* — some have been packaged to be used in kit form, e.g., Microtox®. They are most widely used for determining the relative toxicity of effluents or the presence of toxic contaminants in ambient waters by bringing samples back to the laboratory for testing with the organisms, or by diverting water from the water body through a tank containing the test organisms (see the review by Halmi 2016; a comparison of methods including new innovations by Carvalho et al. 2019 for an analysis of use and future prospects). When used as an early warning system, bioassays can reduce or eliminate the need for the regular use of complex chemical analysis for monitoring unknown or unspecified contaminants by highlighting areas of potential concern and triggering targeted sampling for chemical screening.

Morphological and histopathological changes

The usage of morphological changes as an indicator of changing water quality has been successful with fish

(Liebel et al. 2013) due to their responsiveness to the combined effects of all causes of water quality deterioration, including toxic compounds. While they do not identify the specific cause of deterioration in water quality without additional physical and chemical monitoring, they can serve to trigger additional or new monitoring activity. Commercial and recreational fishermen can observe signs of disease in fish, such as gill color and condition, growths on the skin surface, presence of parasites, deformities, etc. Such observations have been included in marine and coastal water monitoring in the UK and the USA for decades as an indication of the possible presence of toxic contaminants (Vethaak and ap Rheinalt 1992; Lang and Dethlefsen 1996), e.g., the Clean Safe Seas Environmental Monitoring Programme (CSEMP)²⁷ and in aquaculture facilities (for instance, the tool developed by WorldFish²⁸). When coupled with an online reporting mechanism, such as a smartphone app with geolocation, such an approach can be used for inland fisheries for long-term trend monitoring or in the identification of poor water quality areas or water pollution incidents.

Monitoring Innovations Applicable to Africa

Based on the discussion in the preceding sections, Table 3 presents an assessment of the applicability of such innovations within the African context. The criteria used in this assessment are based on one or more of the following principles:

- **Consistency** - clear definition of terms and objectives and the standardization of protocols on the collection, analysis and reporting of data to ensure comparability between different areas
- **Representativeness** - includes measurement of a full range of the core components of water quality, including those needed for reference conditions, benchmarks, etc.
- **Robustness** - rigorous science with justified selection of components and indicator variables based on empirical evidence
- **Informativeness** - easily understood
- **Flexibility** - can be meaningfully applied across a wide range of water bodies
- **Scalability** - application remains consistent across spatial scales (from river reach to sub-basin, basin, regional, national, and international scales)
- **Feasibility** - not highly demanding on time, labor or financial resources

²⁶ https://www.regions.noaa.gov/great-lakes/index.php/great_lakes-restoration-initiative/toxics/mussel-watch-expansion/

²⁷ https://www.bodc.ac.uk/projects/data_management/uk/merman/project_overview/

²⁸ <https://digitalarchive.worldfishcenter.org/handle/20.500.12348/4896>

Table 3. Monitoring innovations and potential for use in Africa.

| Category | Approach/innovation/technique | Purpose | Potential use in Africa | Comments |
|---|---|---|-------------------------|--|
| Monitoring program network design | Statistical analysis and modelling | Refinement of monitoring network | LIMITED | Large amounts of existing monitoring data required |
| | Satellite imagery to identify monitoring locations | Reduction in time required to visit and select locations | HIGH | High resolution imagery available freely from Google Earth |
| | HydroBASINS | Network design for river catchments | HIGH | Useful for initial selection of monitoring locations |
| Selection of monitoring parameters | Co-location of hydrometric and water quality monitoring locations | Facilitates calculation of loads/fluxes | HIGH | May require cooperation between two different government agencies and data sharing |
| | Priority pollutant approach | Focuses monitoring on high-risk compounds for human and ecosystem health | HIGH | Optimizes use of resources but must be tailored to local and/or national priorities |
| Sample collection and field analyses | Sample collection with drones | Access to difficult locations | LIMITED | Small volumes of sample only; local flight regulations may be prohibitive |
| | Remotely operated underwater vehicles | Depth sampling in mid-water situations without a boat | LIMITED | High purchase and operating costs limit use for routine sample collection |
| | Multi-parameter sensors for basic water quality variables | In situ results; no requirement for laboratory analysis | HIGH | Widely available and affordable; limited range of parameters |
| | Smart monitoring: in situ sensors with telemetry for data transfer | Reduced visits to sampling locations; real time data; reduced transcription errors | MEDIUM | Large initial financial outlay; frequent maintenance requirements to ensure high quality data; requires infrastructure for telemetry |
| Laboratory analysis | Kits and portable instruments for measuring water quality parameters in the field, e.g., N, P, turbidity, fecal coliforms | Useful for remote locations; results available on-site | HIGH | Limited range of parameters and accuracy and precision often not as good as equivalent laboratory analyses, but improvements constantly underway |
| | Standardized methods | Enables comparability between monitoring locations and laboratories performing analyses | HIGH | Standards readily available for different levels of analytical complexity |
| Multiple parameter analytical instruments | Advanced extraction and analytical techniques for pollutants of emerging concern | Analysis of residues from agricultural chemicals, veterinary and human pharmaceuticals | MEDIUM | High initial and maintenance costs, requirement for specialized personnel |
| | Multiple parameter analytical instruments | Reduction in sampling and sample processing. Increased laboratory throughput | HIGH | Resource dependent; suitable training and maintenance contracts are essential to ensure the impact of high-end equipment is maximized |

(Continued)

Table 3. Monitoring innovations and potential for use in Africa. (Continued)

| Category | Approach/innovation/technique | Purpose | Potential use in Africa | Comments |
|--|--|--|--|---|
| Biological monitoring | Biotic index based on selected indicator organisms, primarily benthic macroinvertebrates and diatoms | Indicator of general health of freshwater ecosystem | HIGH | Existing systems can be refined for national use |
| | Contaminant monitoring in fish and crustaceans | Bioaccumulation of contaminants in human food species; confirmation of presence of contaminants when concentrations in the water are below analytical detection limits | HIGH | Useful for heavy metals in mining areas and persistent organic compounds |
| | Microbiological monitoring | Risk to human health during recreation or when used as a drinking water source | HIGH | Field kits available for use in remote locations; economic laboratory methods |
| | eDNA metabarcoding and molecular techniques for species identification | Ecosystem health and pollution source identification, especially diffuse sources | LOW | Reduces the need for specialized taxonomical knowledge but training and further research needed |
| Citizen/community monitoring | Bioassays | Monitoring for the presence of unknown contaminants or mixtures of contaminants | MEDIUM | Economical early warning system. Useful for identifying when and where additional toxin monitoring required |
| | Physical and chemical monitoring with simple kits and data upload by mobile phone | Potential for greater spatial and temporal monitoring coverage than can be achieved by national agencies | HIGH | Provides supplemental data for national and international monitoring — requires training for local communities in order to ensure reliable data collection; regular engagement and feedback necessary |
| | Optical measurements for lakes using smartphones | Validation of satellite data | HIGH | Training and coordination required and availability of mobile data networks |
| | Fish kill and algal bloom recording with smartphone apps | Identification of localized pollution incidents and protection of public health | HIGH | Apps can be tailored or custom-made; mobile data networks required |
| | Monitoring using invertebrate species and smartphone identification and recording | Determination of ecosystem health and presence of pollution | HIGH | Can be tailored to local species for improved reliability |
| Observations of fish morphology and health reported by means of a smartphone app | Indicating presence of toxic pollutants | HIGH | Observation and reporting can be done by local fishing communities | |

(Continued)

Table 3. Monitoring innovations and potential for use in Africa.(Continued)

| Category | Approach/innovation/technique | Purpose | Potential use in Africa | Comments |
|---------------------|---|--|-------------------------|---|
| Sediment monitoring | Collection of particulate matter and analysis for key elements/contaminants Monitoring of sediment budgets | Tracking pollutant distribution Assess impacts of activities that affect sediment dynamics at the catchment scale | HIGH HIGH | Can be done with standard analytical laboratory facilities Will require international cooperation for transboundary rivers |
| Earth Observation | Use of satellite data for monitoring suspended solids, turbidity, chlorophyll and algal blooms in large lakes | High spatial and temporal resolution monitoring in near real-time | HIGH | Satellite data freely available. Requires trained personnel and dedicated in situ validation monitoring |
| Modelling | Predicting concentrations for selected parameters based on known emissions Predicting occurrence of harmful algal blooms in reservoirs | Reduces the need for intensive sampling and analysis Early warning for risks to human health | MEDIUM MEDIUM | Useful where effluent data are available but requires validation sampling Requires regular environmental and water quality monitoring data from the reservoirs |

Innovations in Water Quality Management

Introduction

Managing water pollution is critical in maintaining ecosystem services as well as in sustaining human development and economic productivity. Both water quality monitoring and management should receive key focus for the identification of pollution and to respond in a timely manner using the appropriate tools. All water bodies are unique, with water quality being influenced by natural phenomena as well as anthropogenic activities such as agriculture, industrial activity and wastewater. To address the challenges posed by climate change, the predicted population growth and increase in socioeconomic development in Africa, as well as the emergence of new pollutants, innovation in water pollution management is essential for ensuring the health of both humans and the ecosystems.

Limitations of Conventional Water Quality Management Approaches and Practices in Africa

This section focuses on the measures to manage and control pollution with reference to the issues underscored in phase 2 of this project (Figure 1). It highlights areas that could be strengthened when compared with practices in other world regions, such as the need to reinforce pollution control mechanisms and improve wastewater treatment. The limitations of failing to apply suitable water quality assessment measures and wastewater management practices are also described.

Environmental Water Quality Guidelines, Standards and Objectives

Ambient water quality guidelines and standards differ in their scope depending on their specific purpose. As a general principle, they serve to protect water resources focusing on the health of aquatic life and freshwater ecosystems. They define either numerical concentrations of water quality parameters (characteristics) or describe biological or other conditions such as hydrological flows that should be met to ensure the sustainability of the water resource.

Water quality standards and guidelines for specific activities and uses of water are prominently used. In contrast, standards for the water quality in rivers, lakes and groundwater that are neither linked to a particular use nor to a specific activity are relatively rare in Africa. Recent efforts to establish such standards are evident in several countries, for instance, in Zambia, Nigeria and Rwanda. While some are either undergoing development or have recently been developed, others have already been incorporated into national legislation, e.g., in South Africa (DWA 2011).

Defining the quality of water for particular uses — such as water for drinking (WHO 2017), irrigation for agriculture, supply for industrial processes, or for food or drink production — is more straightforward than for ambient water. Human use and industrial processes have clear water quality requirements — humans require drinking water free from chemical or pathogenic pollutants, low in dissolved salts and low in nitrate. Requirements for ecosystem health are more challenging to define and are dependent on numerous elements such as the local geology, geography and climate (Warner et al. 2020).

The methodology of the United Nations Sustainable Development Goal indicator 6.3.2 *Proportion of bodies of water with good ambient water quality* (UNEP GEMS/Water 2020b), stipulates that countries compare measured concentrations of nutrients, pH, dissolved oxygen and electrical conductivity against target values to classify a water body as either having good water quality or not. During the most recent round of data collection in 2020, improvements in the suitability of targets used to classify water quality were observed compared with the first global data drive of 2017, although many countries continued to use targets that were unsuitable (UNEP 2021). For ecosystem health, the most notable was the use of the WHO drinking water target value for nitrate (50 mg l^{-1} as NO_3). This is generally considered to be too high for the protection of most freshwater ecosystems — concentrations of nitrate found in unimpacted freshwaters are often much lower.

Data Management and Sharing

Poor management of water quality data limits effective water resources management in many African countries. Protocols around data recording, inputting, retrieval and archiving are rare. Centralized databases are uncommon — many countries rely on spreadsheets rather than database software, and such data are stored on computers that are rarely networked, particularly in remote laboratories.

Failure to apply data standards and protocols impedes data sharing. This is true for multiple levels from the most local, such as between laboratories within the same organization, to the global level, i.e., between national and international organizations. Data sharing can generally be straightforward if standards and formats are applied but, if this is not the case, then organizing and outputting data from a suboptimal system can be labor intensive and prone to errors. The Open Geospatial Consortium (OGC) has developed a best practice paper on water quality data management (OGC 2014) that has been incorporated widely into many national and regional data management policies. Adoption of these best practices in Africa can facilitate data sharing and interoperability around water resources management.

Application of common data standards and protocols allows data from disparate sources to be collated more easily, for instance, by bringing together data from governmental, academic and private sector organizations for a common water quality river basin assessment. This is especially relevant in the context of developing an Africa-wide data sharing policy (discussed further in phase 5 of the project [Mukuyu et al. 2024b]).

Pollution Control

Phases 1 and 2 highlighted the inadequacy of the efforts to collect and treat wastewater in Africa to maintain good water quality in the environment (Nikiema et al. 2013; AfDB, UNEP and GRID-Arendal 2020). Significant improvements in both the volume treated, and the technologies used to treat wastewater are urgently needed. Efforts to define the scale of wastewater-related water quality problems are hampered by a lack of information regarding the source and volume of wastewater generation (FAO 2021). Without transparency about wastewater generated, and how much of it is generated, appropriate management is incredibly difficult.

Ensuring that wastewater flows are discharged either into sewer systems and subsequently treated or, alternatively, treated on site or stored and transported for treatment, requires critical action. In the absence of real-world data on treatment rates, only estimations are possible. When considering the treatment of household wastewater, the estimated global average that is safely treated is 55.5%, as compared with the estimate of only 27.6% for sub-Saharan Africa (UN Habitat and WHO 2021).

This paucity of data on the volume being produced and the degree of treatment suggests that the wastewater-related impacts on freshwaters are difficult to assess. This is compounded by the reality that even when effluent is collected, treated and monitored at the point of entry into a freshwater system, the downstream impact is rarely monitored. While a well-designed ambient water quality monitoring program informed by such pollution sources will track changes in water quality over time, and measure improvements in response to management actions, this is scarcely the case in Africa.

Guaranteeing the availability of sufficient wastewater treatment capacity to meet the predicted need is vital for strategic planning. As people move up the sanitation ladder and communities are increasingly connected to sewers, an associated rise in water use and amount of wastewater generated is visible. This is especially relevant for Africa given the predicted population rise (UNDESA 2019),²⁹ but in light of the current state of information available on the impacts of wastewater, there is significant scope for improvement in the understanding of the impacts of these effluents on freshwater resources.

The important effects of agriculture on water quality are widespread and diverse. Ensuring maximized food production may sometimes compete with the goal of protecting water bodies from pollution (Chen et al. 2018). Agricultural pollution can be both point and diffuse, but the latter is often more difficult to assess and control. The discussion in the section *Management Innovations Applicable to Africa* examines some solutions to improve agricultural management practices.

Organizational Disconnect

Water quality is managed both directly and indirectly across multiple sectors with contributions from government institutions as well as the private sector. These sectors include water supply, sanitation, agriculture, forestry, industry, mining, health and tourism.

At a governmental level, several ministries are involved, with multiple organizations within each ministry having overlapping mandates and contrasting objectives. This situation lends itself to disjointed management with no clear overview by one organization. This is exemplified by legacy issues that have led to some countries managing surface water and groundwater by separate organizations housed in different ministries. The inseparable connection between surface water and groundwater means that comprehensive management can only be achieved if close and constant communication between the relevant parties is undertaken.

The titles of host ministries of organizations mandated to monitor and manage water quality elucidates the complicated arrangements. In some countries, it may be a ministry primarily associated with the environment, but in others the primary role may be associated with energy production, irrigation or mining. While the title of the host ministry is not necessarily an issue, the competing internal pressures are challenging, and the protection of water resources may not be the main priority. Establishing an overarching organization such as an authority to combine the ongoing efforts of various ministries with the long-term goal of assimilating them can help ensure that oversight is provided and prioritized as needed. In Zambia, for instance, there is the Water Resources Management Authority (WARMA), while in Sierra Leone, the National Water Resources Management Agency (NWRMA) plays this coordination role.

River basin or catchment management plans have been adopted as the primary mechanism to assess and ameliorate water quality in many countries globally, for example in Rwanda.³⁰ These plans recognize that solutions to water quality problems transcend inter-sectoral differences and can only be achieved by bringing together multiple stakeholders at the river basin scale. This approach will be detailed in phase 5 of this project

²⁹ <https://www.un.org/development/desa/pd/>

³⁰ https://waterportal.rwb.rw/publications/catchment_plans

(Mukuyu et al. 2024b) and is also considered in the section *Catchment-based Management*. One of the key aspects of this approach is to recognize that pollution flows downstream — the benefits of the activity are retained at the point of pollution, whereas the impacts often manifest downstream.

Awareness

Awareness of the interlinkages between human activities, water quality and the benefits of healthy freshwater ecosystems for sustainable development must be elevated across all levels of society. While decision-makers and policy makers from economic or engineering backgrounds may not readily appreciate these links communicated from a scientific standing, improving water quality assessments and communicating their relevance in terms of socioeconomic benefits can help safeguard progress. A successful instance of this is discussed in Damania et al. (2019), where the direct economic impacts of water pollution are highlighted.

Awareness of gender implications and water quality are relevant for many African countries. Often, women and children in low-income countries play a greater role in water provision, cooking, cleaning and caring — roles which may require greater direct contact with water. Additionally, if the nearest source of water for household use is polluted, those responsible for water collection travel further to collect clean water, spending more time performing this essential task rather than spending time working or at school.

Similarly, the proportion of women in management roles is lower in African countries as compared with the global average. UNEP's GEMS/Water program surveyed technical focal points responsible for reporting for SDG indicator 6.3.2. These focal points are usually at a management level within the national organization which monitors water quality. While the gender balance was near-equal globally, in sub-Saharan countries, the bias towards men in these roles was clear — 13 of the 15 focal points were men (pers. comm.).³¹ Raising awareness of this disparity is essential to ensure that the perspectives of women and their experiences are included in water resource decision-making and policy formulation.

Management Innovations Being Tested and Used Globally

Impacts on water quality and freshwater ecosystems arise from many different pressures, such as human settlements, agricultural activities, industry and mining, tourism, and climate change. Traditionally, the associated impacts — excess nutrients, human pathogen pollution, release of potentially toxic compounds (pesticides, pharmaceutical residues) and heavy metals — have been managed by

regulating their discharges. Although this may work well for point sources of pollution, it does not always take into consideration the potential multiple sources of different types of pollution within the same catchment, including diffuse sources that are much harder to regulate. In addition, regulation requires rigorous checking for compliance, leading to a high (quality assured) standard of water quality monitoring. Even when an adequate regulatory monitoring program is in place, water quality deterioration may still arise due to:

- detection of the pollution problem after the 'failure' and hence after environmental damage has occurred (i.e., the approach is reactive)
- routine regulatory monitoring failing to include unexpected contaminants; therefore, it misses other compounds such as new contaminants of health concern
- new or unofficial activities discharging to the water body not being picked up by the source-directed approach

For the above reasons, harmonized catchment-wide monitoring is essential, including some of the more integrative monitoring approaches, such as biological monitoring, that enable areas to be identified where the ecosystem has been disturbed. A few links to sites that may provide guidance are provided in Annex 3.

Policy and Regulation

Policies to address pollution at source typically involve regulations and economic instruments, such as taxes on polluting substances, and subsidies or incentives to modify the activity. Innovations may be needed, for example, to encourage conversion of land use to less-polluting activities or for introducing buffer strips along rivers to absorb nutrients. The Conservation Reserve Program in the USA offers an annual rental to farmers to take land out of production for 10–15 years in an effort to clean up rivers, lakes and estuaries.³² Policies that aim to change behavior and incentivize the uptake of good practices are also an essential component of preventing pollution at source. With respect to agricultural sources of pollution, policies that regulate or encourage behavioral change must account for free advisory services and training for farmers, such as the provision of advice on improved methods and timing of fertilizer application to reduce runoff to water bodies. Within the European Union, regulations control when farmers are permitted to spread manure on the land in order to minimize nitrate runoff (EC 1991). The precise timing of the periods when manure spreading is allowed is set by each country within the European Union.

An alternative policy approach is to set water quality objectives or targets that define the optimum or acceptable status of water quality in different water bodies

³¹ Personal communication with an official from the UNEP GEMS/Water program on October 4, 2021.

³² <https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program>

or catchments. These targets can further be used to define the suitability of ambient water quality for different uses such as drinking water abstraction and irrigation. Water quality can be characterized by physical, chemical and biological parameters and, to ensure that the freshwater ecosystem is protected, objectives should be set to ensure protection of human and ecosystem (usually fishery) health. Objectives or targets are frequently set for critical pollutants (DWA 2011) but less so for parameters reflecting ambient water quality. Activities that cause water quality objectives to be breached and water quality to degrade are then targeted for management action, such as being required to modify or, in extreme cases, ordered to discontinue discharges altogether.

The Drivers, Pressures, State, Impacts and Responses (DPSIR) framework is a useful tool for assessing the state of the environment with the aim of guiding policy. This approach can be used as an analytical framework to assess specific environmental compartments, such as freshwaters, and tailored to assist in developing management and policy options. For example, it was modified to guide the framework for freshwater ecosystem management that was developed by UNEP (UNEP 2018). Mateo-Sagasta et al. (2017) utilized this approach to determine policy needs with respect to water pollution arising from agriculture. They concluded that policy measures should include a combination of approaches implemented at national or river basin scale.

Catchment-based Management

While Integrated Water Resources Management (IWRM) is not particularly new, it includes several individual activities for which innovations are possible (Borchardt and Ibsch 2013). It requires a coordinated approach to management of all aspects of water use (both quantity and quality) from all possible stakeholders, such as drinking water, wastewater and energy generation utilities, land developers, food producers, etc., for sharing water resources equitably while ensuring sustainability of the resources and their ecosystems. The importance of IWRM as a tool for sustainable management of freshwater resources has been recognized by its inclusion as a target of Sustainable Development Goal 6 for Clean Water and Sanitation.³³ Since water bodies do not necessarily fall within the territory of a single nation, IWRM should also encompass transboundary water bodies and include relevant stakeholders from all nations sharing the same water resources.

Transboundary cooperation is a fundamental aspect of successful River Basin Organizations (RBOs). RBOs can cover any size of river and offer the potential for effective and consensual management of the water quality of the river system. They operate in many different ways and with different degrees of success (Lautze et al. 2013), as

highlighted by Medinilla (2018) for RBOs in Africa. Two examples of successful RBOs covering some of the most heavily developed international water bodies, have been in operation for decades for the River Danube³⁴ and the River Rhine³⁵ in Europe. An essential contributing factor to the success of RBOs for managing water quality is the sharing of relevant data and information. Transboundary data and information exchange is often limited (Mukuyu et al. 2020), hence developing joint monitoring systems is an important consideration to facilitate shared data. Further enabling the development of standardized and harmonized monitoring methods is a critical step in ensuring data usability and interoperability. When participating countries follow agreed monitoring protocols and share the data in a single database accessible to all participants, then it is possible for data and information sharing to be facilitated more easily. However, this approach may be impacted by several factors that could decrease the usefulness of the shared information, such as political influence, change of national monitoring stations and protocols, fluctuations in availability of resources in participating countries, etc. An alternative approach is a harmonized monitoring program operated and implemented at designated stations within the river basin on an agreed timeframe by all participating countries (Chapman et al. 2016).

Data Management and Sharing

Successful water quality management depends on relevant high-quality data available at the appropriate scale, i.e., by catchment and/or nationally, and even internationally. Recent improvements in access to the internet globally has allowed for transmission and storage of large quantities of data generated from water quality monitoring activities. Open Access software packages also facilitate data storage and data analysis. At present, there are no comprehensive data management services specifically for water quality data, but a good data structure for handling these data in a relational database is available in the Observations Data Model Version 2 (ODM2).³⁶

A lack of trained personnel, especially in developing countries, with the understanding and skills to take advantage of these developments in data management, is a challenge.

It is essential that all data relevant for water quality management are available at least at the national level in order to facilitate an integrated management approach. For water quality monitoring data, this involves a central repository and a data sharing network for all regional laboratories. For shared data to be useful they must be quality assured and in a comparable format. Such checks can be built into many database packages, thereby relieving the burden of manual verification of large quantities of data.

³³ <https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program>

³⁴ <https://www.icpdr.org/main/>

³⁵ <https://www.iksr.org/en/>

³⁶ <https://www.odm2.org/>

Many private sector entities use freshwater within their processes, including water directly abstracted from surface water and groundwater. This water is usually analyzed for physical and chemical quality prior to use, but the data are rarely shared outside of the organization. However, such data could be a useful supplementary source of water quality information for management of the water body, and sharing through a national repository should be encouraged.

Wastewater Treatment and Reuse

Adequate treatment of all forms of wastewater before discharge to the environment is essential to protect the water quality and the ecosystem of the receiving water body. Traditional wastewater treatment involves a combination of several processes, including the physical removal of solids and biological breakdown of organic matter, so that the discharged effluent has reduced polluting potential, especially oxygen demand and suspended solids. Nevertheless, most domestic and municipal wastewaters contain high levels of nutrients and other potential contaminants that affect the water quality of the receiving water bodies. These could present risks for human health and the ecosystem. Innovations in wastewater treatment typically involve refinements to the individual treatment processes, or to their use in combination. Examples are nutrient removal processes (Hasan et al. 2021) for areas where water quality is subject to eutrophication, and disinfection where there is a risk to human health from the receiving water body (Collivignarelli et al. 2018). The utilization of such refinements are dependent on the scale of the wastewater treatment, i.e., local decentralized or centralized for larger population centers, and the continuing financial and technical resources to operate and maintain them. Decentralized wastewater systems treat up to 1,000 cubic meters of wastewater per day near the source where it is generated, i.e., homes and businesses. They are particularly useful for low-income countries and for rural areas where they can be used to turn wastewater into a soil fertilizer and conditioner, or into a biomass fuel for energy generation. Examples of a globally used system are available from the Bremen Overseas Research and Development Association (BORDA),³⁷ an NGO. Recent innovations in on-site wastewater treatment systems suitable for low-income countries include solar septic tanks (SSTs). These systems use solar power to heat the effluent in the septic tank, which results in more efficient biodegradation of the wastewater and less pollution of surface water and groundwater with pathogens (e.g., Koottatep et al. 2020).

Developments in technology for treating wastewater often concentrate on reducing the energy demand of the system or on augmenting the efficiency of existing

processes. Improving existing plants can reduce the need for upscaling existing infrastructure, whilst also increasing the quality of the wastewater discharged. High efficiency, compact processes, such as membrane bioreactors, are now replacing the more conventional activated sludge process, especially in new or upgraded wastewater treatment facilities. The units combine conventional biological treatment with physical liquid-solid separation using membrane filtration; they produce a higher quality effluent from higher volumes over shorter process times, as compared to the conventional activated sludge process. They are, however, more expensive to build, run and maintain at their optimum efficiency. A recent review of MBR technology development and use is given by Al-Asheh et al. (2021). New technology for wastewater treatment processes leading to improvements in effluent quality for discharge or reuse can also be applied at domestic scale,³⁸ although these too are expensive to install, run and maintain.

Worsening water availability in many parts of the world has led to increased attention towards additional sources of water to improve dwindling freshwater supplies (Adewumi et al. 2010; Jeuland 2015). Amid growing populations and corresponding demands for water, wastewater has increasingly become an attractive option as a supplementary water source. Wastewater reuse can be undertaken at various scales: at household level, where wastewater from bathing, bathroom and kitchen sinks (greywater) is reused for watering gardens; at municipal scale, where large volumes of domestic and industrial wastewater are treated and reused; or industry scale, where individual industries reuse water within their operations. In Africa, cases of municipal wastewater reuse are sporadic as countries still grapple with treating wastewater to acceptable qualities; the discharge of poorly treated effluent is also a serious challenge. Nonetheless, the potential for reuse is still widely accepted as a solution to improve water availability and reduce water pollution.

Wastewater has been treated and reused for domestic water supply for decades, such as in Windhoek, Namibia, beginning in 1968 (Haarhoff and Van der Merwe 1996). Public health concerns are critical in wastewater reuse for domestic water supplies and require appropriate regulatory frameworks (Adewumi et al. 2010). Similar interventions to reuse wastewater for domestic water were met with objections in South Africa's eThekweni Municipality, when reclaimed wastewater was tabled by the municipality as a potential source of domestic water (Kalebaila et al. n.d.). After a series of feasibility studies, the municipality is currently producing high-quality reclaimed water from municipal wastewater and supplying it to industry, thereby freeing up large volumes of potable water for residents.³⁹

³⁷ <https://www.borda.org/solutions/decentralised-sanitation-systems-2/#dewats>

³⁸ E.g., <http://ecosoft.org/water-wastewater/wastewater-recovery/>

³⁹ The Durban Water Recycling Project (<https://www.durban.gov.za/pages/residents/ews-services>)

A commonly considered application for treated wastewater is irrigation. Irrigation, at present, consumes just over 80% of the freshwater in Africa. In some cases, local farmers have used untreated wastewater directly to irrigate crops, a practice criticized for potentially spreading diseases. In the city of Ouagadougou in Burkina Faso, residents were using wastewater collected in stormwater canals and polluted with human pathogens and antibiotic resistance genes. It was concluded that this posed a health risk to users through direct contact with the wastewater (Bougnom et al. 2019). Diarrhea and parasitic diseases were reported to be prevalent among exposed small-scale farmers in a village in South Africa, where farmers were using water from a dam receiving effluent from the municipal wastewater treatment plant for vegetable irrigation (Gumbo et al. 2010). A similar observation where irrigation with wastewater resulted in illness among farmers was also noted in Ethiopia (AfDB, UNEP and GRID-Arendal 2020).

Wastewater may also be used for drinking water, either by enabling natural processes to improve its water quality after discharge to a river, lake or groundwater (which inevitably leads to a change in water quality in the receiving water body), or with the application of suitable treatment processes. The latter is an expensive option, most likely to be used in areas where water is very scarce. However, groundwater recharge offers potential for reducing surface water pollution and restoring depleted groundwater resources whilst facilitating the provision of high-quality drinking water. It does, however, still require the wastewater to be treated before it can be used for recharge. In the long term, however, it may provide a solution for water shortages arising from climate change.

Examples of wastewater reuse such as those mentioned above need to be coupled with policy and associated regulations or guidelines that include an adequate water quality monitoring regime to protect human health and the integrity of freshwater ecosystems.

Nature-based Solutions

Runoff, whether from agricultural land or urban areas, is a source of pollution in rivers and lakes and needs to be managed to reduce water quality degradation. It is particularly difficult to manage because the source of pollution is widespread and may vary temporally and spatially in seasons and years. Runoff in urban areas, often referred to as stormwater, may be collected and diverted to a wastewater treatment plant, or collected in drains that carry it directly to the nearest water body. Depending on the nature of the urban catchment, stormwater can contain a wide variety of macro- and micro-pollutants, including fecal pathogens, heavy metals, organic compounds and plastics. Therefore, the management and treatment of stormwater is an essential aspect of protecting water

quality. Reducing the quantity of stormwater relieves pressure on wastewater treatment systems. This can be done, for example, by using the same to maintain and/or create green infrastructure, such as recreational areas, green roofs, and roadside walkways. The city of Philadelphia in the USA is targeting an 85% reduction in stormwater releases to surface water through green infrastructure.⁴⁰

Evidence shows the substantive potential of nature-based solutions (NbS) in mitigating and reducing water pollution. Nature-based solutions is a fairly nascent concept describing how nature can be used to address global challenges such as deteriorating water quality. The solutions are inspired by nature's own natural processes and have features such as cost-effectiveness, providing both social and environmental benefits. Although the term is widely applied in various contexts such as flood mitigation, NbS are notable for reducing water pollution and improving water quality and may be identified under different names such as ecological infrastructure. NbS can also address several challenges simultaneously — improved water quality, for instance, can result in improved biodiversity and habitats as well as improved socioeconomic conditions for rural communities (WWAP 2018). This section synthesizes the progress in the application of NbS in African countries, tracking the use of natural and constructed wetlands in mitigating pollution in particular. Constructed wetlands are the most common type of NbS for water pollution control among other solutions such as infiltration basins and rain gardens (Oral et al. 2020).

Constructed wetlands are one of the most common and successfully implemented NbS for water pollution control. Inspired by the functioning of natural wetlands, constructed wetlands are reported to be largely successful in treating wastewater and improving water quality in and outside Africa (Wood 1995; Acreman et al. 2021). Wastewater treatment occurs through a combination of physical, biological and chemical processes within the components of constructed wetlands, such as the vegetation, and their efficiency is based on their design and the quantity and quality of wastewater (Wood 1995; Oral et al. 2020). The success of constructed wetlands in the control of water pollution has been reported in over 200 African case studies identified by Acreman et al. (2021). These case studies assessed the effectiveness of constructed wetlands in the removal of water pollutants ranging from nutrients (nitrogen and phosphorus), heavy metals, oil and grease, and microbiological contaminants such as *E. coli* and fecal coliforms. In all cases, a marked reduction in pollutant concentrations was observed (ibid). In Tanzania, constructed wetlands have been used to treat domestic wastewater for the past two decades (Ahmada et al. 2018). Despite the general success of constructed wetlands, deficiencies such as clogging and flooding have been reported in Tanzania, resulting in poor treatment

⁴⁰ http://archive.phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan

results, especially in the removal of pathogens (Ahmada et al. 2018). Concerns over increasing urban populations have been raised requiring such inefficiencies to be addressed to meet the increasing wastewater volumes. In Kenya, concerns over appropriate skills in the use of constructed wetlands have been cited for conservation areas and game resorts which rely on on-site sanitation facilities.

An Africa-wide review (Mekonnen et al. 2015) noted that constructed wetlands were effective in treating various types of wastewaters. Case studies from Uganda, Cameroon, Nigeria and Tunisia highlighted largely comparable high efficiencies in the removal of nutrients from wastewater with variations based on the difference in vegetation used in the constructed wetlands. Thus, there is ongoing attention on optimizing the efficiency of constructed wetlands in the treatment of wastewater, and that it is a well-established solution that can be further refined.

Lagoons and wetlands are a traditional means of improving wastewater quality by lowering the organic matter load and reducing the presence of fecal pathogens. Where water resources are scarce, they facilitate the reuse of water, especially for irrigation. Constructed wetlands can also be used to remove or convert pollutants into non-toxic forms in industrial wastewaters (Alexandros 2018). A recent review by Almuktar et al. (2018) has highlighted the different levels of performance associated with recent innovations in design and planting regimes for constructed wetlands, suggesting better performance for pathogen removal when the wetland effluent is subsequently passed through a lagoon. Improving the quality of wastewater in drainage canals to a standard that enables reuse in agriculture has shown some promise in Egypt; Pinelli et al. (2020) have demonstrated the feasibility of upgrading canals using in-stream constructed wetlands and canalized facultative lagoons.

Nature-based solutions are also effective in tackling diffuse water pollution. Studies across European cities showed the significance of NbS such as forest protection, reforestation, cover crops and riparian buffers in reducing sediment and nutrient loading into rivers (Trémolet and Karres 2020). These solutions are strongly linked to land use and sustainable agricultural practices. Buffer strips are strips of vegetation along the boundaries of farms, or along the banks of rivers and lakes, that act as natural filters for fertilizers, pesticides and other contaminants associated with the fine particles transported with runoff (Mateo-Sagasta et al. 2017). In Africa, efforts to promote sustainable land management, such as in the Kagera transboundary basin shared by Burundi, Rwanda, Uganda and Tanzania are ongoing and projected to result in improved water quality (FAO 2017).

Pollution Source Identification

Identifying the sources of water pollution is a critical component of water quality management. Regular and long-term monitoring of water quality is important for the identification of pollution sources. Recent innovations (Lin et al. 2020) have underscored the use of wireless sensor networks, the Internet of Things (IoT) technology and Water Quality Analysis Simulation Program (WASP)⁴¹ models (Wool et al. 2020) to trace pollution sources. Other techniques, such as Pollution Information Assessment Tools combine water quality data with other information such as population density, land use, industrial activity and pollution source inventories in a geographical information system to identify the likely locations of pollution sources. The locations can then be verified and targeted for management action.

The use of drones (see section *Deployment of Instrumentation*) equipped with cameras is also a recent innovation for detecting pollution sources in water bodies.⁴²

Community and Citizen Engagement

In many countries, there is strong interest amongst citizens and communities in becoming involved in the management of their local water bodies for the benefit of the environment and for themselves. Engaging communities in decisions relating to water quality management can aid the participation in, and acceptance of, management activities such as guidelines or regulations to reduce or eliminate polluting activities. Fostering community engagement often involves education in schools, where students can raise the environmental issues within their communities (Mateo-Sagasta et al. 2017). Working with the communities usually includes the active organizing of volunteers by NGOs and/or appointed community liaison staff from relevant water agencies. Community groups are willing to invest time and effort to undertake tasks for which the official water agencies do not have the resources, such as additional water quality monitoring (see section on *Citizen Science*) and clearing of debris such as macroplastics from watercourses. A successful model for community engagement is the Rivers' Trust network in the UK and Ireland.⁴³ It brings together experts on conservation of rivers with citizens to plan and execute river restoration activities, identify pollution sources, and many other activities.⁴⁴

Generating an understanding in citizens of the importance of good water quality and the prevention or management of pollution of water bodies can lay a good foundation for the future sustainability of water resources. Education at all levels is critical in this understanding. Water resources

⁴¹ <https://www.epa.gov/ceam/water-quality-analysis-simulation-program-wasp>

⁴² e.g., <https://waldenenvironmentalengineering.com/environmental-services-blog/using-aerial-thermography-to-spot-water-quality-issues-leaks-and-other-discrepancies/>

⁴³ <https://www.theriverstrust.org/>

⁴⁴ <https://www.theriverstrust.org/our-work/our-impact>

management education can benefit from innovations such as including the use of computer games offering simulations of catchment management where players can experience the role of different stakeholders and witness the impact of their decisions on the water resources within the catchment. One such example is the University of Virginia (UVA) Bay Game based on the Chesapeake Bay watershed.⁴⁵

Management Innovations Applicable to Africa

Table 4 captures the different innovations in order to evaluate management options applicable for Africa which consider important innovation features including affordability, scalability and flexibility.

⁴⁵ <https://web.arch.virginia.edu/baygame/about/>

Table 4. Management innovations and potential for use in Africa.

| Category | Approach/innovation/technique | Purpose | Potential use in Africa | Comments |
|----------------------------|--|---|-------------------------|--|
| Policy and regulation | Regulations and economic instruments, e.g., taxes | Controlling pollution at source | HIGH | Requires enforcement Private sector/community involvement and financial resources required Requires inter-departmental cooperation to share relevant data Reference conditions required for different water body types at national level Requires existing understanding of freshwater ecosystems and their water quantity and quality needs Options to share actual recorded measurements or aggregated summary data |
| | Economic instruments: subsidies and incentives | Reduction of pollution through change of behavior | HIGH | |
| | DPSIR framework | Determining policy needs and assessing effects of policy measures | HIGH | |
| | Water quality objectives | Protect water bodies and their ecosystems from critical pollutants | HIGH | |
| | Ecosystem guidelines | Protection of ambient water quality and freshwater ecosystems | MEDIUM | |
| | Data sharing policy | Improve national and international cooperation | HIGH | |
| Catchment-based management | Integrated Water Resources Management (IWRM) | Sustainable and equitable use of water resources | HIGH | Requires coordination amongst many different agencies and stakeholders Requires coordination amongst many different agencies and stakeholders Participating agencies/countries must commit resources and agree to share the data in a common database Incentivize private sector and academic institutions to contribute existing, and collect new, data on a catchment basis |
| | Transboundary cooperation | Sustainable and equitable use of transboundary water resources | HIGH | |
| | Harmonized monitoring throughout the catchment | Generation of data on locations and types of pollution in order to support targeted management | MEDIUM | |
| | Private sector and academic engagement | Expand data availability from non-governmental sources | MEDIUM | |
| Data management | National database storing and sharing water quality and quantity data from all local and regional agencies/laboratories Promotion of the use of data management standards | National water quality assessments to provide information for policy development Improve interoperability and sharing of data between national and international organizations | HIGH MEDIUM | Open access software available; 'Cloud' sharing of data via internet or central data storage and network Requires capacity development in data management |

(Continued)

Table 4. Management innovations and potential for use in Africa. (Continued)

| Category | Approach/innovation/technique | Purpose | Potential use in Africa | Comments |
|--------------------------------------|---|--|-------------------------|---|
| Wastewater treatment and reuse | Nutrient removal during wastewater treatment | Protection of water bodies from eutrophication | MEDIUM | Requires new infrastructure or upgrading of existing infrastructure; associated ongoing maintenance costs |
| | Disinfection of wastewater or treated effluent | Protection of human health when effluent is discharged to drinking water sources | HIGH | Various disinfection options are available based on the available budget and volume of effluent to be treated |
| | Decentralized wastewater systems | Small rural communities and businesses converting wastewater into energy and soil fertilizer | HIGH | Can be constructed with local resources; returns benefits to the community |
| | Lagoons and constructed wetlands | Reducing organic matter and pathogen loads; reduction of toxic pollutants for industrial wastewaters | HIGH | Cost-effective and enables water to be reused, e.g., for irrigation |
| | Membrane bioreactors | Removal of organic matter and pathogens from wastewater | MEDIUM | High initial financial outlay and regular maintenance costs required |
| | Groundwater recharge | Enhancing drinking water supplies where water is scarce | LOW-MEDIUM | Location specific; effluent must be treated to a high standard before being used for recharge |
| | Advanced treatment and disinfection | Reuse for potable water | LOW | Expensive and only suitable where drinking water is very scarce |
| Pollution source identification | Monitoring and modelling using pollution source inventories | Pollution source identification and control | MEDIUM | Requires regular water quality monitoring data from emission sources and receiving water bodies |
| | Remote sensing and use of drones | Aerial detection of pollution discharges, accidental spills | MEDIUM-HIGH | Validation in the field required |
| Runoff and diffuse pollution control | Ecological infrastructure such as buffer strips | Reduction of sediment and nutrient runoff | HIGH | Low cost; education and awareness of purpose needed |
| | Stormwater collection and usage in green infrastructure | Reduction in organic matter and associated pollutants draining into water bodies during rainstorms | HIGH | Low cost; education and awareness of purpose needed |
| | Sectoral Best Management Practice campaigns | Improve awareness of causes of pollution and methods to reduce it | MEDIUM | Suitable for agricultural, industrial and mining sectors |

(Continued)

Table 4. Management innovations and potential for use in Africa. (Continued)

| Category | Approach/innovation/technique | Purpose | Potential use in Africa | Comments |
|--------------------------------|---|---|-------------------------|---|
| Restoration and rehabilitation | Community driven restoration programs | Enables greater spatial and temporal restoration activity | HIGH | Local community liaison personnel needed |
| | Educational programs and simulation games for young people | Sustainable use of water resources | HIGH | Simulations and games can be tailored to represent local situations |
| | Involving all stakeholders in planning and implementing mitigation activities | Sustainable and equitable use of water resources | HIGH | Entails frequent feedback |

Conclusion

This paper has discussed and undertaken a detailed analysis of the innovation in water quality monitoring and management with the aim of proposing interventions to strengthen Africa's current water quality monitoring and management efforts. Promising potential innovations are identified for particular aspects of water quality monitoring and management. Such innovations are not only limited to technological advancements; they also include options and conceptualizations of managing water pollution. Summary Tables 4 and 5 have categorized the identified innovations as 'low', 'medium' or 'high' in their potential application and usefulness within the African context.

Innovations pertaining to monitoring program design, analytical techniques and instruments, deployment of instrumentation and approaches to water quality monitoring have been presented together with their applicability and suitability for implementation in Africa. Similarly, water quality management interventions — policy and regulatory mechanisms, catchment-based management, data management and sharing, wastewater reuse and nature-based solutions among others — are considered, with the most suitable of these proposed for African contexts based on a set of defined criteria. These criteria examine important innovation features such as affordability, scalability and flexibility, among others. AWaQ, therefore, offers the opportunity to ensure that best practices are established and scaled up rather than being merely imitated from the past.

Key Messages

The deterioration of water quality in Africa calls for urgent concerted efforts to curb further deterioration. The limitations of current water quality monitoring and management, including capacity and data gaps, have been indicated for most African countries. A number of innovations have been identified as possessing the most potential for strengthening current water quality monitoring and management approaches. The following points encapsulate the main aspects of this paper.

Monitoring:

- Biological monitoring is a high priority intervention for inclusion into national water quality monitoring programs since it can be an effective tool with minimum technology and can integrate water quality by showing the direct impacts of water quality deterioration in the whole ecosystem.
- New technological advancement such as earth observation offer great potential for adoption in a rapidly digitizing environment.
- The lack of basic capacity for water quality monitoring and management among some African countries, as identified in phase 2, hinders

innovation. A fundamental level of capacity is required for innovations to be effective; innovations thus need to take into consideration the available capacity. At present, innovations are limited to those that are low-tech or that avoid the need for highly skilled people.

- In-service training is a priority for ensuring that water quality monitoring staff are able to carry out basic and specialized tasks.
- There is potential for utilizing existing analytical capacity that currently supports only drinking water supply and sanitation services. This could provide a short-term mechanism to enable the analysis of ambient water quality samples by building capacity in these facilities without the immediate need for building new laboratories. This approach is currently proving successful in some countries and its potential should be further explored. However, this should not preclude mid- and long-term investment in laboratory infrastructure and testing equipment which is also urgently required in many countries.
- National-level coordination and management of water quality data is essential for effective management of national water resources. Robust investment is needed in IT systems, data management software and in training personnel, so that water quality monitoring data can be used more effectively to support water resources management.
- There is scope for community and citizen engagement throughout the various processes of monitoring and management of water resources. There is evidence to show that this enables success where governments do not have the monitoring capacity or adequate resources.
- Contributions from private sector and academic stakeholders should be encouraged in the formation of AWaQ. Private sector data are often siloed and not shared, with many academic institutions that may collect and hold water quality data that could be useful for national water quality assessments.
- Data sharing is central to the success of AWaQ to allow for full disclosure and accountability of the activities surrounding transboundary cooperation.

Management:

- Catchment-based water quality management needs promotion. While this approach requires stakeholder involvement and coordination, it holds great potential for success.
- Nature-based solutions, such as constructed wetlands and buffer strips, offer great potential for pollution management from point and diffuse sources in African countries.

- On-site sanitation treatment systems that produce energy or fertilizers are a noteworthy intervention for managing fecal waste and reducing fecal pollution.
- Developing awareness on the importance of good water quality is essential. It can foster the need to monitor and protect water resources, thereby supporting evidence-based management.

References

- Acreman, M.; Smith, A.; Charters, L.; Tickner, D.; Opperman, J.; Acreman, S.; Edwards, F.; Sayers, P.; Chivava, F. 2021. Evidence for the effectiveness of nature-based solutions to water issues in Africa. *Environmental Research Letters* 16(6):063007. <https://doi.org/10.1088/1748-9326/aco210>
- Adewumi, J.R.; Ilemobade, A.A.; Van Zyl, J.E. 2010. Treated wastewater reuse in South Africa: Overview, potential and challenges. *Resources, Conservation and Recycling* 55(2):221–231. <https://doi.org/10.1016/j.resconrec.2010.09.012>
- AfDB (African Development Bank); UNEP (United Nations Environment Programme); GRID-Arendal. 2020. *Sanitation and wastewater atlas of Africa*. Abidjan, Côte d'Ivoire: African Development Bank; Nairobi, Kenya: United Nations Environment Programme (UNEP); Arendal, Norway: GRID-Arendal.
- Ahmada, W.; Katima, J.H.Y.; Kimwaga, R.; Van Deun, R. 2018. Pathogens removal from wastewater using sustainable treatment wetlands in Tanzania: A review. *American Journal of Environmental Engineering* 8(2):17–24.
- Al-Asheh, S.; Bagheri, M.; Aidan, A. 2021. Membrane bioreactor for wastewater treatment: A review. *Case Studies in Chemical and Environmental Engineering* 4:100109. <https://doi.org/10.1016/j.cscee.2021.100109>
- Alexandros, S. 2018. *Constructed wetlands for industrial wastewater treatment*. Chichester, UK: John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781119268376>
- Alfonso, L.; Gharesifard, M.; Wehn, U. 2022. Analysing the value of environmental citizen-generated data: Complementarity and cost per observation. *Journal of Environmental Management* 303:114157. <https://doi.org/10.1016/j.jenvman.2021.114157>
- Almuktar, S.A.A.A.N.; Abed, S.N.; Scholz, M. 2018. Wetlands for wastewater treatment and subsequent recycling of treated effluent: A review. *Environmental Science and Pollution Research* 25:23595–23623. <https://doi.org/10.1007/s11356-018-2629-3>
- Altenburger, R.; Brack, W.; Burgess, R.M.; Busch, W.; Escher, B.I.; Focks, A.; Hewitt, L.M.; Jacobsen, B.N.; de Alda, M.L.; Ait-Aissa, S.; Backhaus, T.; Ginebreda, A.; Hilscherová, K.; Hollender, J.; Hollert, H.; Neale, P.A.; Schulze, T.; Schymanski, E.L.; Teodorovic, I.; Tindall, A.J.; de Aragão Umbuzeiro, G.; Vrana, B.; Zonja, B.; Krauss, M. 2019. Future water quality monitoring: Improving the balance between exposure and toxicity assessments of real-world pollutant mixtures. *Environmental Sciences Europe* 31(12). <https://doi.org/10.1186/s12302-019-0193-1>
- August, T.A.; West, S.E.; Robson, H.; Lyon, J.; Huddart, J.; Velasquez, L.F.; Thornhill, I. 2019. Citizen meets social science: Predicting volunteer involvement in a global freshwater monitoring experiment. *Freshwater Science* 38(2):321–331. <https://doi.org/10.1086/703416>
- Barbour, M.T.; Gerritsen, J.; Snyder, B.D.; Stribling, J.B. 1999. *Rapid bioassessment protocols for use in streams and wadeable rivers: Periphyton, Benthic macroinvertebrates, and fish*. 2nd Edition. EPA 841-B-99-002. Washington, DC, USA: United States Environmental Protection Agency (USEPA), Office of Water. 339p. Available at <https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1164.pdf> (accessed on March 8, 2023).
- Binding, C.E.; Greenberg, T.A.; Watson, S.B.; Rastin, S.; Gould, J. 2015. Long term water clarity changes in North America's Great Lakes from multi-sensor satellite observations. *Limnology and Oceanography* 60(6):1976–1995. <https://doi.org/10.1002/lno.10146>
- Bishop, I.J.; Warner, S.; van Noordwijk, T.C.G.E.; Nyoni, F.C.; Loiselle, S. 2020. Citizen science monitoring for Sustainable Development Goal Indicator 6.3.2 in England and Zambia. *Sustainability* 12(24):10271. <https://doi.org/10.3390/su122410271>
- Borchardt, D.; Ibsch, R. 2013. *Integrated water resources management in a changing world: Lessons learnt and innovative perspectives*. IWA Publishing. <https://doi.org/10.2166/9781780405278>
- Bougnom, B.P.; Zongo, C.; McNally, A.; Ricci, V.; Etoa, F.X.; Thiele-Bruhn, S.; Piddock, L.J.V. 2019. Wastewater used for urban agriculture in West Africa as a reservoir for antibacterial resistance dissemination. *Environmental Research* 168:14–24. <https://doi.org/10.1016/j.envres.2018.09.022>
- Brewin, R.J.W.; Brewin, T.G.; Phillips, J.; Rose, S.; Abdulaziz, A.; Wimmer, W.; Sathyendranath, S.; Platt, T.A. 2019. A printable device for measuring clarity and colour in lake and nearshore waters. *Sensors* 19(4):936. <https://doi.org/10.3390/s19040936>

- Burggraaff, O.; Perduijn, A.; van Hek, R.F.; Schmidt, N.; Keller, C.U.; Snik, F. 2020. A universal smartphone add-on for portable spectroscopy and polarimetry: iSPEX 2. *Proceedings SPIE 11389, Micro- and Nanotechnology Sensors, Systems, and Applications XII, 113892K, May 20, 2020*. <http://doi.org/10.1117/12.2558562>
- Capdevila, A.S.L.; Kokimova, A.; Ray, S.S.; Avellán, T.; Kim, J.; Kirschke, S. 2020. Success factors for citizen science projects in water quality monitoring. *Science of the Total Environment* 728:137843. <https://doi.org/10.1016/j.scitotenv.2020.137843>
- Carere, M.; Dulio, V.; Hanke, G.; Polesello, S. 2012a. Guidance for sediment and biota monitoring under the Common Implementation Strategy for the Water Framework Directive. *TrAC Trends in Analytical Chemistry* 36:15–24. <https://dx.doi.org/10.1016/j.trac.2012.03.005>
- Carere, M.; Polesello, S.; Sollazzo, C.; Gawlik, B.M. 2012b. Chemical monitoring and emerging pollutants in the Common Implementation Strategy of the Water Framework Directive. *TrAC Trends in Analytical Chemistry* 36:12–14. <http://dx.doi.org/10.1016/j.trac.2012.04.008>
- Carvalho, R.N.; Niegowska, M.; Cortes, L.G.; Lettieri, T. 2019. *Testing comparability of existing and innovative bioassays for water quality assessment. A European wide exercise*. EUR 29505 EN, JRC114143. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2760/565375>
- Chapman, D.V.; Bradley, C.; Gettel, G.M.; Hatvani, I.G.; Hein, T.; Kovács, J.; Liska, I.; Oliver, D.M.; Tanos, P.; Trásy, B.; Várbíró, G. 2016. Developments in water quality monitoring and management in large river catchments using the Danube River as an example. *Environmental Science & Policy* 64:141–154. <http://doi.org/10.1016/j.envsci.2016.06.015>
- Chen, B.; Han, M.Y.; Peng, K.; Zhou, S.L.; Shao, L.; Wu, X.F.; Wei, W.D.; Liu, S.Y.; Li, Z.; Li, J.S.; Chen, G.Q. 2018. Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. *Science of the Total Environment* 613-614:931–943. <https://doi.org/10.1016/j.scitotenv.2017.09.138>
- Chilton, J. 2020. *SDG indicator 6.3.2 technical guidance document no. 3: Monitoring and reporting for groundwater*. United Nations Environment Programme (UNEP) Global Environment Monitoring System for Freshwater (GEMS/Water). Available at https://communities.unep.org/download/attachments/32407814/CDC_GEMI2_TechDoc3_Groundwaters_20200402.pdf?version=3&modificationDate=1595422085358&api=v2 (accessed on March 8, 2023).
- Collivignarelli, M.C.; Abbà, A.; Benigna, I.; Sorlini, S.; Torretta, V. 2018. Overview of the main disinfection processes for wastewater and drinking water treatment plants. *Sustainability* 10(1):86. <https://doi.org/10.3390/su10010086>
- Dalu, T.; Froneman, P.W. 2016. Diatom-based water quality monitoring in southern Africa: Challenges and future prospects. *Water SA* 42(4). <http://doi.org/10.4314/wsa.v42i4.05>
- Damania, R.; Desbureaux, S.; Rodella, A-S.; Russ, J.; Zaveri, E. 2019. *Quality unknown: The invisible water crisis*. Washington, DC, USA: World Bank.
- de Lima, R.L.P.; Boogaard, F.C.; de Graaf-van Dinther, R.E. 2020. Innovative water quality and ecology monitoring using underwater unmanned vehicles: Field applications, challenges and feedback from water managers. *Water* 12(4):1196. <https://doi.org/10.3390/w12041196>
- DWA (Department of Water Affairs). 2011. *Procedures to develop and implement resource quality objectives*. Pretoria, South Africa: Department of Water Affairs.
- Dickens, C.W.; Graham, P.M. 2002. The South African Scoring System (SASS) version 5 rapid bioassessment method for rivers. *African Journal of Aquatic Science* 27(1):1–10. <https://doi.org/10.2989/16085914.2002.9626569>
- EC (European Commission). 1991. Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC). *Official Journal of the European Communities* L 375:1–8. Available at <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31991L0676&qid=1682661764109> (accessed on June 7, 2023).
- EMCO (Reduction of environmental risks, posed by Emerging Contaminants, through advanced treatment of municipal and industrial wastes); CSIC (Consejo Superior de Investigaciones Científicas); TMF (Faculty of Technology and Metallurgy, University of Belgrade). 2007. *Proceedings of the 2nd EMCO workshop on emerging contaminants in wastewaters: Monitoring tools and treatment technologies, April 26-27, 2007, Belgrade, Serbia*. Available at https://www.oieau.fr/eaudoc/system/files/documents/44/220348/220348_doc.pdf (accessed on March 14, 2023).

- EU (European Union). 2013. Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. *Official Journal of the European Union* 226:1-17. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:226:0001:0017:en:PDF> (accessed on April 28, 2023)
- Filik Iscen, C.; Emiroglu, Ö.; Ilhan, S.; Arslan, N.; Yilmaz, V.; Ahiska, S. 2008. Application of multivariate statistical techniques in the assessment of surface water quality in Uluabat Lake, Turkey. *Environmental Monitoring and Assessment* 144:269-276. <https://doi.org/10.1016/j.scitotenv.2020.137843>
- FAO (Food and Agriculture Organization of the United Nations). 2017. *Sustainable Land Management (SLM) in practice in the Kagera Basin: Lessons learned for scaling up at landscape level - Results of the Kagera Transboundary Agro-ecosystem Management Project (Kagera TAMP)*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). 440p.
- FAO. 2021. AQUASTAT database. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). Available at <https://www.fao.org/aquastat/en/> (accessed on January 23, 2023).
- Graham, P.M.; Dickens, C.W.S.; Taylor, R.J. 2004. miniSASS - A novel technique for community participation in river health monitoring and management. *African Journal of Aquatic Science* 29(1):25-35. <https://doi.org/10.2989/16085910409503789>
- Gumbo, J.R.; Malaka, E.M.; Odiyo, J.O.; Nare, L. 2010. The health implications of wastewater reuse in vegetable irrigation: A case study from Malamulele, South Africa. *International Journal of Environmental Health Research* 20(3):201-211. <https://doi.org/10.1080/09603120903511093>
- Haarhoff, J.; Van der Merwe, B. 1996. Twenty-five years of wastewater reclamation in Windhoek, Namibia. *Water Science and Technology* 33(10-11):25-35. [https://doi.org/10.1016/0273-1223\(96\)00403-9](https://doi.org/10.1016/0273-1223(96)00403-9)
- Hadj-Hammou, J.; Loisel, S.; Ophof, D.; Thornhill, I. 2017. Getting the full picture: Assessing the complementarity of citizen science and agency monitoring data. *PLoS ONE* 12(12):e0188507. <https://doi.org/10.1371/journal.pone.0188507>
- Hagedorn, C.; Blanch, A.R.; Harwood, V.J. 2011. *Microbial source tracking: Methods, applications, and case studies*. New York, USA: Springer. <https://doi.org/10.1007/978-1-4419-9386-1>
- Halmi, M.I.E. 2016. Rapid ecotoxicological tests using bioassay systems - A review. *Journal of Biochemistry, Microbiology and Biotechnology* 4(1):29-37. <https://doi.org/10.54987/jobimb.v4i1.286>
- Hanna, D.E.L.; Solomon, C.T.; Poste, A.E.; Buck, D.G.; Chapman, L.J. 2015. A review of mercury concentrations in freshwater fishes of Africa: Patterns and predictors. *Environmental Toxicology and Chemistry* 34(2):215-223. <https://doi.org/10.1002/etc.2818>
- Hasan, M.N.; Altaf, M.M.; Khan, N.A.; Khan, A.H.; Khan, A.A.; Ahmed, S.; Senthil Kumar, P.; Naushad, M.; Rajapaksha, A.U.; Iqbal, J.; Tirth, V.; Islam, S. 2021. Recent technologies for nutrient removal and recovery from wastewaters: A review. *Chemosphere* 277:130328. <https://doi.org/10.1016/j.chemosphere.2021.130328>
- Hynds, P.; Regan, S.; Mooney, E.; O'Dwyer, J. 2018. Development of a pocket technology Groundwater Risk Application for Local Evaluation (GRAPPLE) in highly groundwater reliant populations. European Geosciences Union General Assembly 2018. *Geophysical Research Abstracts* 20:EGU2018-7685. <https://doi.org/10.13140/RG.2.2.23484.33928>
- IAH (International Association of Hydrogeologists). 2017. *The UN-SDGs for 2030: Essential indicators for groundwater*. IAH Strategic Overview Series. Available at <https://iah.org/education/professionals/strategic-overview-series> (accessed on March 14, 2023).
- IOCCG (International Ocean-Colour Coordinating Group). 2018. *Earth observations in support of global water quality monitoring*. Dartmouth, Nova Scotia, Canada: International Ocean-Colour Coordinating Group (IOCCG). 125p. (Reports of the International Ocean-Colour Coordinating Group, No. 17). <http://dx.doi.org/10.25607/OBP-113>
- Jan, F.; Min-Allah, N.; Düstegör, D. 2021. IoT based smart water quality monitoring: Recent techniques, trends and challenges for domestic applications. *Water* 13(13):1729. <https://doi.org/10.3390/w13131729>
- Jeuland, M. 2015. Challenges to wastewater reuse in the Middle East and North Africa. *Middle East Development Journal* 7(1):1-25. <https://doi.org/10.1080/17938120.2015.1019293>

- Kalebaila, N.; Ncube, E.J.; Swartz, C.D.; Marais, S.; Lubbe, J. n.d. *Strengthening the implementation of water reuse in South Africa*. Working Paper. Pretoria, South Africa: Water Research Commission. Available at <https://wrc.org.za/?mdocs-file=60799> (accessed on March 10, 2023).
- Kenney, M.A.; Sutton-Grier, A.E.; Smith, R.F.; Gresens, S.E. 2009. Benthic macroinvertebrates as indicators of water quality: The intersection of science and policy. *Terrestrial Arthropod Reviews* 2:99–128. <https://doi.org/10.1163/187498209X12525675906077>
- Khader, A.I.; McKee, M. 2014. Use of a relevance vector machine for groundwater quality monitoring network design under uncertainty. *Environmental Modelling Software* 57:115–126. <https://doi.org/10.1016/j.envsoft.2014.02.015>
- Khalil, B.; Ouarda, T.B.M.J.; St-Hilaire, A. 2011. Estimation of water quality characteristics at ungauged sites using artificial neural networks and canonical correlation analysis. *Journal of Hydrology* 405(3-4):277–287. <https://doi.org/10.1016/j.jhydrol.2011.05.024>
- Kolkwitz, R.; Marsson, M. 1902. Grundsätze für die biologische Beurteilung des Wassers nach seiner Flora und Fauna. (Principles for the biological assessment of water bodies according to their flora and fauna). *Kl. Mitt. d. Kgl. Prüfungsanstalt f. Wasserversorgung und Abwässerbeseitigung* 1:33–72.
- Koottatep, T.; Connelly, S.; Pussayanavin, T.; Khamyai, S.; Sangchun, W.; Sloan, W.; Polprasert, C. 2020. ‘Solar septic tank’: Evaluation of innovative decentralized treatment of blackwater in developing countries. *Journal of Water, Sanitation and Hygiene for Development* 10(4):828–840. <https://doi.org/10.2166/washdev.2020.168>
- Koparan, C.; Koc, A.B.; Privette, C.V.; Sawyer, C.B. 2018. In situ water quality measurements using an unmanned aerial vehicle (UAV) system. *Water* 10(3):264. <https://doi.org/10.3390/w10030264>
- Kovács, J.; Kovács, S.; Magyar, N.; Tanos, P.; Hatvani, I.G.; Anda, A. 2014. Classification into homogeneous groups using combined cluster and discriminant analysis. *Environmental Modelling & Software* 57:52–59. <http://dx.doi.org/10.1016/j.envsoft.2014.01.010>
- Kovács, J.; Kovács, S.; Hatvani, I.G.; Magyar, N.; Tanos, P.; Korponai, J.; Blaschke, A.P. 2015a. Spatial optimization of monitoring networks on the examples of a river, a lake-wetland system and a sub-surface water system. *Water Resources Management* 29(14):5275–5294. <http://dx.doi.org/10.1007/s11269-015-1117-5>
- Kovács, J.; Márkus, L.; Szalai, J.; Kovács, I.S. 2015b. Detection and evaluation of changes induced by the diversion of River Danube in the territorial appearance of latent effects governing shallow-groundwater fluctuations. *Journal of Hydrology* 520:314–325. <https://doi.org/10.1016/j.jhydrol.2014.11.052>
- Kugathas, S.; Williams, R.J.; Sumpter, J.P. 2012. Prediction of environmental concentrations of glucocorticoids: The River Thames, UK, as an example. *Environmental International* 40:15–23. <https://doi.org/10.1016/j.envint.2011.11.007>
- Lally, H.T.; O’Connor, I.; Jensen, O.P.; Graham, C.T. 2019. Can drones be used to conduct water sampling in aquatic environments? A review. *Science of the Total Environment* 670:569–575. <https://doi.org/10.1016/j.scitotenv.2019.03.252>
- Lang, T.; Dethlefsen, V. 1996. *Fish disease monitoring - a valuable tool for pollution assessment?* Cuxhaven, Germany: International Council for the Exploration of the Sea. Available at https://www.ices.dk/sites/pub/CM%20Documents/1996/E/1996_E17.pdf (accessed on March 8, 2023).
- Lautze, J.; Wegerich, K.; Kazbekov, J.; Yakubov, M. 2013. International river basin organizations: Variation, options and insights. *Water International* 38(1):30–42. <http://dx.doi.org/10.1080/02508060.2013.747418>
- Leal Filho, W.; Hunt, J.; Lingos, A.; Platje, J.; Vieira, L.W.; Will, M.; Gavriletea, M.D. 2021. The unsustainable use of sand: Reporting on a global problem. *Sustainability* 13(6):3356. <https://doi.org/10.3390/su13063356>
- Lee, C.; Paik, K.; Yoo, D.G.; Kim, J.H. 2014a. Efficient method for optimal placing of water quality monitoring stations for an ungauged basin. *Journal of Environmental Management* 132:24–31. <https://doi.org/10.1016/j.jenvman.2013.10.012>
- Lee, C.; Paik, K.; Lee, Y. 2014b. Optimal sampling network for monitoring the representative water quality of an entire reservoir on the basis of information theory. *Journal of Water and Climate Change* 5(2): 151–162. <https://doi.org/10.2166/wcc.2014.104>
- Liebel, S.; Tomotake, M.E.M.; Ribeiro, C.A.O. 2013. Fish histopathology as biomarker to evaluate water quality. *Ecotoxicology and Environmental Contamination* 8(2):9–15. <http://doi.org/10.5132/eec.2013.02.002>

- Lin, Y.P.; Mukhtar, H.; Huang, K.T.; Petway, J.R.; Lin, C.M.; Chou, C.F.; Liao, S.W. 2020. Real-time identification of irrigation water pollution sources and pathways with a wireless sensor network and blockchain framework. *Sensors* 20(13):3634. <https://doi.org/10.3390/s20133634>
- Liska, I.; Wagner, F.; Sengl, M.; Deutsch, K.; Slobodnik, J. 2015. *Joint Danube survey 3: A comprehensive analysis of Danube water quality*. Final scientific report. Vienna, Austria: International Commission for the Protection of the Danube River (ICPDR). Available at http://www.danubesurvey.org/jds3/jds3-files/nodes/documents/jds3_final_scientific_report_1.pdf (accessed on March 8, 2023).
- Mateo-Sagasta, J.; Marjani Zadeh, S.; Turrall, H.; Burke, J. 2017. *Water pollution from agriculture: A global review. Executive summary*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 35p. Available at <https://www.fao.org/3/i7754e/i7754e.pdf> (accessed on March 8, 2023).
- Medinilla, A. 2018. *African river basin organisations: From best practice to best fit*. Discussion Paper No. 236. Maastricht, Netherlands: European Centre for Development Policy Management (ECDPM). Available at <https://ecdpm.org/publications/african-river-basin-organisations-from-best-practice-to-best-fit/>
- Mekonnen, A.; Leta, S.; Njau, K.N. 2015. Wastewater treatment performance efficiency of constructed wetlands in African countries: A review. *Water Science and Technology* 71(1):1–8. <https://doi.org/10.2166/wst.2014.483>
- Mukuyu, P.; Lautze, J.; Rieu-Clarke, A.; Saruchera, D.; McCartney, M. 2020. The devil's in the details: Data exchange in transboundary waters. *Water International* 45(7-8):884–900. <https://doi.org/10.1080/02508060.2020.1850026>
- Mukuyu, P.; Jayathilake, N.; Tijani, M.; Nikiema, J.; Dickens, C.; Mateo-Sagasta, J.; Chapman, D. V.; Warner, S. 2024a. *State of water quality monitoring and pollution control in Africa: Towards developing an African Water Quality Program (AWaQ)*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 44p. (IWMI Working Paper 207). doi: <https://doi.org/10.5337/2023.216>
- Mukuyu, P.; Dickens, C.; Jayathilake, N.; Tijani, M.; Chapman, D. V.; Warner, S. 2024. *A framework for an African Water Quality Program (AWaQ)*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 22p. (IWMI Working Paper 209). doi: <https://doi.org/10.5337/2024.202>
- Naloufi, M.; Lucas, F.S.; Souihi, S.; Servais, P.; Janne, A.; De Abreu, T.W.M. 2021. Evaluating the performance of machine learning approaches to predict the microbial quality of surface waters and to optimize the sampling effort. *Water* 13(18):2457. <https://doi.org/10.3390/w13182457>
- Necibi, M.C.; Dhiba, D.; El Hajjaji, S. 2021. Contaminants of emerging concern in African wastewater effluents: Occurrence, impact and removal technologies. *Sustainability* 13(3):1125. <https://doi.org/10.3390/su13031125>
- Nikiema, J.; Figoli, A.; Weissenbacher, N.; Langergraber, G.; Marrot, B.; Moulin, P. 2013. Wastewater treatment practices in Africa - Experiences from seven countries. *Sustainable Sanitation Practice* 14: 26–34. <https://hdl.handle.net/10568/40210>
- O'Flynn, B.; Regan, F.; Lawlor, A.; Wallace, J.; Torres, J.; O'Mathuna, C. 2010. Experiences and recommendations in deploying a real-time, water quality monitoring system. *Measurement Science and Technology* 21(12):124004. <https://doi.org/10.1088/0957-0233/21/12/124004>
- O'Hare, M.T.; Gunn, I.D.M.; Critchlow-Watton, N.; Guthrie, R.; Taylor, C.; Chapman, D.S. 2020. Fewer sites but better data? Optimising the representativeness and statistical power of a national monitoring network. *Ecological Indicators* 114:106321. <https://doi.org/10.1016/j.ecolind.2020.106321>
- Oliver, D.M.; Heathwaite, A.L.; Haygarth, P.M. 2010. A 'culture' change in catchment microbiology. *Hydrological Processes* 24(20):2973–2976. <https://doi.org/10.1002/hyp.7837>
- Oliver, D.M.; van Niekerk, M.; Kay, D.; Heathwaite, A.L.; Porter, J.; Fleming, L.E.; Kinzelman, J.L.; Connolly, E.; Cummins, A.; McPhail, C.; Rahman, A.; Thairs, T.; de Roda Husman, A.M.; Hanley, N.; Dunhill, I.; Globevnik, L.; Harwood, V.J.; Hodgson, C.J.; Lees, D.N.; Nichols, G.; Nocker, A.; Schets, C.; Quilliam, R.S. 2014. Opportunities and limitations of molecular methods for quantifying microbial compliance parameters in EU bathing waters. *Environment International* 64:124–128. <https://doi.org/10.1016/j.envint.2013.12.016>

- Oosterhuis, M.; Sacher, F.; ter Laak, T.L. 2013. Prediction of concentration levels of metformin and other high consumption pharmaceuticals in wastewater and regional surface water based on sales data. *Science of the Total Environment* 442:380–388. <https://doi.org/10.1016/j.scitotenv.2012.10.046>
- OGC (Open Geospatial Consortium). 2014. *WaterML-WQ – an O&M and WaterML 2.0 profile for water quality data*. Best Practice Paper 14-003. Available at <http://docs.opengeospatial.org/bp/14-003/14-003.html> (accessed on March 8, 2023).
- Oral, H.V.; Carvalho, P.; Gajewska, M.; Ursino, N.; Masi, F.; van Hullebusch, E.D.; Kazak, J.K.; Exposito, A.; Cipolletta, G.; Andersen, T.R.; Finger, D.C.; Simperler, L.; Regelsberger, M.; Rous, V.; Radinja, M.; Buttiglieri, G.; Krzeminski, P.; Rizzo, A.; Dehghanian, K.; Nikolova, M.; Zimmermann, M. 2020. A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. *Blue-Green Systems* 2(1):112-136. <https://doi.org/10.2166/bgs.2020.932>
- OECD (Organisation for Economic Co-operation and Development). 2019. *Pharmaceutical residues in freshwater: Hazards and policy responses*. OECD Studies on Water. Paris: OECD Publishing. <https://doi.org/10.1787/c936f42d-en>
- Park, J.; Kim, K.T.; Lee, W.H. 2020. Recent advances in Information and Communications Technology (ICT) and sensor technology for monitoring water quality. *Water* 12(2):510. <https://doi.org/10.3390/w12020510>
- Pawlowski, J.; Kelly-Quinn, M.; Altermatt, F.; Apothéloz-Perret-Gentil, L.; Beja, P.; Boggero, A.; Borja, A.; Bouchez, A.; Cordier, T.; Domaizon, I.; Feio, M.J.; Filipe, A.F.; Fornaroli, R.; Graf, W.; Herder, J.; van der Hoorn, B.; Jones, J.I.; Sagova-Mareckova, M.; Moritz, C.; Barquín, J.; Piggott, J.J.; Pinna, M.; Rimet, F.; Rinkevich, B.; Sousa-Santos, C.; Specchia, V.; Trobajo, R.; Vasselon, V.; Vitecek, S.; Zimmerman, J.; Weigand, A.; Leese, F.; Kahlert, M. 2018. The future of biotic indices in the ecogenomic era: Integrating (e)DNA metabarcoding in biological assessment of aquatic ecosystems. *Science of the Total Environment* 637-638:1295–1310. <https://doi.org/10.1016/j.scitotenv.2018.05.002>
- Pinelli, D.; Zanaroli, G.; Rashed, A.A.; Oertlé, E.; Wardenaar, T.; Mancini, M.; Vettore, D.; Fiorentino, C.; Frascari, D. 2020. Comparative preliminary evaluation of 2 in stream water treatment technologies for the agricultural reuse of drainage water in the Nile Delta. *Integrated Environment Assessment and Management* 16(6):920–933. <https://doi.org/10.1002/ieam.4277>
- Quinlivan, L.; Chapman, D.V.; Sullivan, T. 2020a. Validating citizen science monitoring of ambient water quality for the United Nations sustainable development goals. *Science of the Total Environment* 699:134255. <https://doi.org/10.1016/j.scitotenv.2019.134255>
- Quinlivan, L.; Chapman, D.V.; Sullivan, T. 2020b. Applying citizen science to monitor for the Sustainable Development Goal Indicator 6.3.2: A review. *Environmental Monitoring and Assessment* 192(218). <https://doi.org/10.1007/s10661-020-8193-6>
- Raich, J. 2013. *Review of sensors to monitor water quality. ERNCIP thematic area Chemical & Biological Risks in the Water Sector*. Deliverable D1 - Task 1. Luxembourg: Publications Office of the European Union. Available at: https://erncip-project.jrc.ec.europa.eu/sites/default/files/Review_of_sensors_to_monitor_water_%20quality.pdf (accessed on April 28, 2023)
- Rouso, B.Z.; Bertone, E.; Stewart, R.; Hamilton, D.P. 2020. A systematic literature review of forecasting and predictive models for cyanobacteria blooms in freshwater lakes. *Water Research* 182:11595. <https://doi.org/10.1016/j.watres.2020.115959>
- Sibanda, M.; Mutanga, O.; Chimonyo, V.G.P.; Clulow, A.D.; Shoko, C.; Mazvimavi, D.; Dube, T.; Mabhaudhi, T. 2021. Application of drone technologies in surface water resources monitoring and assessment: A systematic review of progress, challenges, and opportunities in the Global South. *Drones* 5(3):84. <https://doi.org/10.3390/drones503084>
- Stasinakis, A.S.; Gatidou, G. 2010. Micropollutants and aquatic environment. In: Virkutyte, J.; Varma, R.S.; Jegatheesan, V. (eds.) *Treatment of micropollutants in water and wastewater*. London, UK: IWA Publishing. pp.1–51.
- Tanos, P.; Kovács, J.; Kovács, S.; Anda, A.; Hatvani, I.G. 2015. Optimization of the monitoring network on the River Tisza (Central Europe, Hungary) using combined cluster and discriminant analysis, taking seasonality into account. *Environmental Monitoring and Assessment* 187:575. <https://doi.org/10.1007/s10661-015-4777-y>
- Tatem, A.J.; Goetz, S.J.; Hay, S.I. 2008. Fifty years of Earth-observation satellites: Views from space have led to countless advances on the ground in both scientific knowledge and daily life. *American Scientist* 96(5):390–398. <https://doi.org/10.1511/2008.74.390>
- Taylor, J.; Graham, M.; Louw, A.; Lepheana, A.; Madikizela, B.; Dickens, C.; Chapman, D.V.; Warner, S. 2022. Social change innovations, citizen science, miniSASS and the SDGs. *Water Policy* 24(5):708–717. <https://doi.org/10.2166/wp.2021.264>

- Thornhill, I.; Loisel, S.; Clymans, W.; van Noordwijk, C.G.E. 2019. How citizen scientists can enrich freshwater science as contributors, collaborators, and co-creators. *Freshwater Science* 38(2):231–235. <https://doi.org/10.1086/703378>
- Trémolet, S.; Karres, N. 2020. *Resilient European cities: Nature-based solutions for clean water*. London, UK: The Nature Conservancy.
- Uddin, M.G.; Nash, S.; Olbert, A.I. 2021. A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators* 122:07218. <https://doi.org/10.1016/j.ecolind.2020.107218>
- UNDESA (United Nations Department of Economic and Social Affairs). 2019. *World population prospects 2019: Highlights*. ST/ESA/SER.A/423. New York, USA: United Nations Department of Economic and Social Affairs, Population Division.
- UNEP (United Nations Environment Programme). 2018. *A framework for freshwater ecosystem management. Volume 4: Scientific background*. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available at https://www.unepdhi.org/wp-content/uploads/sites/2/2020/09/Framework_Freshwater_Ecosystem_Mgt_vol4.pdf (accessed on March 19, 2023).
- UNEP. 2021. *Progress on ambient water quality. Tracking SDG 6 series: Global indicator 6.3.2 updates and acceleration needs*. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available at https://www.unwater.org/sites/default/files/app/uploads/2021/09/SDG6_Indicator_Report_632_Progress-on-Ambient-Water-Quality_2021_EN.pdf (accessed on July 21, 2023).
- UNEP GEMS/Water CDC (Capacity Development Centre of the Global Environment Monitoring System for freshwater for the United Nations Environment Programme). 2020a. *Water quality monitoring capacity scoping for Africa: Summary report 2020*. Cork, Ireland: UNEP GEMS/Water Capacity Development Centre (CDC), Environmental Research Institute, University College Cork.
- UNEP GEMS/Water. 2020b. *An introduction to SDG indicator 6.3.2: Proportion of bodies of water with good ambient water quality*. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available at: [https://communities.unep.org/display/sdg632/Documents+and+Materials?preview=/32407814/38306458/SDG_632_Introduction%20to%20the%20Methodology_EN%20\(3\).pdf#DocumentsandMaterials-Intro](https://communities.unep.org/display/sdg632/Documents+and+Materials?preview=/32407814/38306458/SDG_632_Introduction%20to%20the%20Methodology_EN%20(3).pdf#DocumentsandMaterials-Intro) (accessed on March 19, 2023).
- UN Habitat (United Nations Human Settlements Programme); WHO (World Health Organization). 2021. *Progress on wastewater treatment – Global status and acceleration needs for SDG indicator 6.3.1*. Geneva, Switzerland: United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO).
- WWAP (United Nations World Water Assessment Programme)/UN-Water. 2018. *The United Nations world water development report 2018: Nature-based solutions for water*. Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO).
- Vethaak, A.D.; Ap Rheinallt, T. 1992. Fish disease as a monitor for marine pollution: The case of the North Sea. *Reviews in Fish Biology and Fisheries* 2(1):1–32. <https://doi.org/10.1007/BF00042915>
- Wajzman, D.; Rudén, C. 2006. Identification and evaluation of computer models for predicting environmental concentrations of pharmaceuticals and veterinary products in the Nordic environment. *Journal of Exposure Science & Environmental Epidemiology* 16(1):85–97. <https://doi.org/10.1038/sj.jea.7500440>
- Wälchen J.; Mäder, P. 2018. Machine learning for image based species identification. *Methods in Ecology and Evolution* 9(11):2216–2225. <https://doi.org/10.1111/2041-210X.13075>
- Wang, N.; Dai, T.; Lei, L. 2018. Optofluidic technology for water quality monitoring. *Micromachines* 9(4):158. <https://doi.org/10.3390/mi9040158>
- Warner, S.; Chapman, D.; Dickens, C. 2020. Good ambient water quality. In: Leal Filho, W.; Azul, A.M.; Brandli, L.; Lange, S.A.; Wall, T. (eds.) *Clean water and sanitation*. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. https://doi.org/10.1007/978-3-319-70061-8_83-1
- Webber, J. 2020. *Continuous water-quality monitoring: Deployment techniques and applications*. Virginia and West Virginia Water Science Center, United States Geological Survey (USGS). Available at https://www.chesapeakebay.net/channel_files/41695/2020.12.02_diwg_webber.pdf (accessed on March 19, 2020).
- WHO (World Health Organization). 2017. *Guidelines for drinking-water quality: Fourth edition, incorporating the first addendum*. Geneva, Switzerland: World Health Organization (WHO). <https://www.who.int/publications/i/item/9789241549950> (accessed on March 19, 2020).

WHO. 2019. *Strengthening drinking-water surveillance using risk-based approaches*. Copenhagen, Denmark: World Health Organization (WHO) Regional Office for Europe. <https://apps.who.int/iris/handle/10665/329396>

Wood, A. 1995. Constructed wetlands in water pollution control: Fundamentals to their understanding. *Water Science & Technology* 32(3):21–29. [https://doi.org/10.1016/0273-1223\(95\)00601-X](https://doi.org/10.1016/0273-1223(95)00601-X)

Wool, T.; Ambrose, Jr. R.B.; Martin, J.L.; Comer, A. 2020. WASP 8: The next generation in the 50-year evolution of USEPA's water quality model. *Water* 12(5):1398. <https://doi.org/10.3390/w12051398>

Zolkefli, N.; Sharuddin, S.S.; Yusoff, M.Z.M.; Hassan, M.A.; Maeda, T.; Ramli, N. 2020. A review of current and emerging approaches for water pollution monitoring. *Water* 12(12):3417. <https://doi.org/10.3390/w12123417>

Annex 1. Examples of Standard Methods for Water Quality Analysis.

| Parameter | Standard method | Description |
|--|---|---|
| Electrical Conductivity | ASTM D 1125 | Standard test methods for electrical conductivity and water resistivity |
| | EPA 120.1 | Conductance, specific conductance |
| | ISO 7888, DIN EN 27888 | Water quality — determination of electrical conductivity |
| | SCA, Blue book 14 | The measurement of electrical conductivity and the laboratory determination of the pH value of natural, waste and treated waters |
| | USP 645 APHA 2510 | Water conductivity |
| pH | ASTM D 5464 | Standard test method for pH measurement of water of low conductivity |
| | EPA 150.2 | pH, electrometric (continuous monitoring) |
| | DIN EN ISO 10523 | Water quality — pH determination |
| | SCA, Blue book 14 | The measurement of electrical conductivity and the laboratory determination of the pH value of natural, waste and treated waters |
| | SLMB 602.1 APHA 4500-H ⁺ B | pH value of drinking water Potentiometry |
| Fluoride | ASTM D 1179; ASTM D 3868 DIN 38405-4 | Standard test methods for fluoride ion in water; Standard test method for fluoride ions in brines, brackish water and seawater German standard methods for the examination of water, sludge and wastewater; anions (group D); determination of fluoride (D 4) |
| | EPA 340.2 ISO 10359-1 | Fluoride (potentiometric, ion selective electrode) Water quality — determination of fluoride — part 1: electrochemical probe method for potable and lightly polluted water |
| | SCA, Blue book 62 | Fluoride in waters, plants, soils, effluents and sludges |
| | SLMB 626.1 | Fluoride in drinking water, potentiometric |
| | APHA 4500 F | |
| Ammonium and Kjeldahl Nitrogen Anions and Cations | ASTM D 1426; ASTM D 3590 | Standard test methods for ammonia nitrogen in water; standard test methods for total Kjeldahl nitrogen in water |
| | DIN 38406-5 | German standard methods for the examination of water, sludge and wastewater; cations (group E); determination of ammonia-nitrogen (E 5) |
| | EPA 350.2; EPA 350.3; EPA 351.3; EPA 351.4 | Nitrogen, ammonia (colorimetric; titrimetric; potentiometric — distillation procedure); Nitrogen, ammonia (potentiometric, ion selective electrode); Nitrogen, Kjeldahl total (colorimetric; titrimetric; potentiometric); Nitrogen, Kjeldahl total (potentiometric, ion selective electrode) |
| | ISO 5663, DIN EN 25663 | Water quality — determination of Kjeldahl nitrogen — method after mineralization with selenium |
| | ISO 5664; ISO 6778 | Water quality — determination of ammonium — distillation and titration method; potentiometric method |
| | SCA, Blue book 126 | Kjeldahl nitrogen in waters |
| | ASTM D 4327 | Standard test method for anions in water by suppressed ion chromatography |
| | ASTM D 5085 | Standard test method for determination of nitrate, chloride and sulfate in atmospheric wet deposition by chemically suppressed ion chromatography |
| | ASTM D 5257 | Standard test method for dissolved hexavalent chromium in water by ion chromatography |
| | ASTM D 5542 | Standard test methods for trace anions in high purity water by ion chromatography |
| | ASTM D 5996 | Standard test method for measuring anionic contaminant in high purity water by online ion chromatography |
| | ASTM D 6581 | Standard test method for bromide, bromate, chlorite, chlorate in drinking water by suppressed ion chromatography |
| | ASTM D 6919 | Standard test method for determination of dissolved alkali and alkaline earth cations and ammonium in water and wastewater by ion chromatography |

(Continued)

| Parameter | Standard method | Description |
|------------------------------------|---|---|
| | EPA 218.6 | Determination of dissolved hexavalent chromium in groundwater, drinking water and industrial wastewater effluents by ion chromatography |
| | EPA 300.0 | Determination of inorganic anions by ion chromatography |
| | EPA 300.1 | Determination of inorganic anions in drinking water by ion chromatography |
| | EPA 314.0 | Perchlorate in drinking water by ion chromatography |
| | EPA 317.0 | Oxyhalide disinfection byproducts (DPBs) and bromide by ion chromatography |
| | EPA 326.0 | Inorganic oxyhalide DPBs in drinking water by ion chromatography with postcolumn reagent for trace bromate analysis |
| | DIN EN ISO 10304-1; DIN EN ISO 10304-3; DIN EN ISO 10304-4 | Water quality — determination of dissolved anions by liquid chromatography of ions — part 1: determination of chloride, bromide, fluoride, nitrate, nitrite, sulfate and phosphate; part 3: determination of chromate, iodide, sulfite, thiosulfate and thiocyanate; part 4: determination of chloride, chlorate, chlorite in water with low contamination |
| | DIN EN ISO 14911 | Water quality — determination of dissolved, Li ⁺ , Na ⁺ , NH ₄ ⁺ , K ⁺ , Mn ²⁺ , Ca ²⁺ , Mg ²⁺ , Sr ²⁺ and Ba ²⁺ using ion chromatography - method for water and wastewater |
| | DIN EN ISO 15061 | Water quality - determination of dissolved bromate - method by liquid chromatography of ions |
| | SLMB 631.1 | Chloride, nitrate, sulfate in drinking water |
| | SLMB 658.1 | Chlorite, chlorate in drinking water |
| | APHA 4500-NO ₃ F; 4500-NH ₃ F; 4500-N C | Automated Cadmium reduction method; Automated Phenate method; Persulfate method |
| Heavy metals | ASTM D 3557 ASTM D 3559 DIN 38406-16; DIN 38406-17 | Standard test methods for cadmium in water Standard test methods for lead in water German standard methods for the examination of water, wastewater and sludge; determination of zinc, cadmium, lead, copper, thallium, nickel, cobalt by voltammetry (E 16) |
| | EPA 7063 | Arsenic in aqueous samples and extracts by anodic stripping voltammetry (ASV) |
| | EPA 7198 | Hexavalent chromium by differential pulse polarography |
| | EPA 7472 | Mercury in aqueous samples and extracts by ASV |
| | SLMB 613.1 APHA 3125 | Copper, lead, cadmium, zinc in drinking water, polarographic |
| Chemical Oxygen Demand (COD) | DIN 38409-41; DIN 38409-44 DIN 38414-9 EPA 410.1; EPA 410.2; EPA 410.3 ISO 6060 SCA, Blue book 215 APHA 5210 | German standard methods for the examination of water, wastewater and sludge; summary action and material characteristic parameters (Group H); determination of the COD in the range over 15 mg/L (H 41); determination of the COD, ranging from 5 to 50 mg/L (H 44) German standard methods for the examination of water, wastewater and sludge; sludge and sediments (group S); determination of the COD (S 9) COD — titrimetric, mid-level; titrimetric, low level; high-level for saline water Water quality — determination of the COD The determination of COD in waters and effluents |

(Continued)

| Parameter | Standard method | Description |
|-------------------|--|--|
| Water Hardness | ASTM D 511 | Standard test methods for calcium and magnesium in water |
| | ASTM D 1126 | Standard test methods for hardness in water |
| | ASTM D 1067 | Standard test methods for acidity or alkalinity of water |
| | ASTM D 3875 | Standard test methods for alkalinity in brines, brackish water and seawater |
| | DIN 38406-3; | German standard methods for the examination of water, wastewater and sludge — cations (group E) — part 3; determination of calcium and magnesium, complexometric method (E 3); summary indices of actions and substances (group H); water hardness (H 6); determination of acid and base-neutralizing capacities (H 7) |
| | DIN 38409-6; | |
| | DIN 38409-7 | |
| | DIN EN ISO 9963-1 | Water quality — determination of alkalinity — part 1: determination of total and composite alkalinity |
| | EPA 130.2 | Hardness, total (mg/L as CaCO ₃) (titrimetric, EDTA) |
| | EPA 215.2 | Calcium (titrimetric, EDTA) |
| | EPA 310.1 | Alkalinity (titrimetric, pH 4.5) |
| | ISO 6058 | Water quality — determination of calcium content — EDTA titrimetric method |
| | ISO 6059 | Water quality — determination of the sum of calcium and magnesium — EDTA titrimetric method |
| | ISO 9963-2 | Water quality — determination of alkalinity — part 2: determination of carbonate alkalinity |
| SCA, Blue book 43 | Total hardness, calcium hardness and magnesium hardness in raw and potable waters by EDTA titrimetry | |
| SCA, Blue book 44 | The determination of alkalinity and acidity in water | |
| SLMB 639.1 | Total hardness in drinking water | |
| SLMB 640.1 | Alkalinity of drinking water, pH 4.3 and 8.2 | |
| APHA 2340 C | EDTA titrimetric method | |
| Free Chlorine | ASTM D 512 | Standard test methods for chloride ion in water |
| | ASTM D 1253 | Standard test method for residual chlorine in water |
| | DIN 38405-1 | German standard methods for the examination of water, wastewater and sludge; anions (group D); determination of chloride ions (D 1) |
| | EPA 330.1; EPA 330.2; | Chlorine, total residual |
| | EPA 330.3 | |
| | DIN EN ISO 7393-1; | Water quality — determination of free chlorine and total chlorine — part 1: titrimetric method using N,N-diethyl- 1,4-phenylenediamine; part 3: iodometric titration method for the determination of total chlorine |
| | DIN EN ISO 7393-3 | |
| | APHA 4500-F | |

Source: <https://www.azom.com/article.aspx?ArticleID=14579>

Note: ASTM - American Society for Testing and Materials; DIN - German Institute for Norms; EPA - United States Environmental Protection Agency; EN - European Norm; ISO - International Organization for Standardization; USP - United States Pharmacopeia; SLMB - Swiss Book for the Analysis of Food; SCA - Standing Committee of Analysts (Blue Books)

Annex 2. Examples for Online Water Quality Monitoring Sensors Available in the Market.

| Sensor | Description | Approximate cost* |
|---------------------------|---|-------------------|
| Kapta™ 3000 AC4 | Developed under the SecurEau project. Measures free chlorine, pressure, temperature and conductivity. Commercialized by ENDETEC (Veolia Water). | USD 3,600 |
| Spectro::lyser™ | Developed by S::CAN (Vienna-Austria). Provides a full range of plug-and-measure water quality sensors for different water types. The Spectro::lyser™ UV-Vis probe online-monitors an individual selection of TSS, turbidity, NO-N, COD, BOD, TOC, DOC, UV254, color, BTX, O ₃ , H ₂ S, AOC, fingerprints and spectral-alarms, temperature and pressure. | USD 12,000 |
| i::scan | An in-pipe LED-based spectrometer probe measuring color (div. standards), UV254, organics (TOC, DOC, COD, BOD), turbidity and UV-Vis spectral-alarm. | USD 4,000 |
| EventLab | Developed by Optiqua Technologies. Offers a real-time water quality monitoring solution or EWS for water distribution networks with no consumables and low maintenance. The integrated system is based around Optiqua's patented optical Mach-Zehnder Interferometer (MZI) technology, with dedicated electronics, data communication, event detection algorithms and control software. | USD 14,000 |
| Lab-on-Chip | Developed by Optisense. Lab-on-Chip sensor can be tailored for the detection of any specific (bio) chemical substance by applying selective bio-chemical layers to the generic platform. | - |
| TOX control | A toxicity monitor developed by MicroLAN. It is an automated system that uses freshly cultivated light emitting bacteria (<i>Vibrio fischeri</i>) as a biological sensor. The luminescence is measured before and after exposition to calculate the inhibition in percentage. | USD 40,000 |
| Algae Toximeter | Developed by BBE Moldaenke. Standardized algae are mixed with the sample water and the instrument detects the photosynthetic activity of the algae. It determines the percentage of active chlorophyll under illumination and serves as a toxicity measurement. | USD 30,000 |
| COLIGUARD® | Developed by Mb Online GmbH to detect <i>Escherichia coli</i> . Uses the technology of Fluorescent optical analysis of biochemical activity. | USD 50,000 |
| WQ 101 | A water quality monitoring sensor to measure temperature. Vendor - Global water. | - |
| WQ401 | A water quality monitoring sensor to measure DO. Vendor - Global water. | - |
| WQ600 | A water quality monitoring sensor to measure ORP. Vendor - Global water. | - |
| WQ730 and WQ720 | A water quality monitoring sensor to measure Turbidity. Vendor - Global water. | - |
| WQ-COND | A water quality monitoring sensor to measure EC. Vendor - Global water. | - |
| WQ201 pH Sensor | A water quality monitoring sensor to measure pH. Vendor - Global water. | - |
| FC80 free chlorine sensor | A water quality monitoring sensor to measure Free Chlorine. Vendor - Fierce Electronics | - |
| Proteus water sensor | A multi-parameter probe uses fluorescence to monitor BOD, COD, TOC and Total coliforms (and variations thereupon) in real time. | - |
| Parasitometer | Developed by Water Optics Technology. An Optofludic sensor to identify disease causing microbes | - |

Source: Raich 2013; Jan et al. 2021; Wang et al. 2018.

Note: * As indicated in the Source (2013).

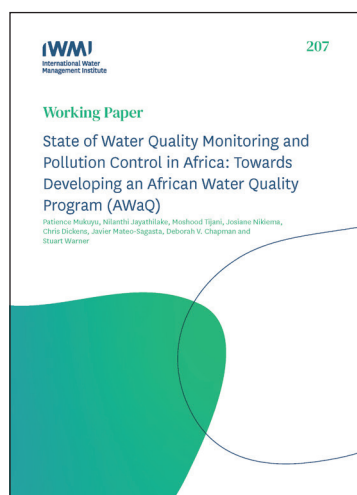
Annex 3. Links to Additional Resources.

- <https://www.lovibond.com/en/PW/Water-Testing/Products/Microbiology/ColiformE.Coli>
- https://rainfresh.ca/product/water-test-kits/#tab-product_editor_12294_tab
- <https://www.idexx.com/en/water/water-products-services/colilert/>
- <https://ec.europa.eu/research-and-innovation/en/horizon-magazine/new-tests-identify-contaminated-drinking-water-minutes-not-weeks>
- <https://www.vermicon.com/products/water/test-kit-analysis-ecoli-coliforms>
- <https://blogs.worldbank.org/water/future-water-how-innovations-will-advance-water-sustainability-and-resilience-worldwide>
- https://www.epa.sa.gov.au/files/8522_water_objectives.pdf
- Geo AquaWatch: an Initiative that aims to develop and build the global capacity and utility of EO-derived water quality data, products and information to support water resources management and decision-making: <https://www.geoaquawatch.org/>
- NASA's EO portal: <https://search.earthdata.nasa.gov/>
- International Water Association (IWA) webinar on EO technologies for water quality management: <https://iwa-network.org/learn/earth-observation-technologies-for-water-quality-management/>
- Joint Nature Conservation Committee (JNCC) Resource list: Using EO for Water Quality Monitoring: Resources and information: https://jncc.gov.uk/media/4681/eo4water_resources_website_final.pdf
- EU WFD: Papathanaopoulou, E., Simis, S. et al. 2019. Satellite-assisted monitoring of water quality to support the implementation of the Water Framework Directive. *EOMORES White Paper*. 28p. <https://doi.org/10.5281/zenodo.3463050>

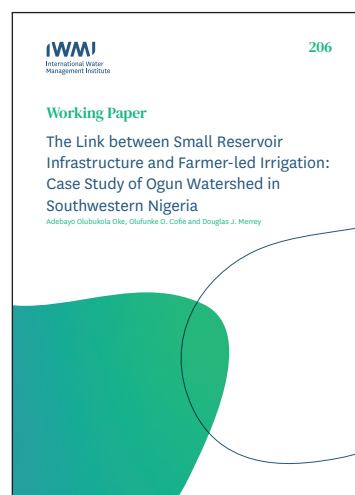
IWMI Working Paper Series



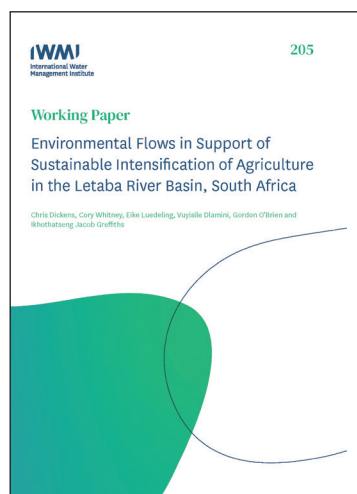
208 Innovations in Water Quality Monitoring and Management in Africa: Towards Developing an African Water Quality Program (AWaQ)
<https://doi.org/10.5337/2023.217>



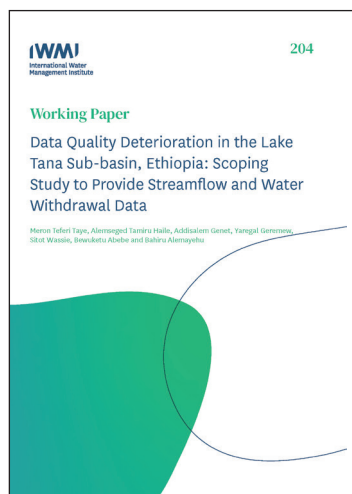
207 State of Water Quality Monitoring and Pollution Control in Africa: Towards Developing an African Water Quality Program (AWaQ)
<https://doi.org/10.5337/2023.216>



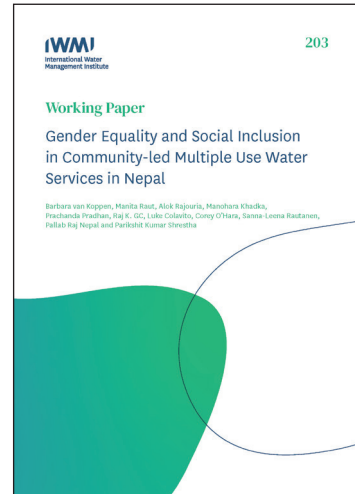
206 The Link between Small Reservoir Infrastructure and Farmer-led Irrigation: Case Study of Ogun Watershed in Southwestern Nigeria
<https://doi.org/10.5337/2022.229>



205 Environmental Flows in Support of Sustainable Intensification of Agriculture in the Letaba River Basin, South Africa
<https://doi.org/10.5337/2022.226>



204 Data Quality Deterioration in the Lake Tana Sub-basin, Ethiopia: Scoping Study to Provide Streamflow and Water Withdrawal Data
<https://doi.org/10.5337/2022.208>



203 Gender Equality and Social Inclusion in Community-led Multiple Use Water Services in Nepal
<https://doi.org/10.5337/2022.200>

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