State of Water Quality Monitoring and Pollution Control in Africa: Toward Developing an African Water Quality Program (AWaQ)

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About IWMI

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Project

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Collaborators

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WWQA World Water Quality Alliance	The World Water Quality Alliance (WWQA)

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Acronyms and Abbreviations

AMCOW	African Ministers' Council on Water
APAGroP	AMCOW Pan-African Groundwater Program
AWaQ	African Water Quality Program
GEMS/Water	Global Environment Monitoring System for Freshwater
IIWQ	International Initiative on Water Quality
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
JMP	Joint Monitoring Programme for Water Supply and Sanitation
SDGs	Sustainable Development Goals
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
WASSMO	Water and Sanitation Sector Monitoring and Reporting System
WHO	World Health Organization
WSP	Water safety plans
WWQA	World Water Quality Alliance

SUMMARY

Responding to water pollution challenges on the African continent requires concerted efforts across various sectors and actors. The African Ministers' Council on Water (AMCOW) envisages an African Water Quality (AWaQ) Program to accelerate the continent's water security agenda. The design of this program, supported by the International Water Management Institute (IWMI), involves five phases taking place during the 2021-22 period and resulting in the main output of a framework for the AWaQ. This report covers the first two of these five phases, which are designed to provide a baseline assessment of the status of water quality monitoring and assessment in Africa, including the capacities available across countries. This assessment considers various past and ongoing initiatives related to water quality monitoring and assessment, capacity development and water pollution control and impact mitigation. While the initiatives presented here are not exhaustive, they do provide a starting point for understanding the state of water quality monitoring—the available capacities and the pollution control measures currently implemented and how the AWaQ can be designed to fill gaps and strengthen ongoing initiatives.

The findings discussed in this report are based on literature reviews, remote interviews and a continentwide survey implemented to better understand various countries' water quality situation. Although there are variations across countries in terms of the available capacities for water quality monitoring and assessment and pollution control, water pollution remains a critical challenge that provides an impetus for the AWaQ program. The survey was rolled out across Africa through the AMCOW network of African country representatives. Thirty-one out of 54 countries responded to the survey, offering their inputs on different water quality-related aspects.

The key findings from this survey were:

- There is an encouraging availability of national water testing laboratory facilities across African countries. Nonetheless, there are weaknesses that require attention to ensure effectiveness and sustainability.
- Regular and ongoing training is needed to keep up with laboratory testing methodologies. However, we observed a low trend in regular training, which does not augur well for keeping abreast of the best practices in water quality monitoring. In the context of emerging pollutants, training needs to be more regular than is currently experienced.
- Water quality monitoring and assessment capacities are patchy. Capacities related to staff training, laboratory infrastructure and monitoring program activities need strengthening.
- Pollution control mechanisms are facing challenges. Regulatory mechanisms and wastewater treatment technologies—the most widely deployed pollution control solutions—may benefit from more concerted investment and the political will and financing to boost their effectiveness.

We observed that several initiatives are currently being implemented at different scales: (i) global (e.g., Global Environment Monitoring System for Freshwater [GEMS/Water], World Water Quality Alliance [WWQA], Water Safety Plans); (ii) continental (e.g., AMCOW Pan-African Groundwater Program [APAGroP], Water and Sanitation Sector Monitoring and Reporting System [WASSMO]); (iii) transboundary (through basin organizations); and (iv) national programs. However, the coverage of these initiatives is not even and could benefit from greater regional coordination. There is scope for the envisaged AWaQ program to fill in the gaps seen in these monitoring initiatives by increasing coverage in participating countries and strengthening monitoring systems that generate water quality data.

INTRODUCTION

Background

In 2016, the United Nations Environment Programme (UNEP) presented a 'snapshot' of global water quality (UNEP 2016). Key findings from that report indicate an increasing threat to and observed deterioration in water quality across the world's rivers, including those in Africa. As the world's second-driest continent, having only about 9% of global freshwater resources while being home to about 15% of the global population—which is expected to rise to 21.8% by 2050—the availability of and access to water are more crucial in Africa than they are almost anywhere else on Earth (UNEP 2010; UN DESA 2014). Coupled with anthropogenic pressures, most parts of Africa are projected to experience growing impacts of climate change on water quality associated with increased temperatures, prolonged drought periods and flash floods. It is now urgently necessary to strengthen water quality monitoring efforts in order to mitigate impacts such as increased pollutant concentrations when water flows decrease during drought periods as well as acceleration of chemical reactions in warmer waters, among other adverse impacts (Whitehead et al. 2009; IPCC 2021). While water quality, either directly or indirectly, is a key consideration for many of the 17 Sustainable Development Goals (SDGs) set by the United Nations (UN), it has particular relevance to SDG 6: to ensure availability and sustainable management of water and sanitation for all. Further, SDG target 6.3 mainly aims at improving water quality, and indicator 6.3.2 measures whether and to what extent water quality management measures are contributing to improvement of water quality over time[1]. Having a clear grip on water quality monitoring and pollution control will enable the continent to achieve its developmental goals of improved access to clean water and sanitation.

However, sanitation systems in Africa do not adequately address waste containment, disposal and treatment so as to separate waste from human contact. This presents the risk of spreading disease to local communities as well as polluting ground and surface water resources (UNICEF and WHO 2020). As of 2017, close to 70% of the continent's population, mainly in Sub-Saharan Africa, did not have access to basic sanitation services, a situation that poses a threat to water quality and, consequently, risks to human health (AfDB 2020). Most of the rural population in Africa is exposed to risk of disease from contaminated water due to direct dependance on untreated sources (e.g., rivers and streams). Recent estimates indicate that 7% of urban dwellers and 27% of rural people in Sub-Saharan Africa rely on unimproved water sources (WHO and UNICEF 2017). According to the United Nations Department of Economic and Social Affairs (UN DESA), there are 115 deaths every hour in Africa due to diseases linked to poor sanitation, poor hygiene and contaminated water (UN DESA 2014). It has been reported that poor people in Africa spend at least a third of their incomes on treatment for water-related diseases like malaria and diarrhea (SIWI and WHO n.d.). Up to 160 million people living in the rural areas of the continent are estimated to come into close contact with polluted water through daily activities such as bathing (UNEP 2016). In urban areas too, rapidly growing and urbanizing populations could overwhelm the capacity to provide wastewater treatment and sanitation services (AfDB 2020).

It is estimated that low and middle-income countries—which include the majority of African countries—treat approximately 28% of their domestic and industrial wastewater. However, there are important disparities among subregions (WWAP 2017). Often, industrial wastewater treatment technologies fall short of achieving acceptable wastewater quality levels, which leads to the discharge of partially treated industrial water. Given the limited regulatory capacities, much of this pollution goes unregulated for prolonged periods. Diffuse pollution from agricultural return flows and runoff

[1] https://sdg.tracking-progress.org/indicator/6-3-2-proportion-of-bodies-of-water-with-good-ambient-water-quality/

increases the nutrient load in water bodies, resulting in cases of eutrophication and anoxic conditions that hamper ecosystem functions (WWAP 2017).

Several interventions have been implemented with varying degrees of success to address the challenge of water pollution in Africa. Conventionally, at the national level, these have included regulatory mechanisms including licensing of polluters, environmental impact assessment of potentially harmful activities and wastewater treatment. However, water quality monitoring and pollution control measures have been constrained by the common challenges of limited financial and human resource capacities (AfDB 2020). At the regional scale, such interventions have been implemented at the transboundary and sub-regional levels by various international actors. Indeed, there exists an opportunity to develop a continentwide initiative cutting across the multiple aspects of monitoring water quality and mitigating pollution. Well-designed and robust ambient water quality monitoring programs can provide the basis for interventions and timely responses to emerging and existing pollution issues as well as informing long-term planning.

Against this background, we present here a report on the status of water quality monitoring and pollution in Africa and discuss the foundations of a new AMCOW African Water Quality Program. The first two phases of this program involve carrying out a situation analysis of water quality monitoring in Africa, describing the efforts thus far to manage deteriorating water quality. In the subsequent three phases of the program, research innovations that could be included to advance water quality management in Africa are presented. They will form part of the design of a new framework for the monitoring and management of water quality. The key output of this project will be a framework for developing the African Water Quality Program which will assist AMCOW in expanding and strengthening water quality monitoring and management across the continent.

The project's key outcomes will enable the establishment of a working program for monitoring and managing water quality that can be adopted by African countries,bringing them up to a similar level of water quality monitoring. The program will also enable Africa to participate meaningfully in the WWQA to scrutinize a multitude of water quality issues. Further, it will promote a continentwide initiative to collect and provide data to larger repositories such as GEMS/Water. Ultimately, an Africa-wide program will be initiated to manage water quality for the benefit of the environment and all of its inhabitants.

About This Project

The African Water Quality Program (AWaQ) aims to build on the rich experience gained and lessons learned from past and ongoing regional and subregional water quality initiatives taken up across Africa by different players including the African Union institutions and the broader members of the WWQA. For example, the new program is designed to build on existing AMCOW initiatives such as the Water and Sanitation Sector Monitoring and Reporting System (WASSMO). Among the WASSMO l indicators, the AWaQ addresses WASSMO Indicator I4.3(a-d)[2] (closely aligned to SDG indicator 6.3.2)—'proportion of bodies of water with good ambient water quality'—and is based on data collected from member states. The AWaQ will also take into account other water quality initiatives (e.g., the AMCOW Pan-African Groundwater Program (APAGroP) in which IWMI and other partners are strongly involved in support of AMCOW's groundwater management efforts.

It is important to review related initiatives to understand how a new program can be designed to add much-needed value and introduce complementarity in Africa's water quality initiatives. In addition, there is scope for linkages with ongoing initiatives and opportunities for identifying how other key

[2] https://www.africawat-sanreports.org/Ui/core-indicators-table

institutions can contribute to different components of the program. Keeping that perspective in mind, this review is based on literature, secondary data and remote interviews with key informants.

The AWaQ has been conceptualized in five phases. The first two phases are designed to assess past and existing water quality monitoring and management initiatives, while the next two analyze innovations in that space. Finally, a framework for AWaQ is developed in Phase 5 (Figure 1).

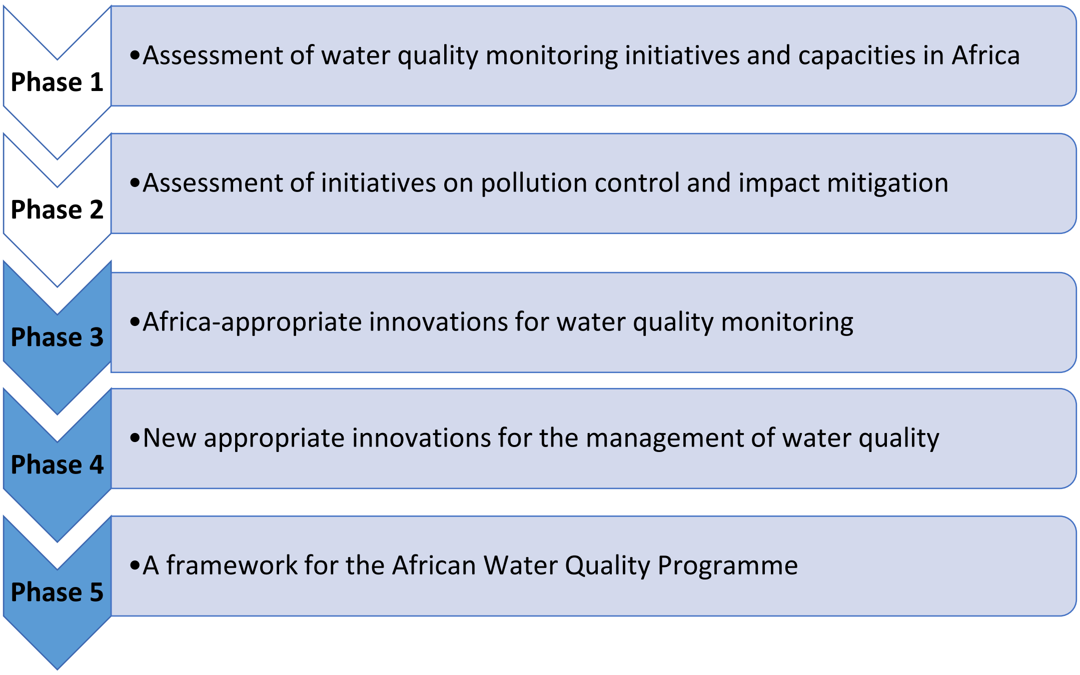


Figure 1. The five phases of the project to develop a framework for the Africa Water Quality Program.

The water quality-related initiatives assessed include programs to monitor pollution loads, water quality degradation of both surface water and groundwater and associated impacts as well as programs put in place to control pollution and mitigate risks in alignment with the Drivers, Pressures, State, Impacts and Response (DPSIR) framework (Figure 2).

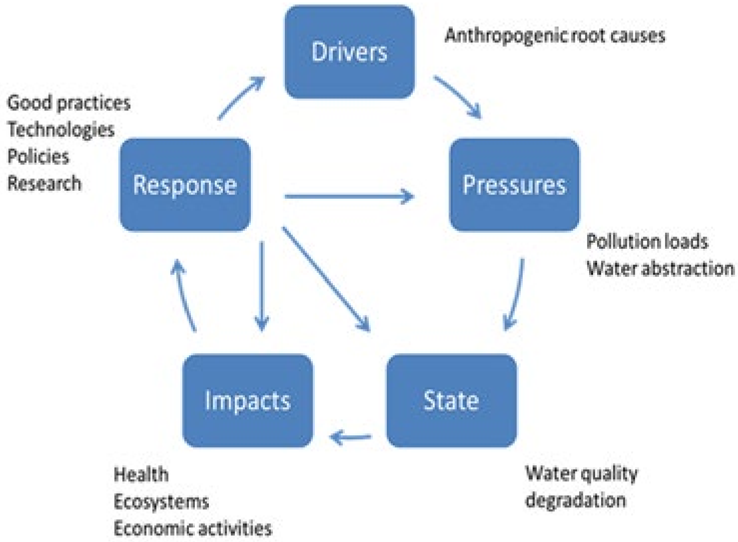


Figure 2. The DPSIR framework and water quality for the development of AwaQ. (*Source:* Mateo-Sagasta et al. 2018)

In this report, we take a closer look at the African context, detailing initiatives undertaken to monitor water quality and pollution and to control and mitigate water pollution, including initiatives on wastewater reuse (Phases 1 and 2 in Figure 1). Our aim is to map the status quo and identify areas of interest for a new Africa Water Quality Program that can advance improved water quality monitoring and pollution control across Africa. A framework for AWaQ will allow for the formulation and rollout of a detailed operational program that will benefit African Union member states under the direction of AMCOW, and bring member states up to a shared state of readiness.

In subsequent sections of the report we present water quality monitoring initiatives taken up at regional and subregional levels across the continent as well as examples from individual countries. The approach we used took four main forms:

- a review of the status of water quality monitoring and analytical capacities across African countries based on a continentwide survey;
- a desktop review of available literature at global, regional, transboundary and national scales with specific focus on water quality monitoring, pollution control and mitigation in Africa.
- an analysis of survey data to identify priority pollutants; and
- a synthesis of country water quality profiles based on the data gathered and the literature reviewed (see Annex).

WATER QUALITY MONITORING AND ASSESSMENT CAPACITY IN AFRICA

As water is critical to human existence by supporting vital socioeconomic and ecological processes, monitoring its quality is essential to ensure the sustained functioning of these processes. Water quality monitoring provides us the data needed to assess conditions and take informed decisions to mitigate impacts (Bartram and Ballance 1996). In more specific applications, information about water quality is essential to guide our efforts to reduce incidence of waterborne illnesses, identify high-risk water sources, determine effective water treatment methods, and contribute to the evaluation of water and sanitation improvement programs (Peletz et al. 2018). According to the International Organization for Standardization, water quality monitoring can be defined as the "programmed process of sampling, measurement and subsequent recording or signalling, or both, of various water characteristics, often with the aim of assessing conformity to specified objectives" (ISO 2021). The success of the envisioned

Africa Water Quality Program would require a solid foundation of water quality monitoring and assessment.

This section summarizes the water quality monitoring and assessment capacities available in African countries, in particular the critical components of water quality monitoring programs such as field sampling, laboratory testing and data interpretation. We draw upon past assessments and inputs from a continentwide survey rolled out as part of this project.

Africawide AMCOW-IWMI Survey

The survey was designed to capture data on key contaminants, the water quality testing and monitoring capacities of African countries and the existing pollution control mechanisms. The following sections summarize the results obtained across 31 countries.

Survey Dissemination

Between July and September 2021, the survey was disseminated through the AMCOW Secretariat to country representatives directly involved in water quality-related activities within national government departments. The same survey was also shared more broadly through network contacts and social media platforms specifically targeted at water quality practitioners. A French version was made available for dissemination in French-speaking African countries. There were 44 questions in the survey (see Section A of Annex) to assess different aspects of water quality monitoring including human and technical capacities, and testing facilities as well as key pollutants, sources and impacts.

Geography and Demographic Insights

Responses were received from different regions of the continent but there was little representation from island states such as the Comoros, Cape Verde, Madagascar and Seychelles. Overall, 31 countries took part in the survey (Table 1; Figure 3).

Table 1. Countries that participated in the AMCOW-IWMI Africawide survey

Region	**P**articipating countries
North Africa	Algeria, Egypt, Tunisia
East Africa	Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Tanzania, Uganda
West Africa	Benin, Cote d'Ivoire, Ghana, Liberia, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Gambia, Togo
Central Africa	Cameroon, Chad, Democratic Republic of Congo
Southern Africa	Botswana, Malawi, Mauritius, Mozambique, South Africa, Zambia, Zimbabwe

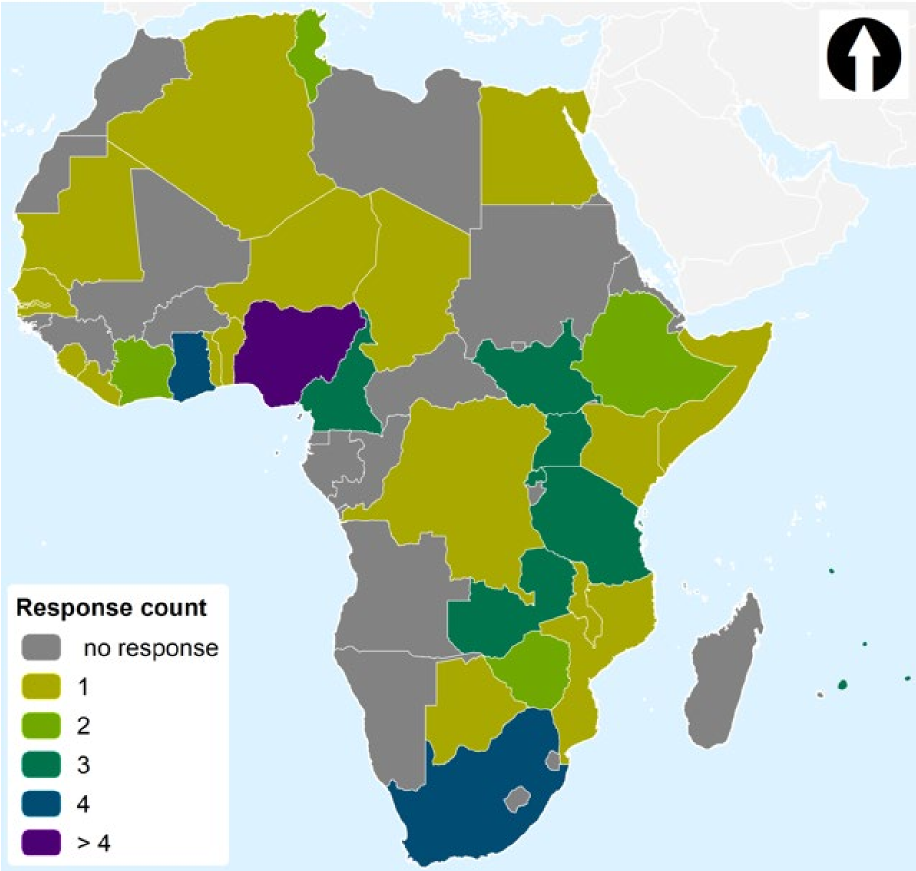


Figure 3. Number of responses received from participating countries.

(*Source:* Authors. *Credit*: S. Warner.)

There was a greater proportion of males (84%) among the respondents than females (16%). About 48% of the respondents were government officials; the rest of them were distributed across private, academic and transboundary institutions. Registering government officials' perceptions in the survey was key in obtaining am informed national perspective on water quality.

Notes on Interpreting Survey Results

Some points to consider when interpreting the survey results:

- While responses came from 31 (56.3%) out of the 55 countries in Africa, the results do provide a good starting point for deducing the current status of water quality monitoring and management on the continent.
- There were multiple unique responses from 13 (42%) out of the 31 countries that responded to the survey while the remainder had only one respondent each. Responses were averaged across respondents from the same country to generate a consolidated country perspective.

Key Insights from the Survey

The survey revealed limitations in respect of laboratory staff capacities, laboratory equipment and reagents, standardization and accreditation of laboratories, and proper mechanisms for data processing and interpretation. In addition, the survey identified proper coordination and cooperation among the relevant agencies, proper data management including establishing data sharing platforms and reporting mechanisms, and adequate funding as the most important needs in order to enhance water quality monitoring capacities. The following section provides some insights from the survey.

Water Quality Monitoring, Training and Capacities

The survey results showed that much of the training received by individuals engaged in water quality monitoring was related to field water sampling, water quality data processing and interpretation, laboratory water analysis and wastewater treatment (Figure 4). The majority of respondents (94%) said they received training as part of a university or college course, while 68% received it as part of a one-off certification program, and 58% of them indicated that they received ongoing regular training. It should be noted that some individuals received more than one type of training.

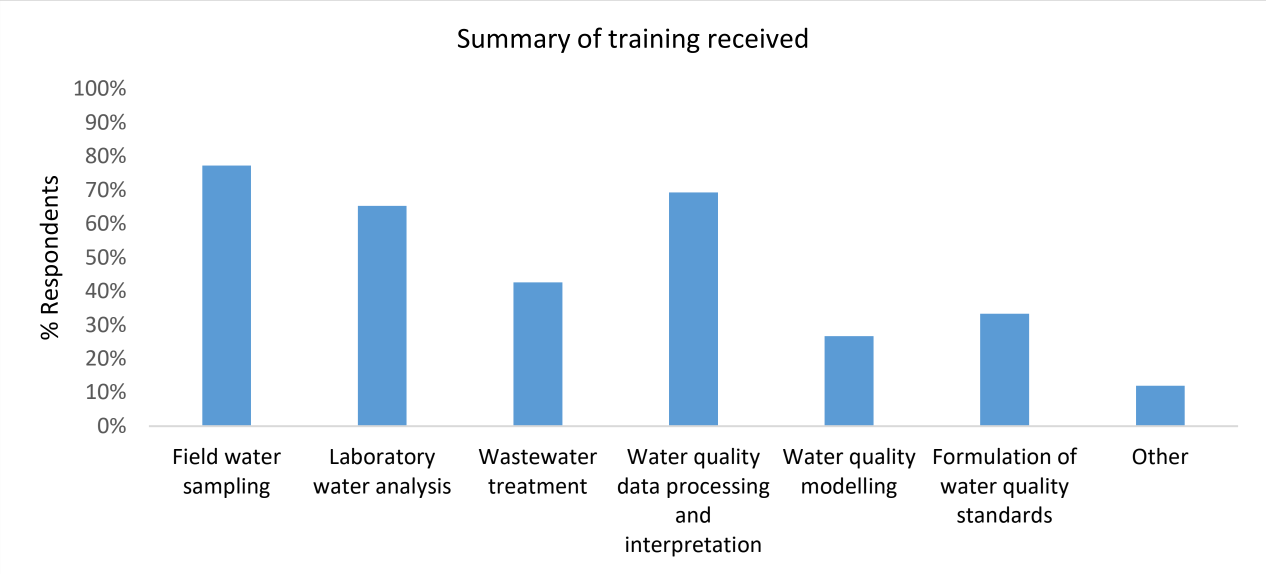


Figure 4. A summary of training received by survey respondents.

The survey also found that 55% of the countries that responded to the survey perceive the technical capacity of their laboratory personnel as adequate (Figure 5)—personnel able to carry out all roles satisfactorily—followed by 29% that described it as average—meaning that technical personnel are able to perform only some of the technical roles. Only 6% of the countries saw their staff as lacking the required capacities to conduct water quality monitoring related activities such as field water sampling and laboratory testing.

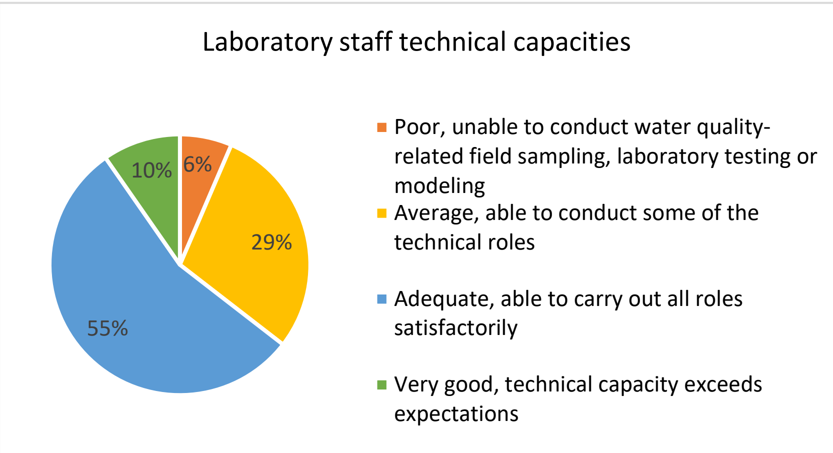


Figure 5. Technical capacities of laboratory staff.

Laboratory Capacities

The survey found that water testing laboratory facilities were available in 90% of the participating countries with 68% of them stating that they were accredited laboratories. In 84% of the countries, some form of national-level registration was required to operate a laboratory. Some 48% said that their laboratories were equipped but not able to carry out all the analyses, while 23% indicated that their labs were underequipped for basic water quality analyses (Figure 6).

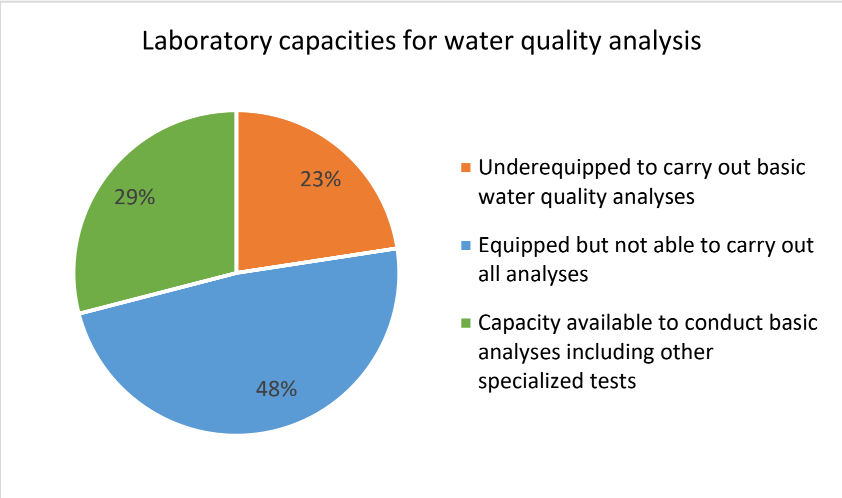


Figure 6. Laboratory capacities for water quality analyses

As for monitoring of water resources, the survey found that in 32% of the participating countries institutions were underequipped for that task while in 45% of them institutions were equipped only for monitoring priority resources. Some 32% of the countries said they lack capacity, for example, in the form of vehicles and equipment to monitor water quality (Figure 7).

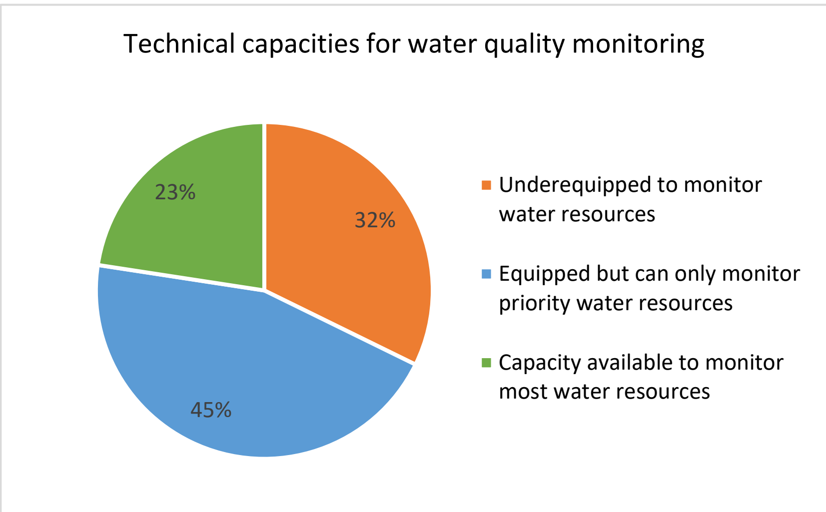


Figure 7. Technical capacities to monitor water quality.

Some 19% of the participating countries reported that they have inadequate capacities to deal with the task of processing and interpreting water quality data in detail while 58% reported that they were able to process and interpret most water quality data. A further 23% reported above-average capacity and ability to interpret water quality data in detail.

GEMS/Water Capacity Development Centre Scoping Exercise

According to the capacity development scoping exercise conducted by GEMS/Water across 29 African countries, only two, South Africa and Rwanda, reported high scores on monitoring program design (UNEP GEMS/Water CDC 2019). Overall, across eight indicators for assessing technical capacities needed for water quality monitoring and assessment[3], only South Africa, Kenya, Rwanda, Tanzania, Uganda and Nigeria scored more than 60%. These results highlight the capacity gaps that exist in Africa across different aspects of water quality monitoring such as water quality analysis, data management, quality control and field techniques.

The GEMS/Water global assessment of freshwater quality monitoring[4] activities showed that although analytical capabilities were generally good, laboratories did not have sufficient financial or human resources to carry out activities such as quality assurance. Key findings from the assessment showed that there was:

- low confidence in monitoring program design;
- low confidence in water quality monitoring knowledge and field skills;
- inadequate quality assurance;
- need for more capacity for data management and data assessment;
- limited knowledge of groundwater; and
- limited knowledge of alternative approaches to monitoring and assessment of water quality.

SUMMARY OF THE STATE OF KNOWLEDGE ON WATER QUALITY DEGRADATION IN AFRICA

Water quality issues are complex. Detailed knowledge of water quality is essential for allocating water to different types of use and to adequately treat and prevent contamination of water sources. However, data scarcity is a major barrier to adequately addressing water quality challenges in Africa. It has been reported that the density of water quality measuring stations in Africa is one hundred times lower than the density elsewhere in the world (UNEP 2018). On the basis of the cost of data from 18 monitoring institutions in Sub-Saharan Africa, a study in 2017 revealed that monitoring the microbial quality of all improved drinking water sources in the region would cost USD 16 million per year, “which is minimal compared to the projected annual capital cost of achieving SDG 6.1 of safe water for all (USD 14.8 billion)” (Delaire et al., 2017:5876). In spite of the relatively low cost, water quality testing levels in Sub-Saharan Africa remain unsatisfactory due to institutional, personnel and economic constraints (Delaire et al. 2017).

[3] The indicators included: Monitoring program design, field techniques, analytical capability, quality assurance and quality control, data management, data assessment, groundwater monitoring and other approaches, e.g., biological (UNEP GEMS/Water CDC 2019).
[4] https://capdevsymp.un-ihe.org/videos/dr-deborah-chapman-global-capacity-development-in-water-quality-monitoring-and-assessment

In the case of transboundary groundwater in Africa, conflicts are often attributed to the lack of information about the boundaries of the physical resource, resource capacity and conditions that impact water quality (AfDB 2020).

Key Pollutants and Sources

Mitigation of water pollution is of urgent importance in Africa, as suggested by the high levels of pollution currently being experienced on the continent. Poor sanitation, improper waste disposal practices, shortage of wastewater treatment facilities, malfunctioning of treatment plants, industrial activities, and urban and agricultural runoff are among the key causes of water pollution (see Box 1). Water quality degradation can occur due to different reasons in the urban areas compared to rural areas. While large quantities of pesticides, fertilizer and animal waste contaminate ground and surface water in farming areas, unsafe domestic wastes are a critical source of water pollution in the cities due to overcrowding, poverty and low sanitation in precarious neighborhoods (Pare and Bonzi-Coulibaly 2013).

In Africa, according to AfDB (2020), domestic, industrial, agricultural and storm water runoff are the main wastewater streams and foremost in the contribution to pollution (Figure 8).

Wastewater and fecal sludge	Agriculture	Industrial wastewater	Stormwater runoff
• Poor performance of wastewater treatment plants (WWTPs) due to increasing population and wastewater loads • Limited financial and technical capacities for operation and maintenance of WWTPs	• Animal waste, pesticide and nutrient-laden runoff from agriculture add to the pollutant load in surface and groundwater • Use of wastewater for irrigation may add to the pollution of receiving waters	• Discharge of untreated wastewater directly into rivers and streams • Toxic contaminants from industry insufficiently treated before discharge	• Poor stormwater management practices • Limited regulatory framework for stormwater management

Figure 8. Main wastewater streams and challenges to water pollution (adapted from AfDB 2020).

Box 1. Water Pollution in Africa- a snapshot

- Up to a quarter (10-25%) of all river stretches in Africa are affected by severe pathogen pollution, one-seventh by severe organic pollution, and one-tenth by severe and moderate saline pollution.
- The largest source of pathogen and organic pollution is non-sewered sanitation.
- The largest anthropogenic source of saline pollution (load of total dissolved solids) is irrigated agriculture.
- Livestock are an important source of anthropogenic phosphorus seen in major lakes.
- Groundwater pollution has the following order of importance: (1) nitrate pollution, (2) pathogenic agents, (3) organic pollution, (4) salinization and (5) acid mine drainage.

Sources: UNEP 2016; WWQA 2021.

Data from the AMCOW-IWMI survey showed that petroleum products contribute the least to water pollution in 54% of the countries while sewage and dumpsites were major contributors in 58% and 50% of the countries, respectively, followed by agriculture (45%) and industry (48%) (Figure 9).

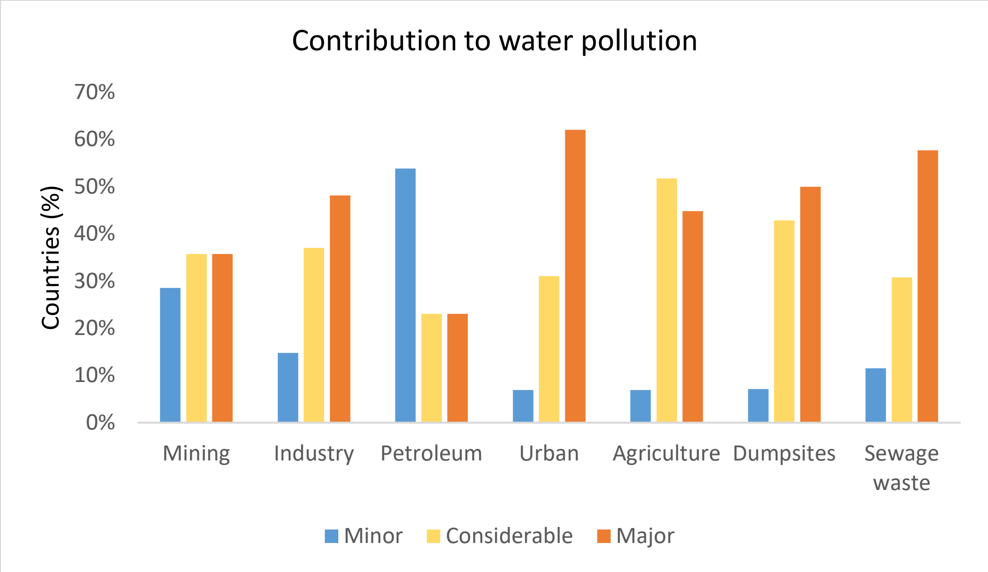


Figure 9. Contribution of various sectors to water pollution in Africa.

Domestic Waste

Data from the most recent WHO/UNICEF Joint Monitoring Programme show that only 33% of the people in Sub-Saharan Africa—the lowest proportion compared to the other regions of the world—have at least basic sanitation facilities. Further, Sub-Saharan Africa has roughly one billion people lacking safely managed sanitation (WHO and UNICEF 2021b). Urban discharge of untreated or poorly treated effluents into water sources has been a major cause of surface water pollution in Africa (Fayiga et al. 2018). It has been estimated that 90% of untreated wastewater in Africa is released directly into rivers, lakes and oceans (WWAP 2017).

Most people in Africa rely on on-site sanitation facilities, which are, if not well-managed, potential sources of pathogens, organic matter and nutrients. It has been reported that only a small fraction of the collected sludge from on-site sanitation systems is treated and a greater percentage of it is indiscriminately disposed, inviting the risk of water pollution and posing a threat to public health.

Solid waste management is a massive challenge in Africa due to the lack of infrastructure for collection, transportation, treatment and disposal of solid waste, proper solid waste management planning, sufficient financial resources, technical expertise and public awareness. Poorly managed solid waste and its decomposing byproducts find their way into wastewater and freshwater flows through runoff and other means (AfDB 2020).

Industrial Wastewater

In addition to domestic wastewater, industrial activity contributes significant amounts of chemical pollutants to Africa's water flows. The typical polluting industries include mining, pulp mills, tanneries, textiles, food and beverage factories, sugar refineries, oil and pharmaceutical production facilities (AfDB 2020). Industries contributing to water quality degradation vary from country to country. For example, in southwestern Ethiopia industrial wastewater discharge from coffee refineries greatly contributes to the deterioration of river water quality (AfDB 2020) while in the Niger Delta oil pollution from the petroleum industry is particularly prolific, with pollution visible in surface water and wetlands (Pare and Bonzi-Coulibaly 2013; Babatunde 2020).

Mining

Mining is one of the most important economic activities in African countries, particularly in Western and Southern Africa (Pare and Bonzi-Coulibaly 2013; Verlicchi and Grillini 2020). Mine water has a negative impact on water resources by increasing the levels of suspended solids, which leads to mobilization of elements such as iron, aluminum, cadmium, cobalt, manganese and zinc, and also a decrease in the pH of the receiving waters (Ochieng et al. 2010). In South Africa particularly, mining has been a major cause of water pollution for decades. For example, the Olifants and Vaal river systems have been severely affected by gold and coal mining. McCarthy (2011) concludes that new mines should probably not be permitted in the catchment areas of the Vaal and other rivers draining the eastern escarpment until economically viable methods are available to prevent pollution or to clean up the pollution that will inevitably be produced.

Agricultural Pollution

Agriculture is the main economic sector in Africa. However, when pesticide and fertilizer use exceeds the assimilation capacity of the agricultural system, it results in runoff with high pollution loads, which ultimately reaches water bodies by way of percolation to groundwater and surface and subsurface flows into streams, rivers and lakes. In addition, livestock production and aquaculture release nutrients too. Agricultural wastewater (from both crop cultivation and livestock production) can contain nutrients, pesticides, salts, sediments, organic matter, pathogens, metals and emerging pollutants (drug residues, hormones, feed additives) that pose a severe threat to water quality in rivers, lakes and aquifers (see Box 2). A case study conducted in three intensive agricultural areas in the Western Cape province of South Africa—Hex River Valley, Grabouw and Piketberg—revealed widespread pesticide contamination, mostly endosulfan, of groundwater, surface water and drinking water sources (AfDB 2020). Studies in Burkina Faso also indicated pesticide contamination of water especially in the cotton-growing areas (Pare and Bonzi-Coulibaly 2013).

Box 2. Emerging pollutants

Emerging pollutants produced by pharmaceutical, personal care and household products and industrial and agricultural chemicals as well as microplastics are known to present a significant challenge to water quality. Verlicchi and Grillini (2020) reported high concentrations of micropollutants such as pharmaceuticals in surface water in rural and periurban areas of South Africa and Mozambique. Concentrations of pharmaceuticals such as ibuprofen, acetylsalicylic acid, clozapine and estriol were found to be very high, some of which could be attributed to over-the-counter drugs obtainable without prescription.

An important point to note is that conventional wastewater treatment plants are often not equipped to treat these emerging pollutants; hence the treated effluent can still contain these pollutants. Haddaoui and Mateo-Sagasta (2021) reported that altogether 290 emerging pollutants were detected in different water matrices across the Middle East and North African (MENA) countries, stemming mainly from industrial effluents, agricultural practices and discharge or reuse of treated wastewater with pharmaceuticals, organic compounds and pesticides being the pollutant groups of great concern.

Groundwater Pollution

The aggregate volume of groundwater in Africa is estimated to be 20 times higher than the freshwater stored in rivers and lakes (MacDonald et al. 2012) and about 15% of the continent's total renewable water resources. Close to 75% of Africa's population relies on groundwater as the major drinking water source (UNEP 2010). However, the water in many shallow groundwater sources is contaminated due to untreated seepage from septic tanks and pit latrines, toxic chemicals from underground storage tanks, leachate from solid waste landfills and acid mine drainage, among others.

A groundwater pollution risk map developed by Ouedraogo et al. (2016) indicated that the northern, central and western parts of the Africa are at high risk to pollution due to shallow groundwater systems and activities such as agriculture. Groundwater contamination by nitrates has been reported by recent studies across the African continent except a large part of the the Sahara desert. It has been estimated that 80 million people are affected by fluoride contamination in the East African rift region with more than 13 million people in Ethiopia living in areas with high fluoride risk (WWQA 2021).

In South Africa in particular, it has been reported that groundwater in the mining district of Johannesburg is heavily contaminated by heavy metals (Ochieng et al. 2010). A study that investigated groundwater quality in 42 boreholes in rural and peri-urban South Africa found biological pollution with fecal contamination and high nitrate concentration in a majority of the samples, suggesting that on-site sanitation systems are grossly polluting aquifers (Masindi and Foteinis 2021). Lapworth et al. (2017) discuss cases of groundwater pollution in a number of African countries associated with sanitation (e.g., pit latrines) and nonsanitation sources (e.g., landfills, industrial sources).

Main Impacts of Water Quality Degradation in Africa

Poor water quality has implications for the health of both humans and the environment at large in terms of socioeconomic conditions, ecosystem services and environmental impacts. Impaired access to clean water, impacts on food security and livelihoods, loss of biodiversity, increased water treatment costs and health effects associated with water-related infections are among the major impacts caused by water quality degradation. Table 2 presents a few selected examples from across Africa highlighting the impacts on health, ecosystems and economy associated with water quality degradation.

In addition to causing a variety of tropical diseases such as typhoid, cholera, dysentery and diarrhea, contamination of water sources leads to water scarcity which affectspeople in other ways. People, in particular, women and girls, have to travel long distances to collect water for their household. This has implications for the education of girls. A study covering 24 countries in Sub-Saharan Africa estimated that 3.36 million children and 13.54 million women were responsible for household water collection requiring collection times greater than 30 minutes (Graham et al. 2016).

Water quality degradation also leads to an increase in the cost of restoring water resources. Human-induced eutrophication is a scenario related to water quality degradation that is commonly observed across Africa. Eutrophication, which is the process of nutrient enrichment and associated excessive plant growth in water bodies, increases the cost of treatment of drinking water and puts pressure on the drinking water supply budgets of African countries (AfDB 2020).

Table 2. Impacts of water pollution on health, ecosystems and the economy in Africa

Impacts	Selected water pollution examples from Africa	Reference
Health	Between 100,000 and 200,000 cholera cases are officially reported each year in Africa. A total of 123,986 cases with 3,763 deaths were reported in 2002.	WWAP 2006
Health	In Sub-Saharan Africa, exposure to nitrate pollution emanating from upstream urban agglomerations lowers height-for-age scores and increases the likelihood of stunting in children younger than five years. More than 35% of children younger than five years are considered stunted in that region.	WBG 2019
	In some areas of Morocco, prevalence of the blue baby syndrome is higher among infants and children who drink well water with a nitrate concentration >50mg/L.	AfDB 2020
	As pollution in the Akaki River worsened, using untreated wastewater for irrigation purposes increased prevalence of intestinal illnesses among farmers in Addis Ababa.	WWAP 2017; AfDB 2020
	Emerging pollutants can potentially cause endocrine disruption in humans and aquatic wildlife, affecting fertility and population survival. Also, they have the potential to cause cancerous tumors and development of bacterial pathogen resistance, including multi-drug resistance.	AfDB 2020
Ecosystems, biodiversity	Possible extinction of endemic species (e.g., Cichlid fish in Lake Victoria) due to severe eutrophication and dramatically low dissolved oxygen levels as a result of pollution due to increased human activities such as discharge of wastes.	AfDB 2020
	Around Lake Naivasha in Kenya, biodiversity has been shrinking in recent years, possibly due to the deterioration of water quality caused by fertilizer and pesticide use by commercial rose plantations.	Wang et al. 2014
Economic impacts	Due to the release of raw sewage into the Weija Reservoir, the Ghana Water Company which operates the Weija drinking water treatment plant spends close to GHS 40,000 per day (USD 2,000 at the 2011 exchange rate) to treat water drawn from the dam before it is supplied to consumers.	AfDB 2020

The Africa-wide AMCOW-IWMI survey showed that polluted water resources contribute to overall biodiversity loss in 87% of the countries in Africa followed by eutrophication in 77% and disease (health impacts) in 74% of the countries (Figure 10).

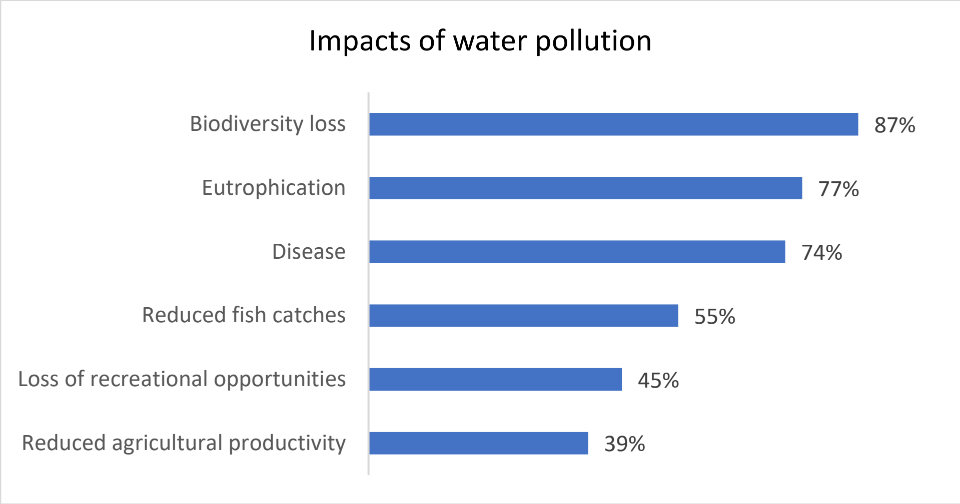


Figure 10. Main impacts of water pollution in African countries.

Continental Policy Framework for Water Quality Monitoring

After the numerous efforts and interventions introduced to address water and sanitation challenges in Africa, evidence suggests that continual improvement in policy actions and adequate implementation are still required to overcome the challenges. In that respect, however, there have been recent advances in water policies, strategies and institutional arrangements. These include greater awareness of and political commitment to integrated water resources management (IWRM), increasing commitment to water policy reform and a strong trend toward decentralization of water institutions (UN-Water/Africa n.d.).

African Union

Under the African Union, the African continental policy framework comprises a number of advanced declarations and resolutions to develop and use water resources for socioeconomic advancement, regional integration and environmental sustainability (WWAP 2016). The Africa Union's Agenda 2063 spells out the aspirations of the continent: among them are prosperity and sustainable development through managing Africa's natural resource base including water (Table 3). Agenda 2063 is implemented through a series of ten-year implementation plans—the current plan covers the period 2013-2023 (AU 2015). It identifies five priority areas that are directly or indirectly linked to water quality: sustainable management of natural resources, ecosystem and biodiversity conservation, water security, sustainable consumption and production patterns, and climate resilience (AU 2015). In addition, the African Union Africa Water Vision 2025 highlights the growing challenges of pollution across the continent and their impact on human health and ecosystem services (UNECA 2003). This vision, articulated as "an Africa where there is an equitable and sustainable use and management of water resources for poverty alleviation, socio-economic development, regional cooperation, and the environment" (UNECA 2003:2), demonstrates the continent's focus on continued socioeconomic development in a manner that can be environmentally sustained. One of the indicators in the Africa Water Vision 2025 is the reform of water resource institutions to create an enabling environment for IWRM.

Table 3. African Union water-related provisions.

Continental policy and institutional response	Scope

Agenda 2063	Provides a collective vision and lays out a road map for development with a specific mention of access to safe water supply and sanitation.
Africa Water Vision 2025	Provides specific policy guidance to countries on developing and implementing programs aimed at strengthening governance of water resources; improving wise use of water; meeting urgent water needs; and strengthening the financial base for the desired water future.
African Ministers' Council on Water (AMCOW)	Provides the sectoral leadership needed to tackle the water challenges in Africa, having included sanitation as one of the strategic pillars in the AMCOW Strategy 2018-2030.
N'gor Declaration on Sanitation and Hygiene	Aims to accelerate the achievement of water and sanitation goals in Africa with commitments framed around issues such as inequalities in access and use; support to the sector at the highest political level; financing and human resource needs; waste management; and government-led monitoring and evaluation of national initiatives.

Source: AfDB 2020

While regional, national, legal and institutional frameworks are needed to introduce instruments for economic governance (such as fees and taxes for water), capacity for compliance enforcement needs to be strengthened too. Other interventions such as promoting participatory approaches to include non-state actors, developing information and knowledge on water and promoting research and capacity development of stakeholders to effectively integrate water quality dimensions would augment the current regulatory frameworks (IUCN n.d.).

National-level Policies

In addition to the continent-level vision outlined above, there are country-specific policies and regulations related to water resource management within which water quality monitoring is a part. Commitments to achieve SDGs have been a key driving force in shaping these policies to include the elements of water quality monitoring. While most countries have water quality management policy frameworks, some of them such as South Africa have a relatively more comprehensive framework. Similarly, African countries do have standards for effluent discharge into surface waters, but data on the extent to which these standards are being enforced are not available (Fayiga et al. 2018). Efforts on the SDG indicator related to tracking IWRM (Indicator 6.5.1) show that there are challenges being faced in terms of cross-sectoral coordination, outdated legal frameworks and unclear institutional mandates as well as challenges related to data and information collection and management (UNEP 2021a).

WATER QUALITY MONITORING INITIATIVES IN AFRICA

Taking stock of past and current efforts aimed at water quality monitoring and pollution control is important because such knowledge can help situate envisaged interventions at the most appropriate level of implementation and target the most critical areas and gaps.

Several initiatives have addressed water pollution challenges in Africa at the global, regional transboundary and national levels, covering different aspects of water quality monitoring processes such as field sampling, laboratory analysis, data handling and processing as well as supporting activities such as capacity building and knowledge sharing among peer networks. For the purposes of this assessment, we identify some examples of such initiatives at the global, regional and subregional levels. Initiatives targeted at drinking water supplies are also included in this assessment. An analysis of these initiatives leads us to four categories based on their implementation focus:

- Sampling, analysis and data management
- Coordination and reporting of water quality related data
- Capacity building
- Scientific network, research and knowledge sharing

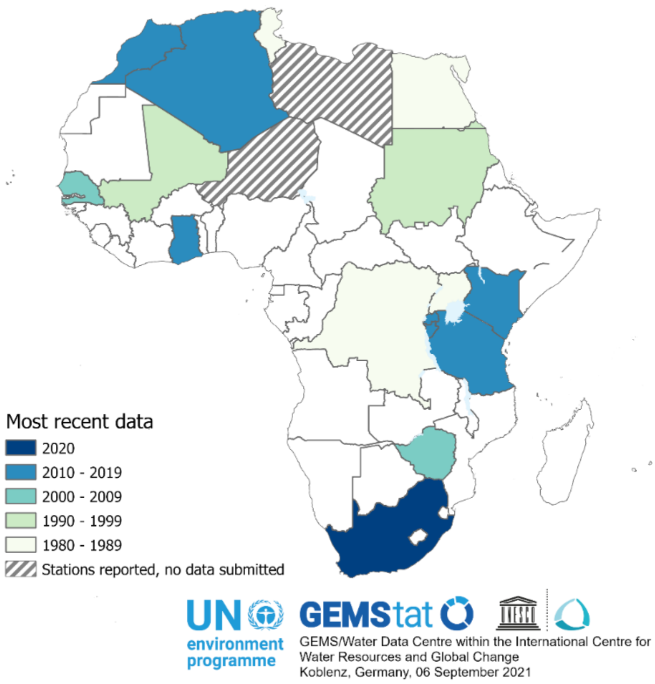
Global Initiatives

SDG Indicator 6.3.2

The United Nations Environment Programme (UNEP) is the custodian of this global indicator which tracks the proportion of water bodies with good ambient water quality. The first reporting cycle was in 2017, and since then many more African countries have reported on progress. There has been good progress in countries such as Sierra Leone where, for example, capacity needs where identified in 2017 and since then a government department official has received training, designed a monitoring program, secured suitable field equipment, implemented the program and collected data (UNEP 2021b).

Global Environment Monitoring System for Freshwater (GEMS/Water)

The GEMS/Water initiative under UNEP is a long-standing initiative that seeks to bring together global data on surface and groundwater quality. Member countries contribute data to the GEMStat Information System which has the aim of assessing the state and trend of global water quality. While the scope of the initiative is global, a number of countries in Africa are currently not contributing data to the database. GEMS/Water also supports the SDG indicator 6.3.2 with data management, quality assurance, indicator calculation and capacity development (UNEP 2021b). GEMStat contains water quality data for close to 500 parameters including the SDG 6.3.2 core parameters: dissolved oxygen, nitrogen, phosphorus and pH. However, water quality data availability from African countries is non-existent, patchy or dated as observed on the online global water quality database GEMStat[5] (see also Figure 11).



[5] https://statistics.gemstat.org/

Figure 11. Data availability across African countries as submitted to the GEMS/Water database (*Source:* GEMS/Water and UNEP 2020).

In addition to data collation, the GEMS/Water initiative carries out capacity development activities related to water quality monitoring. The GEMS/Water Capacity Development Centre, based at the Environmental Research Institute of the University College Cork in Ireland was instituted in response to the lack of technical capacities in water quality monitoring. Activities carried out under this program since its inception in 2015 include raising awareness on water quality, conducting training workshops on water quality monitoring and assessment, and supporting efforts toward SDG indicator 6.3.2 for ambient water quality. Training is offered in the form of short online continuous professional development courses and the longer-term postgraduate diploma and master's programs. The courses, delivered online, cover the practicalities of water quality monitoring and assessment, data handling and quality assurance. In addition to the short courses and graduate diplomas, workshops are held in different African countries. In 2018, a workshop was held in Dakar and attended by 13 African countries. As of the writing of this report, there are seven students enrolled for the master's program.

World Water Quality Alliance

The WWQA was established by UNEP and the Joint Research Centre of the European Commission in 2019 to provide water quality assessments and solutions to water quality challenges (UNEP 2019). Bringing together expertise from a wide range of sectors, it has formed a global consortium dedicated to responding to water quality challenges and offering demand-driven solutions. The alliance aims to raise awareness on water quality issues by reviewing the state of freshwater quality and potential impacts on human and ecosystem health and food security (UNEP 2019). In Africa, WWQA supports initiatives to improve water quality monitoring through citizen science and the AWaQ Program.

Water Safety Plans

Water safety plans (WSPs) typically include a systems assessment of the operational monitoring and management of water supply systems. Water safety planning has been promoted to support drinking water supply safety and implemented in several countries across Africa including South Africa, Congo, Egypt, Togo and Uganda (WHO 2017). However, only nine of these countries (Egypt, Ethiopia, Ghana, Morocco, Nigeria, South Africa, Togo, Tunisia and Uganda) have formally approved WSPs included in their national regulatory systems while others are yet to take this step (WHO 2017). Following the COVID-19 pandemic, the importance of water supply services has been receiving increasing attention and priority. When ambient water quality is adequately monitored, the treatment costs of domestic water supply decrease.

WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene

Established in 1990, the WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene is a global initiative that monitors the status of drinking water sanitation worldwide. The program also informs SDG indicators on drinking water and sanitation WHO and UNICEF, 2021b). In 2017, it produced the first global assessment of drinking water and sanitation services. Data on Water Supply, Sanitation and Hygiene (WASH) are managed through a global database (washdata.org). Good ambient water quality is of critical importance where people are directly dependent on surface water sources, as in some parts of Sub-Saharan Africa (WHO and UNICEF 2017).

UNESCO IHP International Initiative on Water Quality (IIWQ)

The IIWQ is a scientific collaborative initiative which addresses water quality issues through joint research activities and knowledge sharing. It focuses on three main thematic areas: safe drinking water and sanitation, water quality management, and wastewater management and reuse. Within these broad themes, IIWQ addresses knowledge and capacity gaps and encourages scientific cooperation and exchange. The IIWQ expert advisory group comprises water quality specialists drawn from different governmental and nongovernmental entities who provide expert advice on water quality challenges (UNESCO 2015).

Regional Initiatives

Continental initiatives

At the continental level, the African Union[6] is the overarching institution that seeks mainly to promote unity and coordinate cooperation across its 55 member states. Through its various implementing arms, the organization provides strategic guidance on Africa's development issues including environmental impact. Within the African Union, the African Ministers' Council on Water (AMCOW)[7] holds the position of a Specialised Committee for Water and Sanitation that oversees water and sanitation-related issues. The activities of AU and AMCOW regarding water quality monitoring are central to our study.

Water and Sanitation Sector Monitoring and Reporting System

WASSMO is an online reporting platform that captures water and sanitation data across African countries. AMCOW has been tasked with reporting the state of water resources on the continent. Countries are trained on the use of the platform to strengthen the quality of reporting. A total of 43 indicators are reported in seven key areas:

1. Water infrastructure for growth
2. Managing and protecting water resources
3. Water supply, sanitation, hygiene and wastewater
4. Climate change and disaster risk reduction
5. Governance and institutions
6. Financing
7. Information management and capacity development

In 2021, Sanitation Policy guidelines were launched to guide the process of improving sanitation provision on the continent (AMCOW 2021). Given the contribution of sanitation provision to the status of water quality, coordinated efforts with water quality monitoring programs such as the envisaged AWaQ may yield positive results.

AMCOW Pan-African Groundwater Program

APAGroP was established to strengthen the exchange of knowledge on groundwater management in Africa. The core vision of this program is to improve groundwater policy and practice so as to ensure sustainable and equitable use of groundwater to support lives and livelihoods. As part of this program, development of country support tools will enable individual countries to develop plans that will ensure sustainable use of groundwater. For example, Namibia is piloting the process of developing such a country support tool (Tijani 2020).

In addition, within the framework of short- and medium-term action plans, AMCOW is collaborating with partners in this flagship groundwater program in six thematic focus areas:

1. Policy, governance and institutional systems strengthening

[6] https://au.int/en/overview

[7] https://amcow-online.org/

2. Groundwater country support management tools and measures
3. Capacity strengthening and drilling professionalism
4. Groundwater knowledge and information sharing platform/hub
5. Groundwater resources assessment and mapping
6. Unlocking private and public investments in the groundwater sector

Transboundary Basin Initiatives

According to the Transboundary Waters Assessment Programme (TWAP) database, about 20% of the world's 286 known transboundary basins are in Africa, and close to 70% of the continent's total area falls within a shared basin. A large proportion of Africa's water resources are, therefore, highly interconnected and interdependent. This makes transboundary initiatives especially relevant for water pollution mitigation efforts, particularly in the context of externalization of pollution. Some examples of basins with ongoing transboundary initiatives include the Orange-Senqu and Okavango in southern Africa and the Senegal and Volta in West Africa (Table 4). In some basins, the focus of such initiatives has been on strengthening shared monitoring systems by setting up monitoring stations and developing information systems. Some success has been reported in developing targeted monitoring systems in the Nile Basin's Regional Hydro-Meteorological Network (Box 3).

Table 4. Examples of transboundary initiatives on water quality monitoring and management.

Transboundary basin	Initiative	Outputs	References
Orange-Senqu Basin	A Framework for Monitoring Water Resource Quality in the Orange-Senqu River Basin	Water resource quality monitoring framework	ORASECOM (2009)
Okavango Basin	Water Quality Monitoring in the Okavango Delta and Chobe River System	Automated monitoring network for water quality and quantity	OKACOM (2021)
	Environmental Monitoring Framework	Aquatic ecological monitoring, water quality, hydrological flows, sediment transport and groundwater	
	Support to the Cubango-Okavango River Basin Strategic Action Programme Implementation (2017-2022)	Joint basinwide surveys which established the baseline status of select physiochemical and chemical parameters including pH, turbidity, electrical conductivity, dissolved oxygen, temperature, nitrates and phosphates	
	Strategic Action Programme for the Sustainable Development and Management of the Cubango-Okavango Basin (2011)	Established the development of surface and groundwater water quality monitoring systems	
Senegal River Basin	Support to operationalise the Senegal River quality network by setting up a	Improve knowledge and monitoring of water quality in the Senegal River basin following on from the study	INBO/RIOB (2022)

Transboundary basin	Initiative	Outputs	References
	durable, interoperable information system	"Operationalisation of the Senegal River Quality network / Current situation and potential scenarios " (CNR & Hydreco Guyane) carried out in 2019:	
Nile Basin Initiative	Nile Basin Initiative Water Quality Monitoring Programme	Nile Basin Regional Hydro-Meteorological Network	NBI (2019)
Zambezi River Authority	Environmental Monitoring Programme (ongoing)	Monthly, quarterly and bi-annual sampling of the Zambezi River and its tributaries	ZRA (n.d.)
Lake Victoria Basin	Promotion of Resource Efficient and Cleaner Production (RECP) in small-scale mining plants in the Lake Victoria Basin 2017-2019	Catalyzing private sector investment in cleaner and more efficient industrial production and supply chains throughout the Lake Victoria basin	UNIDO (2019)
Lake Victoria Basin	Environmental Management Project -Phase 1 (1997-2005) -Phase II (2009-2017)	Watershed management and land rehabilitation - -Monitoring and control of water hyacinth, rehabilitation, sanitation and wastewater treatment facilities, and working with private companies to reduce industrial pollution -Reducing environmental stress in targeted pollution hotspots and selected degraded subcatchments to improve the livelihoods of communities depending on the natural resources of the basin	United Republic of Tanzania (n.d.)
Lake Tanganyika	Lake Tanganyika Water Management (LATAWANA) Project. Funded by the European Union and Implemented by Enabel (2019-2023)	A key outcome of the project is the establishment of the Lake Tanganyika Water Monitoring Network. The monitoring network will involve laboratories from neighbouring countries. The project will finance their compliance, the purchase of sampling and analytical equipment and reagents in	LATAWAMA (2022)

Transboundary basin	Initiative	Outputs	References
		order to monitor the various sampling sites. The quality tracking data will feed into a database and a WebGis (Lake Tanganyika Water Portal) accessible to different audiences.	

Box 3. Nile Basin Regional Hydro-Meteorological Network

The Nile Basin Initiative consists of 10 African countries—Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda—all sharing the Nile River. The entire basin has 949 meteorological and 427 hydrological stations which measure rainfall and temperature although water quality monitoring is still in its infancy. About 80 hydrological and 323 meteorological monitoring stations make up the Nile Basin Regional HydroMet System which is linked to upgraded water quality laboratories within the participating countrie. This system ensures the availability of reliable data and improves water resources planning and management in the basin.

Source: NBI (2019).

STATE OF POLLUTION CONTROL AND IMPACT MITIGATION IN AFRICA

Wastewater Treatment

Countries in Africa generate, mainly within their cities, large amounts of solid and liquid waste, which is mostly discharged untreated into water bodies (AfDB 2020). This makes the water bodies heavily polluted, posing a threat to human health, ecosystems and economic activities. The sanitation challenges highlighted in the earlier sections of this report are prolific sources of pollution. Against this backdrop, the need to attain SDG target 6.3—"by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and at least doubling recycling and safe reuse globally"—is most urgent. However, wastewater treatment efficiency falls far short of the desired level in most African cities (Omosa et al. 2012). Untreated wastewater, identified as one of the key contributors to water pollution across Africa's urban areas, is not sufficiently treated for discharge (Nikiema et al. 2013; AfDB 2020).

The most commonly used wastewater treatment technologies in Africa, are waste stabilization ponds and, in some cases, activated sludge and trickling filter technologies (Omosa et al. 2012; Wang et al. 2014). However, treatment plants are overloaded and subject to other challenges such as power cuts and poor operations and maintenance, leading to the production of poor quality effluent with high nutrient and heavy metal loads (Nikiema et al. 2013; Wang et al. 2014). The FAO AQUASTAT database provides data on produced and treated wastewater, among other variables. However, data on collected wastewater are scanty for most African countries (Table 5). As per FAO AQUASTAT data, Tunisia has the highest treatment rate (79%) based on collected wastewater compared to produced wastewater. Collected wastewater refers to wastewater collected from the total produced wastewater.

Table 5. Percentage of treated wastewater in African countries[8] (2017 data).

Country	Produced municipal wastewater (10^9 m^3 /year)	Collected wastewater (10^9 m^3 /year)	Treated municipal wastewater (10^9 m^3 /year)	Treated wastewater (%) based on produced volumes	Treated wastewater (%) based on collected volume
Algeria	1.5	0.705	0.4	27	57
Botswana	0.011	-	0.008	73	-
Burkina Faso	0.0487	0.0024	0.0014	3	58
Egypt	7.078	6.497	4.282	60	66
Eswatini	0.0132	-	0.009	68	
Ghana	0.28	0.028	0.022	8	79
Kenya	0.0805	-	0.0424	53	-
Mauritania	0.0214	-	0.0007	3	-
Morocco	0.7	-	0.166	24	-
Namibia	0.0195	-	0.006	31	-
Senegal	0.0696		0.0112	16	-
South Africa	3.542	2.769	1.919	54	69
Tunisia	0.287	0.241	0.226	79	94
Zimbabwe	0.194		0.095	49	-

Source: FAO AQUASTAT (2021).

Regulatory Tools for Water Pollution Control

Regulations to control pollution of water resources have been instituted in African countries with varying degrees of success. They have the underlying goals of protecting public and ecological health as well as safeguarding the economy. Water quality regulations can also have a strong human rights mandate by seeking to ensure that citizens are kept safe from harmful pollutants. For example, in South Africa, water quality regulations are rooted in the country's Constitution and Bill of Rights. Typical regulatory instruments include wastewater discharge licenses or permits, water pollution guidelines and standards for drinking water, fisheries, wastewater, on-site sanitation, environmental impact assessment and adoption of best practices such as sustainable agricultural practices (Mateo-Sagasta et al. 2018).

It is important to note that water quality monitoring and pollution control activities are managed across several sectors including health, water supply and sanitation services, environment, agriculture and industry with regulatory frameworks applicable to each). Regulatory instruments are therefore often developed based on the type of water use: for example, the setting of standards for (i) effluent discharge, (ii) ecological functions, (iii) drinking water, and (iv) wastewater reuse, among others. Licenses or permits are also common instruments used to regulate water quality. Several African countries have adopted the Polluter Pays Principle to manage pollution by passing the cost of pollution to the polluter through fines and taxes, for example, in Botswana, Kenya, Nigeria, South Africa, Zimbabwe (GoB 2016; GoZ 2012; Ojo 2021). According to Mateo-Sagasta et al. (2018), the principle is less effective in managing diffuse pollution such as that from agricultural runoff. The

[8] Data for other African countries were not available

successes and failures of this principle are largely associated with the capacity to enforce measures punitive enough such that the cost of pollution deters polluters (Olaniyan 2015).

Enforcement of water quality regulations and ensuring compliance is a complex process. It is marked by shortcomings and inefficiencies which impact the effectiveness of the regulations as a water pollution control tool. Coupled with limited resources, the enforcement-compliance relationship presents complex dynamics even in well-resourced environments. A study by Peletz et al. (2018) highlighted that in countries with a weak regulatory environment, the success of monitoring programs is dependent on staff motivation and incentives for meeting monitoring targets.

Andarge and Lichtenberg (2020) showed that the lower the likelihood of enforcement, the lesser the compliance. In addition, the cost of enforcing pollution regulations in poor environments can be a challenge too, as observed by Weststrate et al. (2019) who found that compliance with on-site sanitation regulations for pit latrine design and fecal sludge management in poor communities was very low in the absence of enforcement. Their study further highlighted the weak regulatory framework available to safely manage fecal sludge in African countries. Recent efforts by AMCOW through the African Sanitation Policy Guidelines are important in strengthening the sanitation regulatory framework with direct implications for water quality when implemented (AMCOW 2021).

At the transboundary level, national and transnational water quality management frameworks converge to manage the water quality of shared resources. Harmonization of policies is therefore critical in ensuring coordinated efforts toward managing water quality. Transboundary agreements such as the Revised Protocol on Shared Watercourses in the Southern African Development Community promotes regional policy coherence.

Water Pollution Control Strategies – Survey Insights

According to the AMCOW-IWMI survey results, pollution control solutions that show interesting potential for impact include:

Regulatory solutions

- Polluter Pays Principles, regulating industrial effluent
- Environmental impact assessments
- Fines, e.g., criminalizing alluvial mining

Management approaches

- Catchment management
- Buffer zone protection and restoration
- Water quality monitoring programs

Civic and private sector movements

- Pressure groups, national clean-up campaigns

Technologies and innovation

- Arsenic removal
- Wastewater treatment
- Implementation of fecal sludge treatment plants countrywide
- Use of resource efficiency and cleaner production approaches

Pollution control regulations were the most popularly employed strategy in 74% of the countries surveyed (Figure 12), followed by nature-based solutions (65%). Least applied were wastewater reuse technologies (29%).

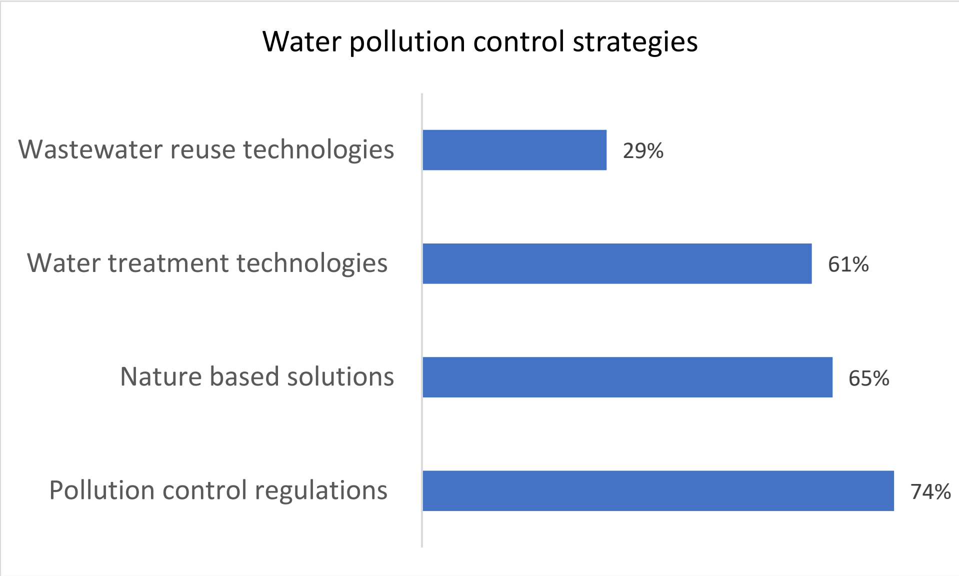


Figure 12. Use of water pollution strategies across African countries.

Results from the survey showed mixed sentiments on the effectiveness of different treatment technologies, nonetheless showing the limitations of such technologies in successfully mitigating pollution. Wastewater treatment, adoption of good agricultural practices and pollution control regulations were perceived to have the least impact compared to other available options for water pollution control (Figure 13).

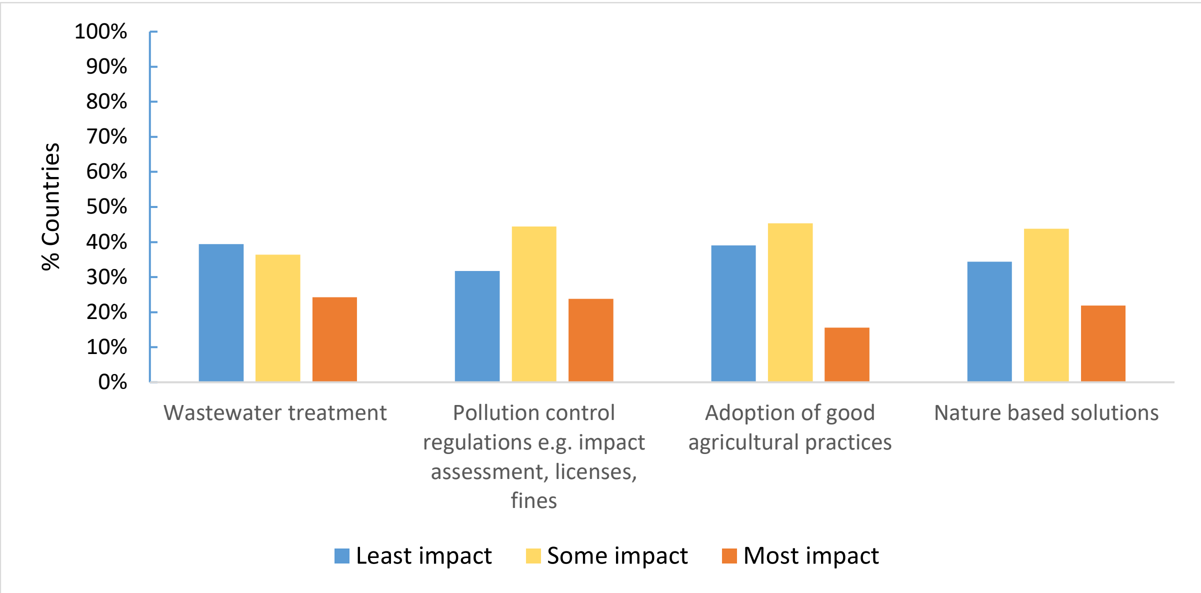


Figure 13. Effectiveness of pollution control strategies.

Regarding government prioritization of water quality, 29% of the countries indicated that their government gave water quality issues low priority while 45% and 16% of the countries indicated moderate and high priority, respectively. Government prioritization is critical in ensuring water quality receives the attention and support required to mitigate adverse impacts.

Investments in Pollution Control and Mitigation Initiatives

Investments by several donors and organizations including the African Development Bank (AfDB) have directed funding toward the rehabilitation and expansion of wastewater treatment plants in Kenya and Egypt (AfDB 2017; AfDB 2018). Similarly, the World Bank has supported several initiatives in Africa related to water pollution control: for example, a USD 115 million grant was awarded to Mozambique in 2019 for improving sanitation and wastewater treatment (WBG 2019).

Other project-based initiatives implemented include research projects and the piloting of innovations in water quality monitoring and pollution control: for example, the European Union's Horizon 2020 funded project in Egypt, Morocco and Tunisia for wastewater treatment technologies as well as the project piloting the CabECO® membrane electrolytic technology for water treatment (European Commission n.d.). The United States Environmental Protection Agency (USEPA) is implementing the West Africa Drinking Water Laboratory Capacity Program, albeit currently only in Ghana (USEPA 2021). The Aquaya Institute has implemented a water monitoring project in Ethiopia, Guinea, Kenya, Senegal, Uganda and Zambia and produced data on microbial water quality through analyses of water samples (Aquaya Institute 2020). Similarly, IWMI has implemented research projects in North Africa, adding knowledge on the safe reuse of wastewater Ng 2018).

CONCLUDING REMARKS

The aim of this review was to highlight the need for the African Water Quality Program within the context of past and existing water quality monitoring and pollution control initiatives. Based on literature reviews and a survey conducted in 31 countries by AMCOW and IWMI, and a preliminary review of the current initiatives, it can be said that there is scope for AWaQ to make an impact by building upon past and present initiatives, strengthening synergies and filling existing gaps.

This report is accompanied by water quality profiles of those countries that responded to the Africawide survey (see Section A of Annex for one example).

Key Messages

The main findings of this review include:

1. While several initiatives are currently being implemented at continental, transboundary basin and national scales, coverage remains patchy. Not all African countries were found to be participating in some of the initiatives, even the global ones such as those led by GEMS/Water and the WHO Water Safety Plans. This may point to the potential for AWaQ to broaden the reach of existing initiatives.
2. There is a synergistic overlap between efforts directed at ambient water quality monitoring and water supply and sanitation-directed initiatives. Further exploration on how they can be better streamlined in line with AWaQ is needed.
3. There is a need to strengthen initiatives focusing on the data generation element of water quality monitoring, e.g., through laboratory infrastructure and testing equipment.
4. Different implementation scales may provide various entry points for the AWaQ.
5. An analysis of the results of the Africawide survey shows that
    a. There is an encouraging availability of national water testing laboratory facilities across African countries. Nonetheless, capacity-related weaknesses require attention to ensure functionality and sustainability.

b. Water quality monitoring and assessment capacities are patchy. Weakness in capacities related to staff training, laboratory infrastructure as well as monitoring program activities was indicated.
c. Pollution control mechanisms require strengthening, particularly regulatory mechanisms and wastewater treatment technologies, which are the most widely deployed pollution control solutions. These mechanisms may benefit from more concerted investment and political will to boost their effectiveness.
d. Ongoing regular training is essential to keep up with laboratory testing methodologies. The observed low trend in regular training may not augur well for keeping abreast of developments in water quality monitoring best practices, especially in view of emerging pollutants.

Next Steps

Ongoing efforts in this project will focus on assessing water quality monitoring and management innovations and how these innovations can be better leveraged to yield results at scale on the African continent. In the final phase of this project, the framework for AWaQ will be developed based on findings from phases 1-4, incorporating inputs received from stakeholders through the survey and other consultation forums such as the Africa Water and Sanitation Week.

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ANNEX. AMCOW-IWMI AFRICAWIDE SURVEY

A. Survey Questions

No.	Question
1.	Please enter your full name
2.	Please provide your contact information (e.g., email address/WhatsApp)
3.	What is your gender?
4.	In which country are you currently based?
5.	Which country are you representing in your responses to this survey? (Please indicate only one country)
6.	What is the name of your organization?
7.	In which sector does your organization work?
8.	What is your job title?
9.	How long have you worked in this role?
10.	What is your area of specialization?
11.	Have you received any training related to the following areas? (You can select multiple options) o Field water sampling o Laboratory water analysis o Water quality data processing and interpretation o Water quality modeling o Wastewater treatment o Formulation of water quality standards o None of the above
12.	Please indicate the format in which training was received o Part of a university or college course o Part of a one-off training certification o One-day workshop o Ongoing regular training
13.	How would you rate the technical capacity of individuals in your country's water testing laboratories to carry out their roles with respect to field sampling, laboratory water analysis, and interpretation of water quality data? o Poor, unable to conduct water quality related field sampling, laboratory testing or modeling o Average, able to conduct some of the technical roles o Adequate, able to carry out all roles satisfactorily

	o Very good, technical capacity exceeds expectations o Do not know
14.	Are there any government environmental (ambient) water quality monitoring programs in your country? o Yes o No o Do not know
15.	If the answer to Q 14 is 'no, how is water quality monitoring conducted in your country? (You can select multiple option) o Project-based monitoring by researchers, NGOs, international organizations, etc. o Private entities (e.g., industry, academia, etc.)
16.	Which type of water bodies are monitored in your country? (You can select multiple options) o Aquifers (groundwater) o Rivers and streams o Lakes and reservoirs o Wetlands o Estuaries o Transboundary waters
17.	Who coordinates national/regional water quality monitoring activities in your country? (You can select multiple options) o National institutions o Provincial institutions o Regional organizations o International organizations/NGOs o Private entities o Do not know
18.	Are there any government national/central/regional water testing laboratories in your country? o Yes o No o Do not know
19.	How many water testing laboratories are currently operational in your country?
20.	Are there any accredited laboratories in your country (e.g., ISO 17025)? o Yes o No o Do not know
21.	Do water testing laboratories require national-level registration? o Yes o No o Do not know
22.	Please indicate the water quality parameters currently analyzed in national water testing laboratories. o Physical parameters (color, temperature, turbidity, odor, etc.) o Major chemical parameters (pH, electrical conductivity, total dissolved solids, etc.) o Major cations (calcium, magnesium, sodium, potassium, etc) o Major anions (carbonates, bicarbonates, fluorides, chlorides, sulfates, etc.)

	o Oxygen (dissolved oxygen, biological oxygen demand, chemical oxygen demand, etc.) o Nutrients – Nitrate compounds (nitrates, nitrites, total nitrogen, ammonia, etc.) o Nutrients – Phosphate compounds (phosphates, total phosphorus, etc.) o Heavy metals (copper, cadmium, zinc, iron, lead, mercury, etc.) o Radioactive elements (alpha- and beta- emitter parameters) o Pesticides (organo-chlorine group, organo-phosphorus group, etc.) o Biological parameters (zooplankton and phytoplankton (chlorophyll a)) o Emerging contaminants (pharmaceutical compounds, personal care products (PCPs), endocrine-disrupting compounds (EDCs), microplastics, etc.) o Microbiological parameters (fecal coliforms, *E. coli*, etc.) o Emerging pathogens (antimicrobial resistant bacteria, viruses, protozoa
23.	Which laboratory equipment is used in national water testing laboratories in your country? o Portable meters (e.g., pH, conductivity, dissolved oxygen) o Benchtop meters (e.g., pH, conductivity, dissolved oxygen) o Spectrophotometer o Gas chromatograph (GC) o High-performance liquid chromatograph (HPLC) o Atomic emission spectrometer (AES) o Mass spectrometer (MS) o Inductively coupled plasma (ICP) o Flame photometer
24.	How often is this equipment serviced and maintained? o Never o When they malfunction o Regular servicing and maintenance o Do not know
25.	How would you rate the technical capacities for water quality monitoring in your country? 1 = Underequipped to monitor water resources (e.g., conduct field sampling) 2 = Equipped, but can only monitor priority water resources 3 = Capacity available to monitor most water resources o 1 o 2 o 3
26.	How would you rate the laboratory technical capacities for water testing in your country? 1 = Underequipped to carry out basic water quality analysis 2 = Equipped but not able to carry out all analyses 3 = Capacity available to conduct basic analysis and other specialized tests o 1 o 2 o 3
27.	Please explain your rating choice in Q 27 and Q 28.
28.	How would you rate the technical capacities to process and interpret water quality data in your country? 1 = Underequipped to process and interpret basic water quality data 2 = Equipped to process and interpret most water quality data

<table>
<tr><td></td><td>3 = Able to process and interpret all water quality data in detail
o 1
o 2
o 3</td></tr>
<tr><td>29.</td><td>What happens to the water quality data generated?
o Data are stored in laboratory databases without further processing.
o Data are stored, processed and used to inform operational decisions.
o Data are stored and released as requested by external users.
o Data sharing is coordinated across different government agencies or departments.</td></tr>
<tr><td>30.</td><td>What would you say are the 3 most important laboratory testing capacity needs?</td></tr>
<tr><td>31.</td><td>What would say are the 3 most important water quality monitoring capacity needs?</td></tr>
<tr><td>32.</td><td>Which of the following are the most critical pollutants in your country? (Please select all that apply)
o Physical parameters (color, temperature, turbidity, odor, etc.)
o Major chemical parameters (pH, electrical conductivity, total dissolved solids, etc.)
o Major cations (calcium, magnesium, sodium, potassium, etc)
o Major anions (carbonates, bicarbonates, fluorides, chlorides, sulfates, etc.)
o Oxygen (dissolved oxygen, biological oxygen demand, dhemical oxygen demand, etc.)
o Nutrients – Nitrate compounds (nitrates, nitrites, total nitrogen, ammonia, etc.)
o Nutrients – Phosphate compounds (phosphates, total phosphorus, etc.)
o Heavy metals (copper, cadmium, zinc, iron, lead, mercury, etc.)
o Radioactive elements (alpha- and beta- emitter parameters)
o Pesticides (organo-chlorine group, organo-phosphorus group, etc.)
o Biological parameters (zooplankton and phytoplankton (chlorophyll a))
o Emerging contaminants (pharmaceutical compounds, personal care products (PCPs), endocrine-disrupting compounds (EDCs), microplastics, etc.)
o Microbiological parameters (fecal coliforms, E. coli, etc.)
o Emerging pathogens (antimicrobial resistant bacteria, viruses, protozoa, etc.)</td></tr>
<tr><td>33.</td><td>How would you rate the contribution of these sources to water pollution in your country?
<table>
<tr><th></th><th>Minor Contribution</th><th>Considerable Contribution</th><th>Major Contribution</th></tr>
<tr><td>Mining</td><td>◉</td><td>○</td><td>○</td></tr>
<tr><td>Industry</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Petroleum</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Urban</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Agriculture</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Dumpsites</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Sewage waste</td><td>○</td><td>○</td><td>○</td></tr>
</table></td></tr>
<tr><td>34.</td><td>Please name the most polluted water bodies in your country.</td></tr>
</table>

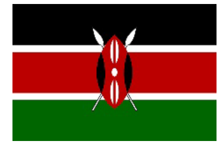
<table>
<tr><td>35.</td><td>What activities are dependent on each of the water bodies mentioned in Q 35? (e.g., domestic water supply, ecological significance, recreation and tourism)</td></tr>
<tr><td>36.</td><td>What have been the 3 main impacts of water pollution in your country or region? (Please select up to a maximum of three options)
o Disease
o Biodiversity loss
o Loss of recreational opportunities
o Eutrophication
o Reduced agriculture productivity
o Reduced fish catch
o Reduced tourism</td></tr>
<tr><td>37.</td><td>How is water pollution controlled in your country?
o Water treatment technologies
o Pollution control regulations (e.g., impact assessment, licenses, fines)
o Wastewater reuse technologies
o Nature-based solutions</td></tr>
<tr><td>38.</td><td>Which of these pollution control/management tools has had the most impact in addressing pollution issues in your country?
<table>
<tr><td></td><td>Least impact</td><td>Some impact</td><td>Most impact</td></tr>
<tr><td>Wastewater treatment</td><td>◉</td><td>○</td><td>○</td></tr>
<tr><td>Pollution control regulations (e.g., impact assessment, licenses, fines)</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Adoption of good agricultural practices</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Nature-based solutions</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>Other</td><td>○</td><td>○</td><td>○</td></tr>
</table></td></tr>
<tr><td>39.</td><td>Please name any inter-country water quality program that your country has taken part in, in the past.</td></tr>
<tr><td>40.</td><td>Please name up to 5 organizations/institutions that you have collaborated with on water pollution control, monitoring and analysis (including private institutions and academia). Please specify with names.</td></tr>
<tr><td>41.</td><td>How would you rate the government's attention to interventions on water quality and monitoring issues in your country?
o Low priority to water quality and monitoring issues
o Moderate attention to water quality and monitoring issues
o High priority and proactive actions on water quality and monitoring issues</td></tr>
<tr><td>42.</td><td>What are some water pollution control solutions being implemented in your country that show interesting potential for impact?</td></tr>
<tr><td>43.</td><td>How would you rate the level of awareness of nongovernment actors (communities, NGOs, etc.) regarding water quality issues in your country?
o Poorly informed and unaware of the potential dangers of water quality issues
o Moderately informed and aware of the potential dangers of water quality issues
o Well informed and are proactive in engaging the authority for actions</td></tr>
<tr><td>44.</td><td>Please provide any relevant links to water quality-related data and information pertaining to your country.</td></tr>
</table>

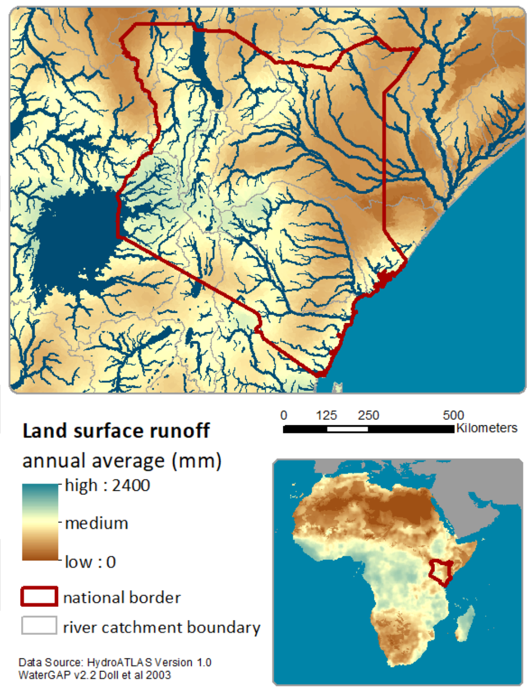
B. Session Notes: Africa Water Week (November 24, 2021)

Challenges	**Solutions**
Low availability of *in situ* water quality data: • Not enough water quality stations, not even in critical control points • Scarcity of qualified staff for sampling and lab analysis • Insufficient laboratory capacities for some parameters, including emerging pollutants	Complement *in situ* data with modeled data and *ex situ* (remote sensing) data. Explore the role of citizen science, not only to involve citizens in data collection and sharing but also as a way to raise awareness of local communities on pollution issues and form a coalition for action, policy and investment in pollution control.
Low accessibility of existing water quality data: • Data frequently stored on paper, CDs, etc. which makes it difficult to share and process • Unwillingness to share data. Fear of the consequences of making data public.	Harmonizing data collection and processing protocols and methodologies across countries and stakeholders Promote MoUs for water quality data sharing between institutions
Different parameters, methods and units used by different stakeholders and countries, which limits comparability, data aggregation and analysis	Build a water quality data platform for data storage and processing where different organizations can upload data
Weak or nonexistent data management systems and limited capacities to operate such systems	Capacity development and training. This will require targeted training for specific staff in institutions. The required capacity for effective monitoring goes beyond improved knowledge and skills of a few individuals; it requires these individuals to operate within effective institutions and different institutions to collaborate effectively on data collection and sharing. Facilitating inter-institutional coordination through country dialogues, workshops or other methods is thus necessary.
Low awareness about the linkage between water quality degradation and broader environmental and health impacts	Motivating funding and stimulate investments by making the best use of existing data to generate awareness stories.
Low investment in water quality monitoring, data processing and data use and communication	Credible water data can stimulate investment, support advocacy, stimulate political commitment, inform policy and monitor effectiveness in time. Sensitizing countries about these benefits will

Challenges	Solutions
	provide an incentive for countries to allocate appropriate financial and human resources. Cooperation to have a shared diagnosis on hotspots to be able to prioritize limited investments

Kenya





Background

- **Population:** 47.2 million
- **Water Supply**: National water coverage – 71.2%; Rural – 63.3%; Urban – 91.3% (WHO and UNICEF 2021b)
- **Sanitation:** National coverage – 58.2%; Rural – 48.1%; Urban – 84%; National open defecation- 8.5%; Rural – 11.3%; Urba n– 1.3% (WHO and UNICEF 2021b)
- **Major water bodies**: Lake Victoria, Athi-Galana-Sabaki River, Tana River, Turkwel, Kerio, Athi-Galana, Northern and Southern Ewaso Ng'iro, Lakes- Magadi, Naivasha, Turkana, Elementaita, Nakuru, Bogoria and Baringo.
- **SDG 6.3.2. score (2020)** – 86.52 (UNEP 2021)

Pollutants, Sources and Impact

Kenya is classified as a water-scarce country with many people living in the rural areas having limited access to quality water. In addition, water resources are under pressure from agricultural chemicals (fertilizer and herbicides) and urban and industrial wastes, as well as from use for hydroelectric power (Kithiia 2012). Past studies have pointed out raw sewage overflowing from blocked or collapsed sewers and filled-up septic tanks and pit latrines in urban areas such as Nairobi as a major source of water pollution. On the other hand, in the rural areas, locating wells in close proximity to pit latrines increases the likelihood of microorganism contamination (Njoroge et al. 2018).

Major Pollution Categories and Examples of Their Occurrence in Kenya

Major categories	Example	References
Organic pollutants	Lake Naivasha – Water quality in the northern parts of the Lake is influenced by agricultural activities whereas the northeastern parts are dominated by domestic effluent.	Ndungu (2014)
	Water in the Likii River is not safe for human consumption because of pesticide residues	Githinji et al. (2019)
Pathogens	Microbiological contamination of the Nairobi and Athi rivers is high as per Kenya standards, and WHO guidelines for drinking water and agricultural use. The waters were highly contaminated with human pathogenic bacteria, dominated by *E. coli.*	Musyoki et al. (2013)
Inorganic pollutants (salts and metals)	The Ngong River at Embakasi indicates high values for most polluting substances including manganese, lead and mercury as a result of upstream industrial activity.	Kithiia (2012)

Policies and Institutions: Stakeholders and Their Responsibilities

Stakeholders	Main responsibilities/duties
Ministry of Water and Irrigation	Responsible for the water sector in Kenya. Formulation of policy and strategy for water and sewerage services, sector coordination and monitoring of other water services institutions.
Water Services Regulatory Board	Regulation and monitoring of urban and rural water services
National Environment Management Authority	Promotes integration of environmental considerations into government policies, plans, programs and projects. Formulates water quality regulations
Water Services Boards	Water Services Boards are responsible for asset management, that is, for the development and rehabilitation of water and sewerage facilities. There are eight regional WSBs.
Water Appeals Board	To settle water-related disputes and conflicts

Sources: MWI (2007).

Water Pollution Monitoring and Control: Policies and Regulatory Environment

Policies, act, regulations	Description
Water Act (2002)	Provides for the management, conservation, use and control of water resources; regulation of the right to use water; regulation and management of water supply and sewerage services
Environmental Management and Coordination (Water Quality) Regulations, 2006 (Cap. 387).	Frames rules relating to the use and discharge of water for different purposes; makes provision for the protection of water resources from pollution; and defines water quality standards.
Guidelines on Drinking Water Quality and Effluent Monitoring, 2008	Focuses on drinking water quality and industrial effluents. Provides guidelines to water service providers to determine effluent quality, check on the operational efficiency of the wastewater treatment system; and monitor industrial effluent in their areas

Water Quality Monitoring and Pollution Control Initiatives

Program	Status/ Year	Objective	Scope	Funded by
GEMS/Water Quality Monitoring Program (Warner 2019)	Active	Extensive ambient water quality monitoring of surface and ground water	Collects data from surface and groundwater 2-4 times per year	UNEP GEMS/Water Capacity Development Centre
Aquaya Institute's Monitoring for Safe Water (MfSW) research program (Ethiopia, Guinea, Kenya, Senegal, Uganda and Zambia)	(2012-2016)	To build capacities for monitoring of water safety in Sub-Saharan Africa	The program has collected qualitative and quantitative data on microbial water quality monitoring activities among the engaged monitoring institutions in six countries	UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO)
Nairobi Rivers Basin Rehabilitation and Restoration Program: Sewerage Improvement project Phase II (NaRSIP-II)	2021	Access to improved sanitation services in Nairobi; improving the quality of rivers within the Nairobi Metropolis	Water quality assessment of Nairobi and its satellite towns and rivers and, subsequently, quarterly surface/ground water quality monitoring	African Development Bank (AfDB), Government of Kenya

Water Quality Monitoring and Testing Capacities

Laboratory Facilities and Capacities

The main Water Resources Authority (WRA)laboratory in Nairobi has the ability to analyze an extensive range of parameters and is staffed by a well-trained team. The laboratory works in line with ISO 17025 standards, and is certified by the Kenya Bureau of Standards. There is an extensive ambient water quality monitoring program that collects data from surface water and groundwater sources 2-4 times a year. Several regional laboratories support the central laboratory, together analyzing over 3,000 samples per year UNEP GEMS/Water 2019).

Innovations in water quality monitoring and management:

Towards developing an African Water Quality Program (AWaQ)

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

August 2022

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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 partnerships, IWMI combines research on 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, and led the CGIAR Research Program on Water, Land and Ecosystems (WLE). www.iwmi.org

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Collaborators

International Water Management Institute (IWMI)

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The World Water Quality Alliance of UNEP also provided funding towards the completion of this project.

AMCOW (African Ministers' Council on Water) are the custodians of this project and will ultimately take ownership for implementation.

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ACRONYMS AND ABBREVIATIONS

AMCOW	African Ministers' Council on Water
ASTM	American Society for Testing and Materials
AWaQ	African Water Quality Program
DIN	German Institute for Norms
EN	European Norm
EPs	Emerging Pollutants
EPA	United States Environmental Protection Agency
GEMS/Water	Global Environment Monitoring System for Freshwater
ISO	International Organization for Standardization
IWRM	Integrated Water Resources Management
NbS	Nature-based Solutions
SCA	Standing Committee of Analysts (Blue Books)
SDGs	Sustainable Development Goals
SLMB	Swiss Book for the Analysis of Food
UNEP	United Nations Environment Programme
USP	United State Pharmacopoeia
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 patchy and irregular 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 report, a detailed analysis of innovation in water quality monitoring and management is undertaken to propose interventions for strengthen Africa's current water quality monitoring and management efforts. Innovations related to monitoring programme 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, basis a set of criteria, are proposed for African contexts. These criteria consider important innovation features including affordability, scalability and flexibility.

Key findings of this report show that:

- 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 programmes 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.

GENERAL INTRODUCTION

This project responds to a request made by the African Ministers' Council on Water (AMCOW) to IWMI in 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 Program on Water Quality (AWaQ) in its 2020–2024 Strategic Operations Plan in light of the AMCOW guiding frameworks such as the Africa Water Vision 2025, Sustainable Development Goals (SDGs), and the African Union's Agenda 2063 'The Africa We Want'. Additionally, this program will be one of the elements of a broader program on water quality in Africa being promoted by the work-streams of the World Water Quality Alliance (WWQA), co-ordinated by the Global Environment Monitoring Unit in the Science Division of 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 to formulate the AWaQ has been conceptualized in five phases (see **Table 1**). The first two phases assess past and existing initiatives and capacity for both monitoring and management, while Phase 3 and 4 analyze potential innovations in ambient water quality monitoring and management that the AWaQ should consider. The last phase develops a framework for AWaQ. This report concentrates on Phase 3 and 4, innovations in monitoring and management.

TABLE 1. Structure of the AWaQ project showing the position of this report, i.e., Phase 3 and 4 (highlighted in green).

Phase	Description
1	Assessment of ambient water quality monitoring initiatives and capacities in Africa
2	Assessment of initiatives on pollution control and impact mitigation
3	Africa-appropriate innovations for ambient water quality monitoring
4	New appropriate innovations for the management of water quality
5	A Framework for the African Water Quality Program

The key output of this project is a framework to guide the development of the African Water Quality Program and is designed to be applied by AMCOW in the expansion of water quality management across the continent. This framework will enable the establishment of a working program to be adopted by all member states for monitoring and management of water quality. The project also promotes Africa's ability to participate meaningfully in the World Water Quality Alliance (WWQA) and the SDGs, where the framework can be used to allow further scrutiny of a multitude of water quality issues. It also sets in motion a continent-wide initiative to collect and to provide data to larger repositories including UNEP's Global Environment Monitoring System for Freshwater (GEMS/Water). The eventual impact of this project should the establishment of an African program to manage water quality that will benefit the environment and all of its inhabitants.

1.1 Objectives

The objective of this report 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 Africa. This objective, informed by Phase 1 and 2 (see Table 1), 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

1.2 Introduction

Water quality monitoring in Africa was established in the first two phases of this study to be largely marked by inconsistences and capacity gaps. 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.[1] 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 in conventional approaches as well as innovations in water quality monitoring with the aim of highlighting their applicability within the African context.

1.3 Limitations of conventional approaches and practices in Africa

Phase 1 and 2 of this project (Table 1) illustrated the inconsistent implementation of water quality monitoring practices across Africa. While some countries operate extensive and advanced programmes, 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.

1.3.1 Capacity gaps

The dedicated personnel working to monitor and assess their country's freshwaters 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 programmes 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 programme design, as well as to interpret results is also observed to be lacking (UNEP GEMS/Water 2020a).

To enable effective monitoring programmes, 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 the awareness of the importance of

[1] As observed in the 2021 AMCOW/IWMI Africa-wide survey

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).

1.3.2 Data gaps

Water quality data are less commonly 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 agricultural runoff, but also, they may be 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 United Nations Environment Programme (UNEP) water quality database GEMStat,[2] 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 Sustainable Development Goal (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 1). This indicator provides a useful snapshot of water quality at the continental scale, and compared with other world regions, Africa is relatively well represented. 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 1000 km^2**. For Africa, however, the density was much lower at **0.82 km^2** (pers. comm. UNEP), i.e., one monitoring station for every 1220 km^2. This suggests that in Africa, significantly less monitoring stations are being utilized to collect data than on a global scale.

[2] https://gemstat.org/

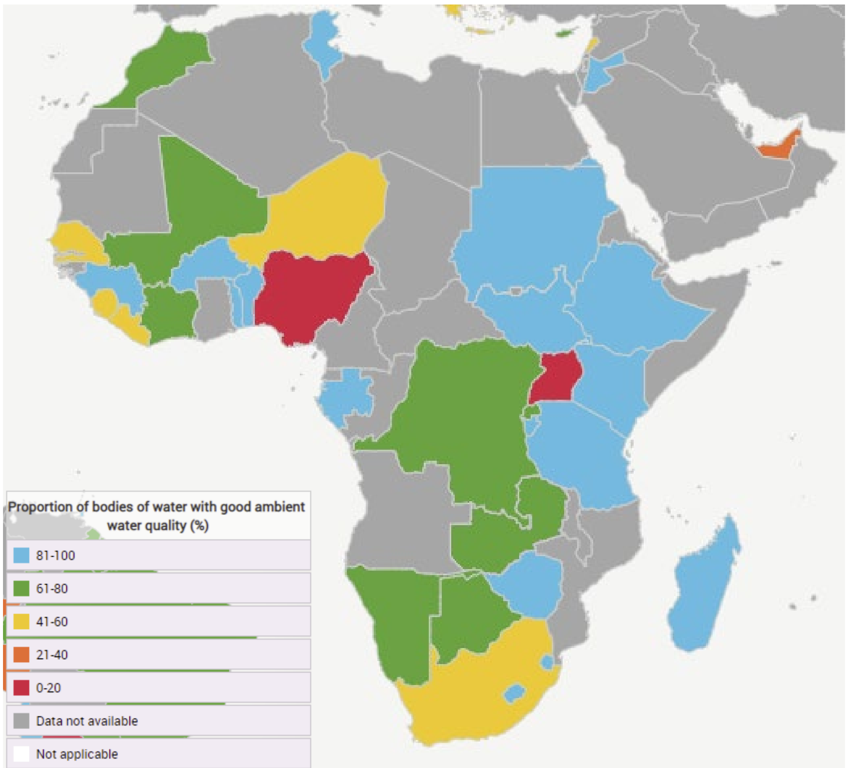

FIGURE 1. Screenshot of UN Water's data portal for SDG indicator 6.3.2 showing the latest available data.

With suitable investment and targeted capacity development, existing monitoring programmes 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 proves 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 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 programme design and the interpretation of any outputs (Chilton 2020).

Biological monitoring, or biomonitoring, forms an essential component of many monitoring programmes globally in provisioning a comprehensive indication of water quality and/or ecosystem health (see Section 2.3.6). Biomonitoring is overall less commonly undertaken in African countries despite the presence of some advanced programmes such as the River Ecostatus Monitoring

Programme 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 programmes that struggle to collect data and assess the impacts of basic physico-chemical 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 2019), efforts to address this data gap should be pursued.

Data on the 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 (Filho et al. 2021). This interplay of pressures on natural sediment flow can have catastrophic socio-economic 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 physico-chemical 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.

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

1.3.3 Information gaps

The significant capacity and data gaps listed above manifest as information gaps for decision 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 programmes 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 target values (water quality standards in some cases); it then applies an 80 per cent 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 the 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.

1.4 Monitoring innovations being tested and used globally

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

1.4.1 Design of monitoring programmes

Monitoring programmes 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 programme 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 programmes 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 programme 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 programme, it is necessary to examine whether they can make a beneficial contribution and meet the needs of the objectives of the monitoring programme. 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 programme, 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 programme. Subsequently, natural causes of variability can be anticipated and factored into the measurement programme and the resultant data assessment.

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

- Reviewing available information on the water bodies, existing monitoring programmes, 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 programme 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 programmes 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 programme design. These basin units, ranging in scale from approximately 10 kilometres wide up to continental size, are appropriate for monitoring programmes of various scales. Ideally, an integrated monitoring approach should include surface and groundwaters. The associated monitoring programmes(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).

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[4] https://hydrosheds.org/page/hydrobasins

[5] https://www.hydrosheds.org/page/hydroatlas

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 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 faecal 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 programmes are increasing rapidly.

1.4.1.1 Selection of monitoring parameters

Some water quality monitoring programmes 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 programmes 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 programmes (see Section 1.4.5), for intensive surveys or for greater spatial coverage. Additional parameters to be included depend on the objectives of the monitoring programme and are typically selected from the following groups: nutrients which drive the productivity of the freshwater ecosystem (i.e., forms of N, P and Si), contaminants (including an increasing number of newly emerging contaminants such as pharmaceutical residues), and pathogens, such as faecal coliforms. Specific innovations for monitoring are elaborated in Sections 1.4.2, 1.4.3 and 1.4.4.

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 *E. Coli* as an indicator of faecal material. The presence of faecal material indicates a potential risk to human health from many different pathogens transmissible through the faecal-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 and ground waters and may be difficult to detect or measure without highly advanced sample preparation and analysis techniques (see Section 1.4.2). Inclusion in a monitoring programme 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 OECD (OECD 2019) can aid in better policy and management for pharmaceutical residues. Modelling concentrations in water bodies can be based on 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 2005), 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).

A priority pollutant approach has been adopted by the European Union, that prescribes a list of compounds that must be included in monitoring programmes. The list includes pesticides and herbicides, some metals, and organic compounds such as polyaromatic hydrocarbons and polybrominated biphenylethers (EU 2013a, 2015). 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).

1.4.1.2 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 programme 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 programmes. Examples using Combined Cluster and Discriminant Analysis (CCDA) for rivers have been provided by Kovács et al. (2014, 2015a,b) and Tanos et al. (2015), for ungauged river basis by Lee et al. (2014b) and for optimizing lake and reservoir sampling locations using information theory by Lee et al. (2014a). Cansu 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.

1.4.1.3 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 run-off, population increases due to tourism, agricultural use of fertiliser 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).

1.4.2 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 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, a large number of 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 et al. 2007).

1.4.2.1 In situ sensors

Evolutions in water quality monitoring have responded to the current needs to more effectively understand and manage water quality. 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. 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:

- 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 (see **Table 2**). 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).

TABLE 2. 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 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)	Used for monitoring of big natural-water systems. Ability for real-time detection of massive data with relatively low costs.

	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.	
WSN and Machine Learning (ML) Techniques Based Water Quality Monitoring	Can be used to assess water quality using a small number of WQM parameters and predict future trends.	High energy requirements, compromised security, low communication speed, storage issues and high installation/maintenance costs.
Smart Water Quality Monitoring (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., TCP/IP protocols), 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 WQM parameters based on measured values of WQM parameters using sensors and can predict future water trends.

Source: Jan et al. 2021

1.4.3 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 sites or difficult to access which hinder monitoring. In addition, sample preservation is also a challenge within some contexts (AMCOW/IWMI Africa-wide Survey 2021). In resource-constrained environments such as those in Africa, this has resulted in the collapse of monitoring programmes due to the high associated 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 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.

1.4.3.1 Remotely operated and unmanned vehicles

Technological advancements in the development of remote operated vehicles (ROVs), also known as underwater drones, has led to opportunities in exploring deep aquatic environments. They help in reducing costs that would otherwise be associated with deploying divers to carry out under water 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 manoeuvring 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 a 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 3**). 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.

TABLE 3. Advantages and disadvantages of UAVs and ROVs as instrument deployment methods.

	Unmanned Aerial Vehicles / Remote 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 manoeuvring 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.

The disadvantages of using drone technology in water quality monitoring in Africa are associated with regulations around using such unmanned aerial vehicles and in their operation, 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.

1.4.4 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 NASA's Landsat 1[6] (Tatem et al. 2008). More recent programmes — the European Space Agency's Sentinel 3 satellites[7] and NASA's Landsat 8[8] — 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 programme 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 programmes. 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. Firstly, 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 along the shoreline. Secondly, 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

[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/

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 resource 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:

- Copernicus Global Land Service: Lake Water Quality: https://land.copernicus.eu/global/products/lwq
- UNEP's Freshwater Explorer for SDG 6.6.1: https://www.sdg661.app/
- NOAA Lake Erie Harmful Algal Bloom Forecast: 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, 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
- Early warning systems of harmful algal blooms in reservoirs (Example from South Africa: https://www.ocims.gov.za/water-quality-theme/)

1.4.5 Citizen Science

Citizen science (CS) 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 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 level (Thornhill et al. 2019). For a successful citizen water quality monitoring programme, 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 programme 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 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,b) 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 on-line databases that can share and visualize the data with the citizens collecting it; and the proliferation of smart phones 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 programmes in the USA such as the Chesapeake Monitoring Cooperative.[10] A broad range of water quality parameters — temperature, bacteria - Coliscan Easygel, pH, dissolved O_2 (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 programmes organized by 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.

[10] https://www.chesapeakemonitoringcoop.org/

2.3.5.1 Examples of methods and instruments used for citizen monitoring

A citizen monitoring programme 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 EU funded project, MONOCLE,[12] along with its partners, have developed a 3D printable mini Secchi disc[13] 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 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 programmes are nutrients (N and P), turbidity, pH, and conductivity. Kits that have been tested and are widely used globally for citizen science efforts include those used by Freshwater Watch[16] and Drinkable rivers[17]. Where drinking water is directly sourced from ambient water bodies, health related parameters, particularly faecal bacteria, are important and should be included in citizen monitoring. Simple kits have been developed to determine the presence or absence of faecal bacteria or more specifically, *E. coli*. There are several commercial monitoring kits[18] but many of these kits are beyond the budget of typical citizen monitoring programmes.

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 smart phone application, such as Bloomwatch[19] in the USA and Bloomin' Algae[20] in the UK. Data from such applications are usually shared openly through an associated on-line data hub and can be used by regulatory bodies and other water-related organizations for management purposes. More advanced citizen science programmes 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 US EPA Cyanomonitoring programme.[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 programme in Australia).[22] A nationwide citizen network in the UK with over 2,000

[11] https://www.nalms.org/secchidipin/
[12] https://monocle-h2020.eu/
[13] https://monocle-h2020.eu/Sensors_and_services/Mini-secchi_disk
[14] http://ispex-eu.org/
[15] http://www.groundtruth.co.za/our-products
[16] https://freshwaterwatch.thewaterhub.org/about
[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

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 Section 1.4.6. While the approach itself is not novel, there have been nascent developments in adapting such methods for use in citizen monitoring programmes, 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. 2021), based on the South African Scoring System (SASS), a biomonitoring method for evaluating river health. Citizen monitoring reliant on smart phone 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 smart phone 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 WHO for drinking water surveillance (WHO 2019).

1.4.6 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 or 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 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 programmes:

- 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

2.3.6.1 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

[23] https://www.riverflies.org/riverflies-gis-home

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 South African Scoring System (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 the International Organisation for Standardisation (ISO) and have associated quality assurance protocols.[24]

Recent innovations attempt to minimize the amount of taxonomic expertise required by focussing 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 1.4.5), 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 (e)DNA metabarcoding, they display potential to be included in routine biomonitoring programmes (Pawlowski et al. 2018). A review of the use of macroinvertebrate monitoring of water quality in relation to use 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 programmes 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 faecal 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 techniques[25] may also make it possible to use microbiological species for regulatory monitoring, although the associated cost may be high (Oliver et al. 2010, 2014).

2.3.6.2 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:

- 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

[24] https://www.iso.org/standards.html
[25] For example https://www.veracet.com/

- Establishing the presence of contaminants where the concentrations in water samples may be below the limits of detection for the analytical methods available

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 Mussel Watch Program using freshwater mussels to monitor contaminants of emerging concern in the Great Lakes of North America (https://www.regions.noaa.gov/great-lakes/index.php/great_lakes-restoration-initiative/toxics/mussel-watch-expansion/). In the European Union, monitoring contaminants in biota has been embodied in the Environmental Quality Standards Directive 2008/105/EC (EC 2008) for use in relation to the Water Framework Directive (Carere et al. 2012a,b). 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 (GCMS) for organic micropollutants.

2.3.6.3 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 behaviour, 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; and EPA undated 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.

2.6.3.4 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 Rheinallt 1992; Lang and Dethlefsen 1996), e.g., the UK National Marine Monitoring Programme[26] and in aquaculture facilities (for instance, the tool developed by WorldFish[27]). When coupled with an on-line reporting mechanism, such as a smart phone app with

[26] https://www.bodc.ac.uk/projects/data_management/uk/merman/project_overview/
[27] https://digitalarchive.worldfishcenter.org/handle/20.500.12348/4896

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.

1.5 Monitoring innovations applicable to Africa

Based on the discussion in the preceding sections, **Table 4** 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, labour or financial resources

TABLE 4. Monitoring innovations and potential for use in Africa.

Category	Approach/innovation/technique	Purpose	Potential use in Africa	Comments
Monitoring programme 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
	Co-location of hydrometric and water quality monitoring locations	Facilitates calculation of loads/fluxes	HIGH	May require co-operation between two different government agencies and data sharing
Selection of monitoring parameters	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
	Remote 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

	Kits and portable instruments for measuring water quality parameters in the field, e.g., N, P, turbidity, faecal 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
Laboratory analysis	Standardized methods	Enables comparability between monitoring locations and laboratories performing analyses	HIGH	Standards readily available for different levels of analytical complexity
	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
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	HIGH	Field kits available for use in remote locations; economic laboratory methods

		used as a drinking water source		
	(e)DNA 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
	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
Citizen/community monitoring	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 smart phones	Validation of satellite data	HIGH	Training and co-ordination required and availability of mobile data networks
	Fish kill and algal bloom recording with smart phone 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 smart phone 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 smart phone app	Indicating presence of toxic pollutants	HIGH	Observation and reporting can be done by local fishing communities
Sediment monitoring	Collection of particulate matter and analysis for key elements/contaminants	Tracking pollutant distribution	HIGH	Can be done with standard analytical laboratory facilities

	Monitoring of sediment budgets	Assess impacts of activities that affect sediment dynamics at the catchment scale	HIGH	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	Reduces the need for intensive sampling and analysis	MEDIUM	Useful where effluent data are available but requires validation sampling
	Predicting occurrence of harmful algal blooms in reservoirs	Early warning for risks to human health	MEDIUM	Requires regular environmental and water quality monitoring data from the reservoirs

INNOVATION IN WATER QUALITY MANAGEMENT

1.6 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 socio-economic 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.

1.7 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 (Table 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.

1.7.1 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 UN's 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 ecosystem — concentrations of nitrate found in unimpacted freshwaters are often much lower.

1.7.2 Data management and sharing

Poor management of water quality data limits the effective water resource 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 they is not the case, then organizing and outputting data from a suboptimal system can be labour 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 resource 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).

1.7.3 Pollution control

Phase 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 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 AQUASTAT 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 safely treated is 55.5 percent, as compared with the estimate of only 27.6 percent 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 programme 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),[28] 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 Section 1.8 examines some solutions to improve agricultural management practices.

1.7.4 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 and groundwaters by separate organizations housed in different ministries. The inseparable connection between surface and groundwaters 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.[29] 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 and is also considered in Section 1.8.2. 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.

[28] https://www.un.org/development/desa/pd/

[29] https://waterportal.rwb.rw/publications/catchment_plans

1.7.5 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 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 socio-economic benefits, can help safeguard progress. A successful instance of the same is discussed in the World Bank report (Damania et al. 2019) where direct economic impacts of water pollution are discussed.

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 programme 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. GEMS/Water). 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.

1.8 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 potentially 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 programme 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.

1.8.1 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 (see below). 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.[30] Policies that aim to change behaviour 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 behavioural change must account for free advisory services and training for farmers, such as the provision of advice on improved methods and timing of fertiliser application to reduce run-off to water bodies. Within the European Union, regulations control when farmers are permitted to spread manure on the land in order to minimize nitrate run-off (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 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 DPSIR (Drivers, Pressures, State, Impacts and Responses) 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.

1.8.2 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 Ibisch 2013). It requires a co-ordinated 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.[31] Since water bodies do not necessarily fall within the territory of a single nation, therefore IWRM should also encompass transboundary water bodies and include relevant stakeholders from all nations sharing the same water resources.

Transboundary co-operation is a fundamental aspect of successful River Basin Organizations (RBOs). River Basin Organizations 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

[30] https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program
[31] https://www.un.org/sustainabledevelopment/water-and-sanitation/

water bodies, have been in operation for decades for the River Danube[32] and the River Rhine[33] 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 programme operated and implemented at designated stations within the river basin on an agreed timeframe by all participating countries (Chapman et al. 2016).

1.8.3 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 ODM2.[34]

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.

Many private sector entities use freshwater within their processes, including water directly abstracted from surface and ground waters. 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.

1.8.4 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 process, 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

[32] https://www.icpdr.org/main/
[33] https://www.iksr.org/en/
[34] https://www.odm2.org/

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 centres, and the continuing financial and technical resources to operate and maintain them. Decentralized wastewater systems treat up to 1,000 cubic metres 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 fertiliser and conditioner, or into a biomass fuel for energy generation. Examples of a globally used system are available from BORDA,[35] 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 and groundwaters 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, (e.g., http://ecosoftt.org/water-wastewater/wastewater-recovery/), 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 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 initially met with objections in South Africa's eThekwini Municipality, where reclaimed wastewater was tabled by the municipality as a potential source of water (eThekwini Municipality 2009). After a series of feasibility studies, the municipality is currently producing high quality

[35] https://www.borda.org/solutions/decentralised-sanitation-systems-2/#dewats

reclaimed water from municipal wastewater and supplying industrial-grade water, thereby freeing up large volumes of potable water for residents.

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 in irrigating 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. 2018). Diarrhoea and parasitic diseases were reported 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 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.

1.8.5 Nature-based solutions

Run-off, 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. Run-off 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 faecal pathogens, heavy metals, organic compounds and plastics. Therefore, the management and treatment of storm water 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.[36]

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 (European Commission 2020). 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

[36] http://archive.phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan

improved biodiversity and habitats as well as improved socio-economic 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 raingardens (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 2005; 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 *Escherichia coli* and faecal 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 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 onsite 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, Cameron, Nigeria and Tunisia highlighted largely comparably 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 faecal 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 practises. 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 fertilisers, pesticides and other contaminants associated with the fine particles transported with run-off (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).

1.8.6 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) models (Wool et al. 2020; https://www.epa.gov/ceam/water-quality-analysis-simulation-program-wasp) to trace pollution sources. Other techniques, such as Pollution Information Assessment Tools[37] 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 1.4.3) equipped with cameras is also a recent innovation for detecting pollution sources in water bodies.[38]

1.8.7 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 1.4.5) and clearing of debris such as macroplastics from water courses. A successful model for community engagement is the River Trusts network in the UK and Ireland.[39] It brings together experts on conservation of rivers with citizens to plan and execute river restoration activities, identify pollution sources, and many other activities.[40]

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 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.[41]

[37] e.g., https://www.waternsw.com.au/water-quality/science/catchment/psat
[38] e.g., https://waldenenvironmentalengineering.com/environmental-services-blog/using-aerial-thermography-to-spot-water-quality-issues-leaks-and-other-discrepancies/
[39] https://www.theriverstrust.org/
[40] https://www.theriverstrust.org/our-work/our-impact
[41] https://web.arch.virginia.edu/baygame/about/

1.9 Management innovations applicable to Africa

Table 5 captures the different innovations in order to evaluate management options applicable for Africa which consider important innovation features including affordability, scalability and flexibility.

TABLE 5. 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
	Economic instruments: subsidies and incentives	Reduction of pollution through change of behaviour	HIGH	Private sector/community involvement and financial resources required
	DPSIR framework	Determining policy needs and assessing effects of policy measures	HIGH	Requires inter-departmental co-operation to share relevant data
	Water quality objectives	Protect water bodies and their ecosystems from critical pollutants	HIGH	Reference conditions required for different water body types at national level
	Ecosystem guidelines	Protection of ambient water quality and freshwater ecosystems	MEDIUM	Requires existing understanding of freshwater ecosystems and their water quantity and quality needs
	Data sharing policy	Improve national and international cooperation	HIGH	Options to share actual recorded measurements or aggregated summary data
Catchment-based management	Integrated Water Resources Management (IWRM)	Sustainable and equitable use of water resources	HIGH	Requires co-ordination amongst many different agencies and stakeholders
	Transboundary co-operation	Sustainable and equitable use of transboundary water resources	HIGH	Requires co-ordination amongst many different agencies and stakeholders
	Harmonized monitoring throughout the catchment	Generation of data on locations and types of pollution in order to support targeted management	MEDIUM	Participating agencies/countries must commit resources and agree to share the data in a common database

Category	Approach/innovation/technique	Purpose	Potential use in Africa	Comments
	Private sector and academic engagement	Expand data availability from non-governmental sources	MEDIUM	Incentivize private sector and academic institutions to contribute existing, and collect new data on a catchment basis
Data management	National database storing and sharing water quality and quantity data from all local and regional agencies/laboratories	National water quality assessments to provide information for policy development	HIGH	Open access software available; 'Cloud' sharing of data via internet or central data storage and network
	Promotion of the use of data management standards	Improve interoperability and sharing of data between national and international organizations	MEDIUM	Requires capacity development in data management
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 available basis the budget and volume of effluent
	Decentralized wastewater systems	Small rural communities and businesses converting wastewater into energy and soil fertiliser	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

Category	Approach/innovation/technique	Purpose	Potential use in Africa	Comments
	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
Run-off and diffuse pollution control	Ecological infrastructure such as buffer strips	Reduction of sediment and nutrient run-off	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	Improves awareness of causes of pollution and methods to reduce it	MEDIUM	Suitable for agricultural, industrial and mining sectors
Restoration and rehabilitation	Community driven restoration programmes	Enables greater spatial and temporal restoration activity	HIGH	Local community liaison personnel needed

Category	Approach/innovation/technique	Purpose	Potential use in Africa	Comments
	Educational programmes 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

1.10 Conclusion

This report 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 programme 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.

1.10.1 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 report.

Monitoring:

- Biological monitoring is a high priority intervention for inclusion into national water quality monitoring programmes 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 co-ordination 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 resource management.

- There is a 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 the 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 need 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 faecal waste and reducing faecal 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.

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Links to further 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

ANNEX 1: 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	Water conductivity
	APHA 2510	
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	pH value of drinking water
	APHA 4500-H^+ B	Potentiometry
Fluoride	ASTM D 1179; ASTM D 3868	Standard test methods for fluoride ion in water; Standard test method for fluoride ions in brines, brackish water and seawater
	DIN 38405-4	German standard methods for the examination of water, sludge and wastewater; anions (group D); determination of fluoride (D 4)
	EPA 340.2	Fluoride (potentiometric, ion selective electrode)
	ISO 10359-1	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

Parameter	Standard method	Description
	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 on-line ion chromatography
	ASTM D 6581	Standard test method for bromide, bromated, 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
	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+, NH4+, K+, Mn2+, Ca2+, Mg2+, Sr2+ and Ba2+ 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
	ASTM D 3557	Standard test methods for cadmium in water

Parameter	Standard method	Description
Heavy metals	ASTM D 3559	Standard test methods for lead in water
	DIN 38406-16; DIN 38406-17	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	Copper, lead, cadmium, zinc in drinking water, polarographic
	APHA 3125	
Chemical Oxygen Demand (COD)	DIN 38409-41; DIN 38409-44	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)
	DIN 38414-9	German standard methods for the examination of water, wastewater and sludge; sludge and sediments (group S); determination of the COD (S 9)
	EPA 410.1; EPA 410.2; EPA 410.3	COD — titrimetric, mid-level; titrimetric, low level; high-level for saline water
	ISO 6060	Water quality — determination of the COD
	SCA, Blue book 215	The determination of COD in waters and effluents
	APHA 5210	
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; DIN 38409-6; DIN 38409-7	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 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 CaCO3) (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

Parameter	Standard method	Description
	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; EPA 330.3	Chlorine, total residual
	DIN EN ISO 7393-1; DIN EN ISO 7393-3	Water quality — determination of free chlorine and total chorine — part 1: titrimetric method using N,N-diethyl- 1,4-phenylenediamine; part 3: iodometric titration method for the determination of total chlorine
	APHA 4500-F^-	

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 State Pharmacopoeia; SLMB - Swiss Book for the Analysis of Food; SCA - Standing Committee of Analysts (Blue Books)

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

ANNEX 2: EXAMPLES FOR ONLINE WATER QUALITY MONITORING SENSORS AVAILABLE IN THE MARKET

Sensor	Description	Appx. 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, NO3-N, COD, BOD, TOC, DOC, UV254, color, BTX, O3, H2S, 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	USD 14 000

Sensor	Description	Appx. Cost*
	dedicated electronics, data communication, event detection algorithms and control software.	
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 (Vibrio fischeri) 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 Escherichia coli. Uses the technology of Fluorescent optical analysis of biochemical activity.	USD 50 000
WQ 101	A water quality monitoring sensor (WQM) sensor to measure temperature. Vendor - Global water.	-
WQ401	A water quality monitoring sensor (WQM) sensor to measure DO. Vendor - Global water.	-
WQ600	A water quality monitoring sensor (WQM) sensor to measure ORP. Vendor - Global water.	-
WQ730 and WQ720	A water quality monitoring sensor (WQM) sensor to measure Turbidity. Vendor - Global water.	-
WQ-COND	A water quality monitoring sensor (WQM) sensor to measure EC. Vendor - Global water.	-
WQ201 pH Sensor	A water quality monitoring sensor (WQM) sensor to measure pH. Vendor - Global water.	-
FC80 free chlorine sensor	A water quality monitoring sensor (WQM) 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 there upon) in real-time.	-
Parasitometer	Developed by Water Optics Technology. An Optofludic sensor to identify disease causing microbes	-

* as indicated in the Source (2013)

Source: EU 2013b; Jan et al. 2021; Wang et al. 2018

Framework for the African Water Quality Program (AWaQ)

International Water Management Institute

December 2022

This report

This is a final report that describes a framework for the African Water Quality Program (AWaQ). It will be used to guide the development of the AWaQ across the African continent.

Citation

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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 partnerships, 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 the 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, and leads the CGIAR Research Program on Water, Land and Ecosystems (WLE). www.iwmi.org

Cover Photo:
Senqu River, Lesotho (Chris Dickens)

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Collaborators

International Water Management Institute (IWMI)

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The World Water Quality Alliance of the United Nations Environmental Programme (UNEP) also provided funding towards the completion of this project.

AMCOW (African Ministers' Council on Water) is this project's custodian and will ultimately take ownership for implementation.

Executive Summary

As the water quality challenges continue to escalate in Africa, a collective response is needed to stem the tide and improve the water quality for millions of people and the environment that depend on it. Anthropogenic water pollution can be exaggerated by climate change impacts such as changes in hydrological regimes and increased temperatures. Climate-induced temperature increases worsen these impacts through higher pollutant concentrations from decreased flows in drought periods and acceleration of chemical reactions in warmer waters, among others. In addition, the growing use of groundwater as surface water quality continues to deteriorate, requires robust monitoring programs that will address both surface and groundwater quality. The African Ministers' Council on Water (AMCOW), envisages the African Water Quality Program (AWaQ) to respond to the water quality challenges for both surface and groundwater that are facing African countries and to develop a continent-wide response program. Water quality directly impacts human and ecosystem health and ultimately impacts socio-economic development. An Africa-wide program will rally African countries to highlight the importance of good ambient water quality and the direct benefits to be derived from monitoring and managing water quality. Further, enhancing the availability and application of water quality data will strengthen management strategies and ultimately improve water quality.

This framework document provides a foundational structure for developing the AWaQ program and is guided by the principles of State-custodianship, co-development, coordination and collaboration. Member States are the overall custodians of the data and information generated as part of the program and will be closely involved in the development of program activities. Further, the AWaQ program entails coordination and collaboration between global, regional and transboundary institutions and initiatives involved in water quality monitoring and assessment.

The framework rests on four core components which were developed based on stakeholder consultations and literature studies:

- Governance
- Water Quality Monitoring
- Data Management
- Capacity Building

Within each of these core component areas, specific strategies will be adopted to strengthen the implementation of the AWaQ program at country and transboundary levels. The AWaQ program governance strategy builds on already existing country governance structures and regulatory provisions through management strategies such as Integrated Water Resources Management and Catchment-Based Water Management. The adopted option for water quality monitoring in the AWaQ program entails collecting basic water quality data to support regional and global indicators. For data management, making use of decentralized national platforms was the adopted option - where countries submit only final national assessments to AMCOW for reporting and planning. Lastly, capacity building would be coordinated through AMCOW, to deliver standardized and tailor-made training courses to Member States.

This framework will be followed by a strategic implementation plan (SIP) that will provide a road map for implementing the AWaQ program. The SIP involves a series of steps, including stakeholder mapping, developing coordination mechanisms, and establishing key progress indicators. Specific

activities under each core component will also be designed to meet the objectives of the AWaQ program.

Contents

AMCOW	African Ministers' Council on Water
AU	African Union
APAGroP	AMCOW Pan-African Groundwater Program
AWaQ	African Water Quality Program
GEMS/Water	Global Environment Monitoring System for Freshwater Programme
IWRM	Integrated Water Resources Management
REC	Regional Economic Commission
RBO	River Basin Organisation
UNEP	United Nations Environment Programme
WQ	Water Quality
WASSMO	Water and Sanitation Sector Monitoring and Reporting System
WWQA	World Water Quality Alliance

ABBREVIATIONS

1. INTRODUCTION

1.1 Project Background

This project prepares the foundations for a new African Water Quality Program (AWaQ). At the invitation of the African Ministers' Council on Water (AMCOW), the International Water Management Institute (IWMI) implemented a study over five phases culminating in a framework for the envisaged AWaQ program. In the first two phases, a situation analysis of water quality monitoring and assessment capacity across Africa highlighted efforts currently undertaken to manage continued deterioration. The next two phases presented water quality monitoring and management innovations that can be considered to advance water quality monitoring and management in Africa. These outputs were stitched into the design of a framework for monitoring and assessing water quality (this document), i.e. the framework for developing the AWaQ program. This framework serves to guide AMCOW in the implementation of a water quality monitoring program across the continent.

The AWaQ program will also provide an African contribution to the monitoring and assessment of water quality at a global level. In this regard, it is supported by the World Water Quality Alliance (WWQA) convened by the United Nations Environment Programme (UNEP), which oversees the periodic World Water Quality Assessment and contributes to understanding emerging water quality issues. Further, the AWaQ will assist in supporting African and global water quality data repositories such as the AMCOW-based Water and Sanitation Sector Monitoring and Reporting System (WASSMO) and the UNEP Global Environment Monitoring System for Freshwater Programme (GEMS/Water), thereby leading to a better understanding and management of water quality across the continent.

1.2 Contextual Background: Water quality monitoring in Africa

Throughout the implementation of this project, the main aim was to determine the key challenges facing African countries concerning water quality monitoring and management and to propose a suitable design framework for the AWaQ program. These efforts were guided by policy frameworks at the African Union (AU) and AMCOW levels (see Box 1) and the supporting studies conducted during the project's implementation. Central to this study was the need to emphasise the importance of the effective use and application of water quality monitoring data to underpin management decisions.

1.2.1 Situation assessment: the need for improved water quality assessment in Africa

In the first two phases of the study[1], an assessment of the state of water quality and monitoring capacity on the African continent was conducted through literature studies, stakeholder consultations supported by an Africa-wide survey and water quality country profiles. The study emphasized the need for the AWaQ program to advance water quality objectives including responding to requests to report on the UN's SDG indicator 6.3.2 on good ambient water quality and the synonymous AMCOW WASSMO indicator (I-4.3). These phases provided background on the status of water quality across African countries with respect to monitoring and management, building a basis for a continent-wide water quality program.

The Africa-wide survey probed laboratory testing capacity, human technical capacity and effectiveness of water quality management efforts and revealed that:

[1] Mukuyu P., Jayathilake N., Tijani M., Nikiema J., Dickens C., Mateo-Sagasta J., Chapman D., Warner S. (2022). State of water quality monitoring and pollution control in Africa: Towards developing an African Water Quality Program (AWaQ). Working Paper 207, International Water Management Institute..

- There is an encouraging availability of national water testing laboratory facilities across African countries. Nonetheless, some weaknesses such as limited laboratory equipment require attention to ensure effectiveness and sustainability.
- Regular and ongoing training is needed to keep up with laboratory testing methodologies. However, we observed a low trend in routine training, which does not augur well for keeping abreast of the best practices in water quality monitoring including quality assurance in the monitoring process. While there are varying degrees of training requirements across the continent, training needs to be more regular than is currently experienced.
- Water quality monitoring and assessment capacities are inconsistent and capacities related to staff training, laboratory infrastructure and monitoring program activities need strengthening.
- Pollution control mechanisms are facing challenges and regulatory mechanisms and wastewater treatment technologies—the most widely deployed pollution control solutions—may benefit from more concerted investment and the political will and financing to boost their effectiveness.

The survey showed that countries are at different levels of implementing monitoring and management programs and that there are extensive financial and technical capacity challenges. Nonetheless, scope exists to develop strong synergies and collaboration across regional initiatives within the proposed AWaQ.

Individual country profiles[2] were developed to show the nuanced water quality challenges in different countries. A common observation is that water quality challenges are real and require immediate and coordinated efforts at the continental, transboundary and national scales to avert a continued deterioration in the continent's water quality situation. Further consultation through a session at the Africa Water Week 2021 showed the importance of transboundary water management and of establishing robust monitoring and data management systems.

1.2.2 Innovations in water quality monitoring and management: potential for Africa

A review[3] of leading, globally tried and tested innovations in water quality monitoring and management led to the identification of potential innovations that can be applied within the African context. Not all innovations are 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 for providing in situ results and lessening the need for laboratory analysis.

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

[2] Country profiles can be viewed here https://bit.ly/3fm7NZR

[3] Mukuyu, P., Warner, S., Chapman, D.V., Jayathilake, N., Dickens, C, Mateo-Sagasta, J. (2022). Innovations in water quality monitoring and management. Towards developing an African Water Quality Program (AWaQ). Working Paper 208. International Water Management Institute.

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 improve subsequent data flows. However, a substantial data gap which proves challenging is the absence of historical data to indicate the reference or baseline conditions and to define the natural state of a water body.

2. A FRAMEWORK FOR THE AFRICA WATER QUALITY PROGRAM

The proposed framework is a foundational structure of ideas and/or concepts, which will guide the formation of a continental water quality program - AWaQ. Thus, in the context of this document, the framework presents only the conceptual structure and does not provide the protocols and detailed plans that would be required for implementation of the AWaQ. It does however present the building blocks toward developing the AWaQ, based on previous studies, and consultations with AMCOW and African water quality experts. As such, the framework can be defined as the foundational basis for developing the AWaQ program. It consists of four components (i) Governance (ii) Water Quality Monitoring (iii) Data Management and (iv) Capacity Development

2.1 Scope

The AWaQ will ideally be a platform where AMCOW can work with Member States to develop the story and narrative around water quality. While of necessity, this would require some level of oversight regarding standard monitoring programs across countries, capacity and laboratory performance, among others. The program is more about interpreting water quality data, helping to inform society about water quality at all levels, including policy development, and thus bettering the lives of all African people and the environment.

2.1.1 Primary stakeholders

African Union Member States will be custodians and implementers of this framework. They will retain ownership of outputs, including the data generated, but in a way coordinated across Africa so that the whole continent can benefit. As such, Member States were consulted to further develop the proposed framework at the Stakeholders' Engagement on AMCOW Strategic Groundwater Program and African Water Quality (AWaQ) Program on the 10th of November 2022 in Dar Es Salaam. During this consultation, a draft of the framework was shared with representatives of the AMCOW Member States who were allowed to provide feedback.

2.1.2 Objective

The main aim of this framework is to guide the AWaQ program's development towards strengthening water quality assessment and monitoring while building the understanding of water quality data and information and helping to mitigate water pollution across African countries.

2.1.3 Key outcomes

Through the implementation of the framework and rollout of the AWaQ, AMCOW will be able to facilitate the coordinated reporting of water quality data to various repositories and formulate continental overviews of water quality. AMCOW can then more assertively communicate the important role of good ambient water quality as related to human and ecosystem health by forming important connections between water quality and observed impacts such as disease outbreaks and loss of biodiversity.

2.1.4 Scale of implementation

The success of AWaQ is supported by national water quality monitoring efforts. While there are initiatives at the transboundary levels, water quality monitoring largely occurs within national boundaries and data is then shared at the basin level. The transboundary and national scales are essential units of analysis and implementation of the AWaQ program. Attention should be paid to strengthening the capacity of national water quality monitoring programs, which, in turn, feed into the basin structures. Basin organizations should play an important role in the strategic direction of water quality monitoring, data management and capacity building.

2.2 Approach to Developing the Framework

A series of steps formed the foundations for developing the framework:

- A situation analysis of the state of Africa's water quality monitoring capacity and management was carried out, and a forward-looking overview of Africa-suitable innovations was presented (see next section).
- A review of existing water quality frameworks across different implementation scales (i) global and regional (ii) transboundary (iii) national, to gain a better understanding of key water quality monitoring and management needs.
- An Africa-wide survey was conducted to solicit input from government representatives of African countries as well as water quality experts across the continent (see next section).
- Individual country profiles were developed for those countries participating in the Africa-wide survey to highlight in-country water quality challenges.
- A session was held at the Africa Water Week 2021 to gain more insights into the challenges encountered in implementing water quality monitoring and management programs at the transboundary level.
- To ensure that this framework aligns with Member States' needs, draft copies were circulated to all Member States, and those present were consulted at the Stakeholders' Engagement on AMCOW Strategic Groundwater Program and African Water Quality Program on the 10th of November 2022 in Dar Es Salaam and were given the opportunity to contribute directly.

At each stage in the framework development process, there was ongoing consultation with AMCOW to ensure alignment with the organization's strategic plans and objectives.

2.2.1 Policy frameworks

The vision and policy objectives on the African continent as presented through the African Union (AU) and AMCOW, provided a basis for the framework. Continental aspirations articulated in the African Union Agenda 2063:The Africa We Want and the Africa Water Vision 2025 are further supported by AMCOW's mission to "*Provide political leadership, policy direction and advocacy in the provision, use and management of water resources for sustainable social and economic development and maintenance of African ecosystems*". Further, AMCOW's strategic objectives in the African Water Resources Management Priority Action Plan (2016-2025) and the Strategic Operation Plan informed the framework and proposed design of the AWaQ program (Box 1).

BOX 1: Guiding Policy Frameworks in Africa	
African Union Agenda 2063[4]	The First Ten Year Implementation Plan (FTYIP) of Agenda 2063 (2013 – 2023) highlights priority areas including Science Technology Innovation Strategy for Africa (STISA). Under STISA, research or innovation areas includes the "Protecting our space" priority through knowledge of the water cycle and river systems as well as river basin management; and "Wealth creation" through managing water resources.
Africa Water Vision 2025[5]	The Vision: "*An Africa where there is an equitable and sustainable use and management of water resources for poverty alleviation, socio-economic development, regional cooperation, and the environment*" It is a Vision of an Africa where: 1. There is sustainable access to safe and adequate water supply and sanitation to meet the basic needs of all; 2. There is sufficient water for food and energy security; 3. Water for sustaining ecosystems and biodiversity is adequate in quantity and quality; 4. Institutions that deal with water resources have been reformed to create an enabling environment for effective and integrated management of water in national and transboundary water basins, including management at the lowest appropriate level; 5. Water basins serve as a basis for regional cooperation and development, and are treated as natural assets for all within such basins; 6. There is an adequate number of motivated and highly skilled water professionals; 7. There is an effective and financially sustainable system for data collection, assessment and dissemination for national and trans-boundary water basins; 8. There are effective and sustainable strategies for addressing natural and man-made water-resources problems, including climate variability and change; 9. Water is financed and priced to promote equity, efficiency, and sustainability; 10. There is political will, public awareness and commitment among all for sustainable water resources management, including the mainstreaming of gender issues and youth concerns and the use of participatory approaches.
African Water Resources Management Priority Action Plan (2016-2025)[6]	Relevant priority action areas include • Improving environmental integrity through wastewater and water quality management • Ensuring water security by managing water pollution • Ensure readiness of AU Member States to achieve SDG 6 and monitor progress towards its targets • Enhance information and knowledge management systems Implementation of these actions is guided by principles such as best practices and the river basin approach.

2.3 Guiding Principles

Three guiding principles were applied in developing a framework for the AWaQ program related to who holds the overall responsibility and benefits from its success.

2.3.1 State-custodianship

Member States remain custodians of water quality data generated during the implementation of the AWaQ Program while at the same time agreeing to share interpreted data and information to develop a trans-African understanding of water quality issues. Member States would need to establish or

[4] African Union Agenda 2063 https://au.int/en/agenda2063/overview
[5] Africa Water Vision 2025 https://bit.ly/3bqfjk6
[6] African Water Resources Management Priority Action Plan (2016-2025) https://bit.ly/3nbwFUq

review national water quality programs in terms of allocated budget and annual work plan to support the implementation of the AWaQ program.

2.3.2 Co-development

The AWaQ program should result from co-development efforts between AMCOW and its Member States to ensure maximum uptake and common goals. Aligning country water quality visions with the vision of the AWaQ is an important first step towards ensuring the program's success. A clear articulation of the importance of a continent-wide initiative on water quality can drive investment in water quality monitoring and management.

2.3.3 Coordination and collaboration

Strategic coordination will be essential so that AWaQ builds on and expands already existing mechanisms such as the reporting requirements of WASSMO, SDG indicator 6.3.2 and UNEP's Global Environment Monitoring System for Freshwater (GEMS/Water) as well as form linkages with programs such as AMCOW Pan-African Groundwater Program (APAGroP). Challenges identified with current efforts to meet the minimum reporting requirements of existing initiatives can form the basis of the AWaQ and potentially bridge the gap. Enhancing the role of partnerships such as Reginal Economic Commissions (RECS) and transboundary basins organizations will further strengthen the program's impact.

3. CORE COMPONENTS OF THE FRAMEWORK

When addressing the continent's multifaceted ambient water quality challenges, there are critical aspects to consider. Based on the findings of Phase 1 and 2 study, four key components were selected to form part of the AWaQ: (i) governance (ii) water quality monitoring (iii) data management and (iv) capacity building. Implementation options for each of the core components were presented to the Member States during a consultative workshop. The final recommended modalities for developing the AWaQ program are highlighted here.

3.1 Component 1: Governance

Across countries in Africa, where the principles of Integrated Water Resources Management (IWRM) have been widely adopted, catchment-based water management institutional structures are well-developed and are operating with varying degrees of success. It is important to note that while IWRM is a widely accepted paradigm, it is not without its shortcomings. Still, it provides a common denominator for managing water resources, including water quality. Building on the general acceptance of IWRM, the governance framework of the AWaQ would build on already existing institutional structures and regulatory provisions aimed towards achieving the goal of improved water quality.

Water quality governance entails special attention to mitigating water pollution and protecting water resources from continued pollution. This framework focuses on water quality monitoring as the foundational step towards understanding water quality, which then informs pollution management. Ensuring a standardized approach is taken in water quality monitoring (i.e. for reporting, sampling and analysis and setting water quality standards) enables a common interpretation of water quality across Africa At the country level, water quality governance requires enforcing pollution control regulations through issuing licenses and permits. Of importance is ensuring that such provisions and directives are enforced, for them to have the desired impact. Resource-constrained environments such as those witnessed in Africa generally suffer in this regard.

Also crucial in water quality governance is the consideration of the knowledge and values of water quality to society, the natural human processes and the human institutions and systems and how these interact with water quality. Diverse actors need to be considered in the AWaQ program to ensure active participation across all spheres of society such as the private sector and civil society.

3.1.1 Governance in the AWaQ program

AMCOW promotes the AWaQ program as a platform for coordinating water quality monitoring for Africa and will continue to oversee its implementation. AMCOW will provide direction for implementing the AWaQ at a country level (while coordinating with regional and transboundary institutions) and coordinate the Africa-wide development of knowledge and the collation of reports. Member States will contribute to AWaQ through established AMCOW structures, including WASSMO and APAGroP. Further, Member States may also engage with communities to collect certain types of data most relevant at a community scale. Nonetheless, such procedures will likely differ in each country. The adopted AWaQ governance structure places the Member States at the centre, while AMCOW provides the framework for participation and the overall coordination and management of program outputs.

3.2 Component 2: Water Quality Monitoring

The basis for improving water quality lies in the strength of the monitoring program. The water quality monitoring strategy under this framework harmonizes operational guidelines for water quality monitoring (i.e. testing and monitoring methods) for a standardized approach. Further stipulating water quality standards and the minimum testing requirements in line with the other existing water-related program (e.g. SDG 6.3.2, WASSMO I4.3, GEMS/Water etc.) will consolidate and strengthen synergies across continental initiatives. Innovations in water quality monitoring (Box 2) can guide Member States in selecting the best options that will work best in their context.

Figure 1 outlines monitoring activities that should form part of the AWaQ, the interconnected nature of these actions and the scale of intervention.

1. ***Water quality in the African context*** Given the many water quality challenges, African countries should develop water quality objectives to preserve ambient water quality for the benefit of people and the environment.
    a. ***Water quality objectives*** can be defined for specific and strategic river systems to guide policies that address the delicate balance between water use and managing pollution for humans and natural ecosystems.
2. ***Water quality monitoring plans*** include establishing water quality monitoring guidelines, standards and laboratory testing and certification. Such plans should also address staff capacity to conduct water quality monitoring including laboratory testing**.**
3. ***Implement water quality monitoring*** considering the available innovations in monitoring technologies, including the development of capacity in laboratory assessment. A diversity of innovations applicable in Africa are presented by Mukuyu et al. (2022).
4. ***Data management systems*** need to manage and coordinate data generated through monitoring efforts so that they are applied and interpreted meaningfully. Developing in-country data management systems, and capacity for interpretation is a critical step to ensure data are not lost in 'data graveyards' but are used to inform decision-making and ultimately improve water quality.
5. ***Reporting data*** from in-country data repositories are linked to existing data networks including WASSMO and GEMS/Water. The AWaQ program should also facilitate the

development of useful knowledge emanating from the data that could be used to improve the situation for the environment and society.

Feedback from monitoring efforts informs capacity-building initiatives and required governance structures. Building technical staff's capacity to interpret data for translation into management actions is critical to deriving benefits from generated data for in-country policy and operational decisions and regional responses. Processing ambient water quality data further facilitates identifying and tracking polluted water bodies and provides a feedback loop for response mechanisms.

3.2.1 Water quality monitoring in the AWaQ program

Options for enhancing water quality monitoring activities were presented to AMCOW and represented Member States. The option to collect only basic water quality data was selected as most appropriate for rollout within the AWaQ. Under this proposed option, a monitoring program that provides basic data in support of regional and global indicators, such as WASSMO Indicator I4.3, and SDG indicator 6.3.2 would be advanced, covering the main impacts on water quality, such as excess nutrients, oxygen depletion and salinization. A key ambition should be the collection of reliable and standardized water quality data at the national or river basin level that helps to better the water quality situation in countries and can feed into larger data repositories.

Collection of basic water quality data to support regional global indicators thus bringing Member States to a basic minimum standard.

Innovations in water quality monitoring are encouraged for application across the region. Innovations such as citizen science and the use of biological indices, are potentially affordable in most countries and could be built into existing national water quality monitoring programs to enhance regional assessment of water quality.

Box 2: Examples of water quality monitoring innovations with high potential for uptake in Africa[7]
Monitoring program network design • Satellite imagery to identify monitoring locations reduce the time to visit and select locations. High-resolution imagery is available free from Google Earth • HydroBASINS: Network design for river catchments useful for the initial selection of monitoring locations • Co-location of hydrometric and water quality monitoring locations facilitates the calculation of loads/fluxes. This may require cooperation between two different government agencies and data sharing *Sample collection and field analyses* • Multi-parameter sensors for basic water quality variables provide in situ results; no requirement for laboratory analysis. Widely available and affordable albeit with a limited range of parameters. • Field kits and portable instruments for measuring water quality parameters in the field, e.g., N, P, turbidity, faecal coliform. Useful for remote locations; results available on-site. There is a limited range of parameters that can be tested. Accuracy and precision are often not as

[7] Adapted from: Mukuyu, P., Warner, S., Chapman, D.V., Jayathilake, N., Dickens, C, Mateo-Sagasta, J. (2022). Innovations in water quality monitoring and management. Towards developing an African Water Quality Program (AWaQ). Working Paper 208. International Water Management Institute.

good as equivalent laboratory analyses, although there is continuous improvement in current technologies.

Laboratory analysis

- Standardized methods enable comparability between monitoring locations and laboratories performing analyses. Standards are readily available for different levels of analytical complexity.
- Multiple parameter analytical instruments allow for the reduction in sampling and sample processing. Increased laboratory throughput. Resource dependent; suitable training and maintenance contracts are essential to ensure the impact of high-end equipment is maximized

Biological monitoring

- Biotic index based on selected indicator organisms, primarily benthic macroinvertebrates and diatoms. Indicators of the general health of freshwater ecosystems. Existing systems can be refined for national use
- Contaminant monitoring in fish and crustaceans. Bioaccumulation of contaminants in human food species; confirmation of the presence of contaminants when concentrations in the water are below analytical detection limits. Useful for heavy metals in mining areas and persistent organic compounds
- Microbiological monitoring identifies risks to human health during recreation or when used as a drinking water source. Field kits available for use in remote locations; economic laboratory methods

Citizen/community monitoring

- Physical and chemical monitoring with simple kits and data upload by mobile phone offer potential for greater spatial and temporal monitoring coverage than can be achieved by national agencies. These kits also provide supplemental data for national and international monitoring. It however requires training for local communities to ensure reliable data collection; regular engagement and feedback are necessary
- Optical measurements for lakes using smartphones validate satellite data. However, training and coordination are required as well as the availability of mobile data networks
- Fish kill and algal bloom recording with smartphone apps assist in identifying localized pollution incidents and protect public health. 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. Can be tailored to local species for improved reliability

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. Satellite data is freely available. Requires trained personnel and dedicated in situ validation monitoring.

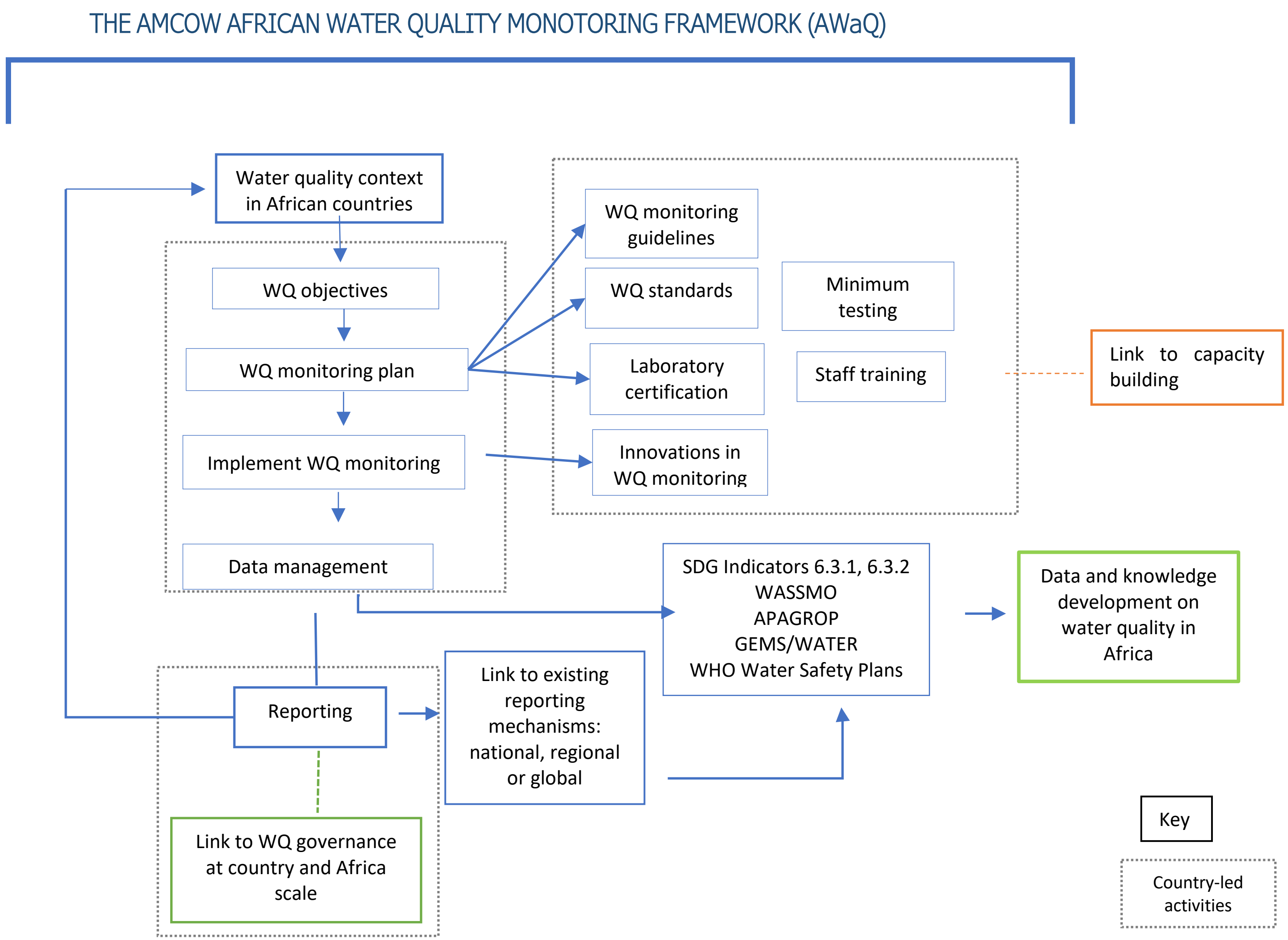

Figure 1: Framework for the AWaQ program water quality monitoring component showing links to capacity building, data and water quality management

3.3 Component 3: Data Management

Generating appropriate water quality data to enable decision-making is a critical focus dependent on well-designed monitoring programs and data management systems. Adequate data generated from strategic water bodies and channelled through robust information systems that tell the stories of water quality in Africa, can enable better-integrated decision-making and feed into overall regional and global reporting programs such as WASSMO and SDG 6. Weaknesses in water quality monitoring program design, data management systems, as well as the capacity to conduct monitoring activities and interpret the data, were identified by most African countries as key areas that need to be addressed.

Applying standard data management practices throughout all stages of the data management cycle will be central to the success of the AWaQ program. This includes defining protocols around data recording, inputting, retrieval and archiving and applying common data standards to management. This will allow assessment at multiple scales to be performed, ensuring the maximum amount of information is extracted from the valuable data collected. Emphasis should be placed on processing data into actionable information for effective decision-making.

There are some essential aspects to be considered in a data management strategy:

- Application of common data management standards (for example, data types, code lists, file formats, dictionaries) [8]
- Development of common data management practices (for example, approaches to quality assurance and quality control, data sharing), e.g. through national data management policies
- Delineation of Africa-wide river-basin water management units (and possibly smaller water body units).
- Addressing capacity requirements in data management
- Establishing principles of intra- and international data sharing

3.3.1 Data management in the AWaQ program

Of the proposed data management strategies, the selected[9] option requires no central water quality portal, but countries submit only final national assessments to AMCOW for reporting and planning purposes. Established national data platforms will form the basis of the strategy. Given that the ultimate aim is for AMCOW to have a complete regional appreciation of water quality trends, this selection was deemed as most suitable to provide such a broad overview. While this strategy would be straightforward to implement across African countries and requires minimum data storage at the centralized scale, there is a risk for limited participation, as is observed in the current WASSMO I4.3 and SDG 6.3.2 reporting. This reporting lethargy will detract from developing the full picture of the continent's water quality and how human and ecosystem health are impacted across the region.

Decentralised national platforms with no central Africa water quality portal. Countries submit only final national assessments to AMCOW for reporting and planning

Success stories developed from the water quality assessment information submitted by Member States can lead to unlocking funding that can be channelled

[8] https://www.ogc.org/standards/waterml.

[9] Selected through consultation with Member States at the Stakeholder engagement meeting in Dar es Salaam, November 2022

towards strengthening water quality monitoring programs, potentially leading to greater participation in the AWaQ by Member States.

Managing water quality data in a manner that supports decision-making and triggers the appropriate response is an adaptive process. While there is a general appreciation of the importance of water quality monitoring, African countries at different implementation levels and data management systems differ in operational design and function. Given the current complexities and contextual challenges around data management, the following considerations may be necessary to understand in implementing a continent-wide initiative such as the AWaQ program.

- A phased approach is essential for reaching optimal standards and bringing countries up to a minimum operational level.
- Harmonizing existing data management systems in the Member States will ensure better reporting.
- Information sharing among Member States will help in identifying gaps and emerging water quality issues. This will provide guidance for future and targeted capacity development activities.

3.4 Component 4: Capacity Development

AMCOW identified capacity development[10] as a critical feature within the AWaQ program with two important aspects to consider:

- Translating data into knowledge and information is most important if there is to be a change of attitude to water quality issues across Africa – one possible way to do this is to build stories to convey the meaning of water testing data.
- Capacity building is key. Country capacities should be enhanced in terms of monitoring, laboratory testing and interpretation of data, among others.

The AWaQ program will establish ongoing and effective capacity development programs at all levels (national, local, basin, civil society etc.). The AMCOW-IWMI (2020) survey carried out in preparation for the AWaQ framework's development revealed a substantial need for capacity development. Capacity development programs can cover a wide range of activities, including:

- training and education in water quality monitoring including fieldwork, water sampling and onsite testing,
- developing the capacity of water utilities and private laboratories, including handling and maintenance of laboratory equipment, data management and reporting, leading to laboratory accreditation and certification,
- establishing citizen science monitoring in local communities,
- integrating WQ monitoring elements into education systems as appropriate (primary, secondary, university education), and
- interpretation of water quality data and how this data tells stories of water quality, its impact on the environment and society and most importantly, exactly what this means for the people of Africa. Such capacity development is key, not only for citizens but for policymakers who need to appreciate the evidence in drafting policy and management plans.

[10] During a meeting with the project team (24/5/22)

3.4.1 Priority areas for capacity development

During the discussions at the stakeholder engagement meeting, Member States identified areas for immediate capacity development as follows:

- Sophisticated and modern laboratory equipment and trained experts
- Training of water quality experts
- Real-time water quality data equipment
- Funding the design/redesign of water quality monitoring programs
- Support the use of water quality models and other water quality data management systems
- Support the sustainability of laboratory equipment including operation and maintenance

Additional areas for training include:

- Monitoring network design and network evaluation
- Incorporating biological indices into ambient water quality assessment
- Incorporating citizen science into ambient water quality assessment
- Using remote sensing data for water quality monitoring – current and future potential
- Quality assurance in water quality monitoring activities in the field and laboratory

It is important to make linkages to the existing capacity building and data collection platforms such as SDG indicator 6.3.2, WASSMO, APAGROP, GEMS/Water, etc. Another important aspect is to identify existing steering committees associated with water quality, water resources, river basin management, IWRM and water safety plans especially in facilitating the capacity development programs. Individual countries should essentially conduct capacity needs assessments to identify the real need before designing their capacity development program to best suit a country's context.

3.4.2 Capacity development in the AWaQ program

Within the various activities involved in water quality monitoring and assessment, there is a need to strengthen and develop human and technical capacities. For the AWaQ program, Member States supported capacity development coordinated through AMCOW, meaning AMCOW would select training courses tailored to suit the agreed final monitoring and management strategy, thereby providing a standardized Africa-wide approach. Further, multiple repeats of the same training courses can be cost-efficient, and AMCOW can potentially engage large donors to fund these activities. While this approach is desirable, AMCOW would be responsible for coordinating the training programs. The alternative option for countries to source training courses independently would lessen this responsibility on AMCOW. However, the quality and level of training would depend on the country's ability to fund it. The lack of a standardized approach could lead to variations in knowledge and practices.

AMCOW selects and coordinates training, providing a standardised Africa-wide approach

AMCOW's role in coordinating this capacity-building component of the AWaQ may be vital for knowledge sharing across water quality professionals, further enabling the development of young professionals in the field.

4. OPERATIONALIZING THE FRAMEWORK

Translating the framework into a functional Africa-wide water quality program with associated protocols would require coordination at multiple levels, including the regional (through AMCOW), transboundary (through basin organizations) and national governments. Structured coordination channels and mechanisms are thus critical for the program's success, highlighting synergies across various initiatives implemented on the continent and harnessing solutions and data generated through these efforts. There is scope for the involvement of specialists to develop guidelines and protocols that address identified areas of the framework and can be shared between Member States. This section proposes the immediate next step in this framework's operationalization and rollout of the AWaQ program.

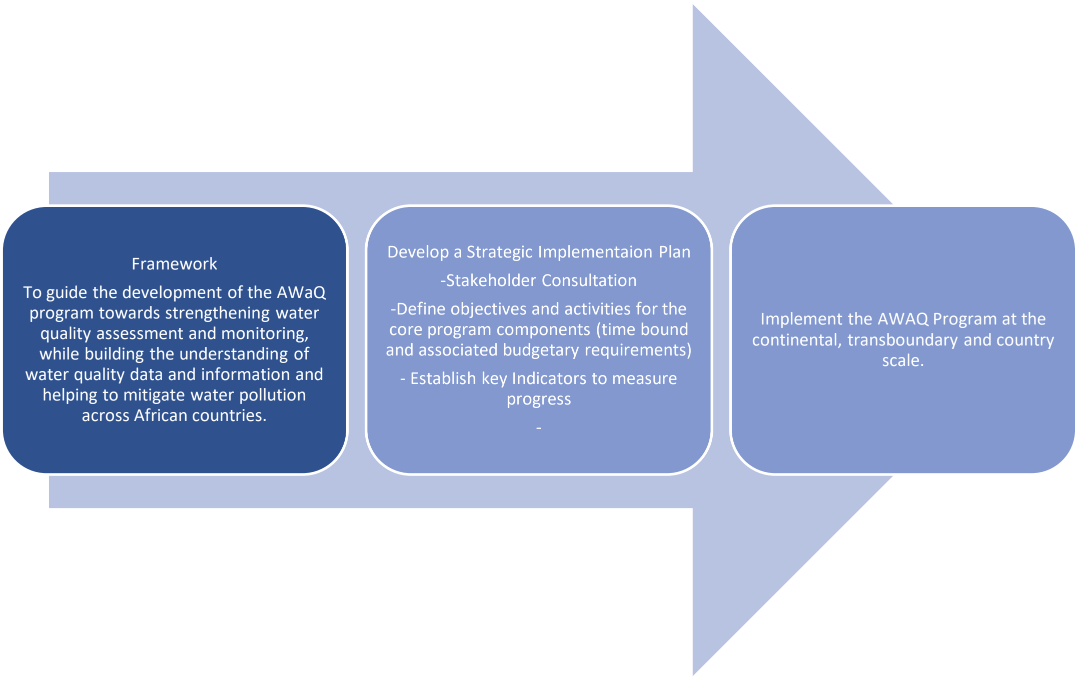

Figure 2: Progress towards implementing the AWaQ Program (i) developing the framework (ii) developing the strategic implementation plan (iii) implementing the program at continental, transboundary and country scales.

4.1 Strategic Implementation Plan

Developing an implementation plan provides a time-bound road map for operationalizing this framework and implementing the AWAQ. The plan should clearly set out the role of various institutions and how they feed into the AWaQ, for example, basin organizations (RBOs) and regional economic commissions (RECs). Further, the plan can define specific activities under the core components presented in this framework (i.e. Governance, Data Management, Water Quality Monitoring and Capacity Building), possible financing mechanisms and indicators for success.

4.1.1 Role of AMCOW, Member States, RBOs and supporting organizations

As pointed out in preceding sections, AMCOW will play a facilitating and coordinating role across the four components of the framework. Through this oversight, AMCOW will develop and implement suitable coordination mechanisms in the governance of AWaQ among the various initiatives, stakeholders and regional institutions; facilitating the flow of water quality information from Member Countries through available platforms such as WASSMO. This information will form the basis for developing water quality stories across Africa to highlight water quality issues in African countries and to attract funding. Further, AMCOW will coordinate capacity-building activities to deliver harmonized training programs, tailored to different country needs. As the main beneficiaries of this program, Member States will, through their formal association with AMCOW implement proposed activities and interventions, both at the river basin and country levels.

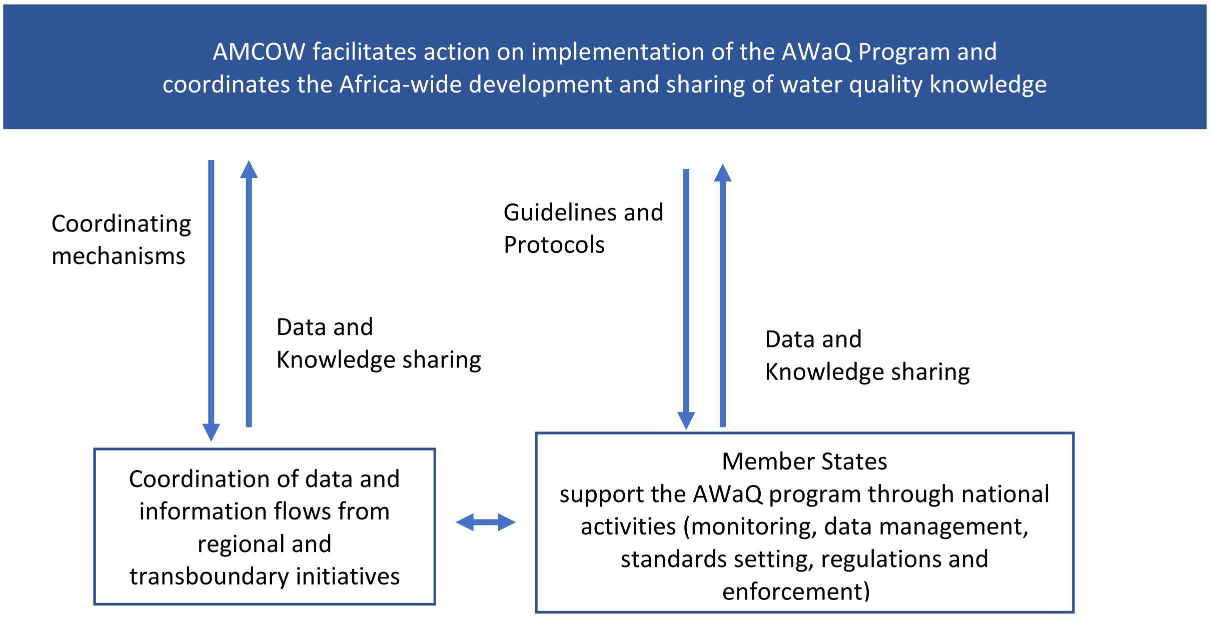

Figure 3: AMCOW, Member States and regional organisations' involvement in the AWaQ program

4.1.2 Activities in preparation of program implementation

During the consultation with AMCOW Member States, it was noted that specific activities must be undertaken to prepare the program for successful implementation. These include (i) stakeholder mapping and establishing coordinating mechanisms (ii) consensus on priority data and/or information that should form part of AWaQ (iii) a performance evaluation of the WASSMO platform on how it can best support the demands of the AWaQ program. This evaluation would address the bottlenecks Member States currently encounter in using the platform and (iv) country capacity building needs assessments that will inform the design and tailor-making of training programs by grouping countries with similar needs for targeted training.

4.1.3 Financing for the AWaQ program

Implementing the AWaQ program at a country level requires financing, and AMCOW can play a central role in attracting funding for program activities. Given the current climate crisis and its impact on water quality, unlocking the potential for leveraging climate finance would be an essential avenue to explore.

5. SOURCE DOCUMENTS

1. Mukuyu P., Jayathilake N., Tijani M., Nikiema J., Dickens C., Mateo-Sagasta J., Chapman D., Warner S. (2022). State of water quality monitoring and pollution control in Africa: Towards developing an African Water Quality Program (AWaQ). Working Paper 207, International Water Management Institute.
2. Mukuyu P., Warner S., Chapman D.V., Jayathilake N., Dickens C, Mateo-Sagasta, J. (2021). Innovations in water quality monitoring and management. Towards developing an African Water Quality Program (AWaQ). Working Paper 208, International Water Management Institute.
3. Country profiles documenting the state of water quality monitoring can be viewed here https://bit.ly/3fm7NZR