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Primer

The Role of Water Quality Monitoring in the Sustainable Use of Ambient Waters

Authors: Deborah V. Chapman and Timothy Sullivan

UNEP GEMS/Water Capacity Development Centre, Environmental Research Institute and School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland

d.chapman@ucc.ie (corresponding author)
timothy.sullivan@ucc.ie

Summary

It is abundantly evident among domain experts that human activities are profoundly shifting the health and functioning of freshwater ecosystems away from their natural state. Aquatic ecosystems are suffering biodiversity loss, and increasingly act as a sink and conduit for anthropogenic pollution. The detailed extent and impact of this remains unclear due to major deficits in our capability, capacity, and willingness to adequately monitor ambient water quality at scale. To reverse this trend, and to understand our ability to restore and return ambient water bodies to a more sustainable baseline, we need to make a societal commitment to increase our monitoring of freshwaters globally. In this Primer we discuss the current status, gaps, and future needs for coordinated water monitoring programmes ~~at scale~~. In the absence of sustained periodic monitoring, intervention and management, the health of aquatic ecosystems and environments, and consequently our own health, prosperity, and wellbeing, will be permanently and irreversibly damaged.

Why do we need water quality monitoring?

It is an often-stated axiom that 'water is life' or that 'water is essential to life', yet the *quality* of that water is often neglected in the face of issues of water quantity and supply. Despite this, it is thought that much of our global freshwater resources are now greatly altered from their natural state, and indeed are often severely polluted, by human activities. Freshwater is used for many purposes, including provision of water for drinking and irrigation, recreational and commercial fisheries, transport of people and goods, and assimilation of wastewater discharges. Some uses have specific requirements for water quality and the water must be monitored before use to ensure it meets the set quality criteria, which are often defined by regulations and standards. A typical example is the protection of human health by ensuring that all water used for drinking or other domestic activities is free of pathogens or elevated concentrations of potentially toxic compounds. Almost all uses lead to impacts on water quality to some extent and therefore monitoring these impacts is required to ensure appropriate management that protects both the aquatic ecosystem and the health of the populations using the water body (Figure 1).

Human populations regularly introduce excess organic matter (typically sewage and domestic wastewater), excess nutrients (e.g., from sewage and fertilizers), and synthetic chemicals like pesticides, herbicides, and personal care products, as well as oils (polyaromatic hydrocarbons) amongst many other materials, into groundwaters and surface waters. We now know that some of these materials and synthetic compounds, like some highly fluorinated compounds for example, or metals like lead, cadmium, or mercury, can persist for decades or longer in freshwaters, and regularly enter our food chain and can severely impact ecological functioning. In tandem with this, human activities that result in landscape scale changes, untreated 'wastewater' release, deforestation, mining and extraction activities (like sand mining) regularly alter natural processes, and the natural balance of sediments or organic matter in freshwaters. Other activities, like extensive and intensive crop irrigation raise salinity levels, and global changes like sea level rise coupled with over-abstraction cause saltwater intrusion into freshwaters in coastal zones around the globe.

From a human population perspective, those regions of the globe with sufficient economic resources can implement technological solutions to treat polluted surface and groundwaters so that water is fit for human consumption (i.e., potable water) and is of sufficient standard for many other industrial or societal needs and activities. On the other side of human water use, advanced technological solutions exist to treat freshwaters that have been used for human needs and released back into the environment (so-called 'wastewaters'). Treated wastewaters can be returned to the environment in a largely unpolluted state, or at least sufficiently unpolluted as to not cause undue harm in the environment. However, not only do some of these technologies use large amounts energy, which presents a dilemma for sustainable use of earth's resources, but many communities globally currently lack the infrastructure and resources to implement these technological solutions at scale. As a result, much of the freshwater that has been used for human activities is still discarded to the environment in a polluted state. This damages freshwater ecosystems and all life that depends on them, including human societies, human health and the very economic development that could lead to improved water and wastewater management.

Unfortunately, it is currently very difficult to give precise statistics on how polluted or impacted freshwaters are by human activity at a global scale, simply because the quality of many freshwater bodies globally has not been, and remains, unmonitored. Ideally, the health of all freshwater bodies (including rivers, lakes and groundwaters) should be monitored to some degree to ensure sustainable use, and to safeguard the ecological communities and human populations which depend on high quality freshwater. The effectiveness of any management activities can only be determined by monitoring the water quality before, during and after the management is implemented.

It has been said that 'that which cannot be monitored, cannot be (effectively) managed': and it is our contention that effective monitoring of global freshwaters is a prerequisite for sustainable development, healthy societies, and a healthy environment. Indeed, the importance of guaranteed availability of good quality water supplies as a prerequisite to stable, equitable and sustainable societies, has been recognised in the United Nations (UN) Sustainable Development Goals (SDGs). The 2030 Agenda for Sustainable Development, "*a plan of action for people, planet and prosperity*" with its 17 Sustainable Development Goals (SDGs), is measuring progress towards 2030 using indicators, many of which involve some form of monitoring. Directly reflecting the fundamental importance of water resources, SDG 6 (known informally as 'the water goal') aims to "*ensure availability and sustainable management of water and sanitation for all*". It recognizes the extent to which human and environmental health, as well as economic prosperity, rely on access to safe water supplies and sanitation facilities stemming from the proper management of freshwater resources. Target 6.3 requires that countries improve water quality by reducing pollution, increasing recycling, and ensuring proper treatment of wastewater, among other measures. Progress towards achieving target 6.3 is measured using information provided by indicator 6.3.2 on the "*proportion of bodies of water with good ambient water quality*". Data for indicator 6.3.2 are gathered through water quality monitoring programmes at national level.

What do we mean by 'water quality monitoring'?

Insufficient (or lack of any) wastewater treatment infrastructure, certain intensive agriculture practices, agricultural runoff, inadequate or ineffective regulation of industrial emissions (as point or diffuse sources), or even legacy contamination from past conflict or industrial activities, are widespread factors in declining ambient water quality across the globe. Evidence, however, in the form of monitoring is often lacking in many countries. Local reasons for deteriorating water quality may be pinpointed by adjacent communities but may not be detected by traditional state-led monitoring activities. A lack of public awareness or education initiatives on the importance of good ambient water quality, means that effective management action at local level rarely occurs and community groups may lack knowledge or tools to collect and present objective evidence for action (Figure 2). This is an overarching challenge because, at global scale, ambient water quality and water resources are monitored infrequently, and sometimes not at all, and where monitoring is carried out, it often lacks the spatial or temporal resolution required for evidence-based management decisions. This means that it is often impossible to understand the true scale and impact of different policies on ambient water quality, or to estimate the extent and impact of different pressures, or effectively estimate the resources required to implement solutions.

Against this backdrop, the purpose of water quality monitoring is to collect specific data at set locations and times that indicate the physical, chemical and/or biological condition of a water body (be that groundwater or surface water). In an ideal world, those data are then converted into useful information, allowing evidence-based management decisions to address different aspects of water quality. Important information that can be generated by a well-run water quality monitoring programme include trends in water quality, identification of critical factors affecting water quality, the effectiveness of remediation measures, the impacts of wastewaters, and the overall status and health of the aquatic environment at national or even global scales. The combination of measurements made, and the spatial and temporal scales at which they are carried out, should be governed by the specific objectives of a particular monitoring programme. Whatever the purpose, or level of complexity of a monitoring programme, there are a few common factors that are necessary to ensure that water quality monitoring generates data that are fit for purpose. These include:

- Clear specification and agreement on monitoring objectives, including the expected outputs for management purposes.
- Transparent selection of the monitoring approaches, together with the specific parameters and methods to be used in the field and laboratory.
- Consideration of any potential constraints on field and laboratory activities, such as access to sampling sites, equipment, and human and financial resources.
- Critical selection of sampling locations, taking into consideration any potential natural and anthropogenic influences on water quality at the chosen locations.
- Appropriate frequency of measurements (sampling frequency) for each parameter, taking into consideration any natural variations, e.g., seasonal, as well as variations caused by anthropogenic influences, such as periodic effluent discharges or seasonal use of agricultural chemicals.
- The need for storage, recording and sharing of monitoring data, and a plan for how the data will be analysed and presented to users.
- Clear, precise, and well documented quality assurance procedures for field and laboratory activities, and for the management of the monitoring data.

Most water quality monitoring programmes measure a few key parameters that indicate the geological and climatological influences on water quality (such as temperature, oxygen concentrations, dissolved salts and nutrients) to which are added parameters that are related to specific issues (e.g., toxic compounds), known impacts (e.g., biochemical oxygen demand), or quality requirements specified by target values or guidelines (e.g., nitrate in drinking water). In a comprehensive water quality monitoring programme, for example of a river in an urbanized and industrialised catchment, this could mean that more than 500 different measurements could be needed. Due to financial constraints, key choices (and often compromises) are usually made in order to reduce the burden on human and technical resources. These can include:

- measuring certain parameters at a reduced frequency compared with others,
- using indicator parameters, e.g., thermotolerant coliforms rather than the full range of potential human waterborne pathogens, or conductivity to represent the presence of dissolved salts and other inorganic chemicals, and
- using alternative methods, such as biological approaches, to indicate non-specific water quality deterioration and to highlight when additional monitoring with specific parameters may be needed.

Leveraging information and communication technology, measurements of key aspects of water quality can now be automated and produced in (near) real-time using water quality sensors placed permanently or temporarily within an aquatic system (Figure 3A). However, this option remains limited and is only readily available at present for a small number of physical and chemical parameters, such as dissolved oxygen, conductivity and nitrate. Most water quality measurements still involve a water scientist visiting a water body, making a few in-situ measurements (Figure 3B), and taking samples of water (Figure 3C) which are then transported back to a laboratory, where a wide range of analyses can then be performed to a high level of accuracy. Of course, this approach only provides a snapshot of water quality at the precise moment in time and exact location where the sample was taken, and it is also vulnerable to the introduction of errors during sampling and transport that can lead to some uncertainty in the final reported analytical result. Strict quality assurance procedures are therefore essential for all steps of the process from taking the sample to final analysis.

Whilst it is relatively straightforward for countries to implement standardised monitoring procedures at national level, it becomes much more difficult for transboundary water bodies involving co-operation for several different monitoring agencies with different capabilities and technical capacities. To determine and track the quality of ambient freshwaters globally, SDG indicator 6.3.2 requires countries worldwide to monitor five cheaply and easily measured water quality characteristics in all, or selected, water bodies in each country on an annual basis. The monitoring parameters were deliberately chosen to facilitate low-income countries with limited monitoring resources, and countries for which no ambient monitoring programme already existed. Although the global participation in monitoring for SDG indicator 6.3.2 has increased since its roll-out in 2017, the recent data report shows that there is still a lack of adequate monitoring for ambient water quality globally, especially in low-income countries.

In recent decades, greater recognition of the need to protect and restore freshwater ecosystems for the benefits they provide to society, has resulted in growth in monitoring approaches that include the biological components of the ecosystem. There are now several well-established biological methods for monitoring water quality. The most widely used approach involves identification and quantification of species and communities present in the waterbody (Figure 3D). This approach is based on the principle that aquatic organisms have specific tolerances or preferences for certain physical and/or chemical characteristics of their environment, i.e., the water quality. Changes in the presence and abundance of particular species, or groups of species, within a community can suggest a departure from the natural water quality. Some contaminants can be accumulated in the tissues of organisms to concentrations that are much higher than the water in which they live and may, therefore, enable detection of the contaminants more easily than by analysing water samples. Analysing contaminants in specific tissues of biota, such as fish, is also useful where there is a potential risk to human health from ingestion of aquatic organisms. In-situ or laboratory-based bioassays that detect the potential presence of contaminants by observing impacts on specific species, such as survival or reproduction rates, are particularly useful if there are complex mixtures of contaminants present in the water.

Recent improvements in the spatial resolution and availability of satellite data are leading to increased use of spectral data for monitoring water quality. At present, satellite monitoring is limited to a few water quality parameters (e.g., chlorophyll, turbidity, suspended solids) in large lakes, although progress is being made at finer resolutions. Confidence in the utility of satellites for monitoring water quality is also hampered by a lack of in-situ data for validation of the satellite data. This means that together with the restricted range of measurements that are possible with satellites, their potential to fulfil the increasingly complex needs of water quality monitoring are likely to remain limited, and in situ monitoring will always be required. Nevertheless, many countries with available resources are beginning to incorporate, or consider how to incorporate, satellite monitoring into their national monitoring strategies.

The need for water quality monitoring at scale

The enormous human and technical resources needed for complex monitoring programmes are driving research for simpler, or more economical approaches to making water quality measurements, while at the same time trying to meet the increasing needs for more reliable instruments with greater levels of accuracy and precision. Improvements and innovations in recent decades have focussed on the technology used for monitoring to increase temporal or spatial coverage with less use of resources. Aside from remote sensing and satellite measurements mentioned previously, recent improvements include the accuracy and range of parameters for in-situ sensors, the advent of near real-time continuous monitoring, facilitated by sensor networks sharing data through advanced communication strategies, through the internet of things (IoT). Modern monitoring programmes generate huge amounts of data that need to be organized, interpreted, and presented for the anticipated users, i.e., water resource managers, policy makers and public. These data frequently need to be shared with different organisations for different uses, making an efficient and interoperable data management system essential. Sharing water quality data is especially critical for the management of international and transboundary water bodies and for determining water quality at global scale. The GEMS/Water global water quality monitoring programme was established in the 1970s to encourage ambient water quality monitoring and to gather the necessary data for global management of freshwater resources by producing global water quality assessments. It has been collecting water quality data for nearly five decades and sharing them through the global water quality database, GEMStat. Since 2017, it has also been supporting countries in monitoring and reporting their ambient water quality for SDG indicator 6.3.2.

It must be emphasised however that technological improvements are not a panacea to the challenges of global water quality monitoring. Very often such technology is not always universally available or suitable (in many cases due to financial or political constraints), and more focus is needed on monitoring approaches that meet all needs. Currently, the potential for using citizens and communities for water quality monitoring is receiving much attention. Many citizens have a vested interest in their local water bodies, i.e., they use them as drinking water for themselves and/or their livestock, for crop irrigation, or for fishing as a source of food or recreation for example. Engaging citizens in monitoring their local water bodies raises awareness and provides them with knowledge and information that can be used to manage their water quality at community level. Data generated can also be used as a supplemental source of data for national and regional level water quality monitoring activities and is encouraged for SDG indicator 6.3.2 for ambient water quality to help fill data gaps in resource-limited countries. One of the most successful uses of citizen monitoring is in 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 App which shares the data openly through an associated on-line data hub. The data can then be used by regulatory bodies and other water-related organisations for management purposes.

Water quality monitoring in the 21st Century

Financial support at a scale that can be considered adequate for widespread monitoring of ambient water quality is still rare across much of the globe, with the possible exception of water resources that are explicitly used as sources of drinking water. Reluctance to adequately finance ambient water quality monitoring can also often still be attributed to a fundamental lack of understanding or appreciation of the extent to which natural water resources play a vital role in the socio-economic development, stability, wellbeing, and overall health of our societies. Until there is a greater understanding and global appreciation of the critical role of good ambient water quality, especially in water scarce regions, improvements to water quality monitoring at global scale will remain very slow. Building a momentum around citizen monitoring could help to drive a bottom-up change in attitude to the benefits of ambient water quality monitoring and more efficient water resource management.

Improvements in the technology associated with water quality monitoring are needed at both ends of the scale of complexity, but always with the ambition of reducing the associated costs. Water quality monitoring at the global scale could greatly benefit from easy-to-use, low cost, precise, accurate and reliable sensors that facilitate rapid in-situ measurements, and that can take advantage of rapidly evolving data transmission and storage methods. Unfortunately, these devices and instruments are still not widely available for most aspects of water quality that we would wish to measure. In contrast, there is an ever-growing number of aquatic contaminants that pose an established or potential risk to the ecosystem and human health. These often now include potent synthetic compounds that can still have a significant impact at barely detectable concentrations, and which require more sensitive sample preparation techniques and instrumentation with lower detection limits. Such compounds challenge analytical capabilities, even in countries with established and well-resourced monitoring programmes.

It must be stated that the collection of water quality data is a potential waste of resources, unless those data are converted into useful information that is accessible, understandable and actionable for managers, policy makers or the public. Reliable and accurate water quality data are an essential component of the information needed for freshwater resources management, in conjunction with the appropriate hydrological information, such as water level and discharge, and the engagement of all stakeholders, including direct and indirect users. Water quality management is most effective if applied at catchment scale based on the principles of Integrated Water Resources Management (IWRM), as is being encouraged for SDG 6. Water quality monitoring is fundamental to the success of IWRM. To meet the needs of sustainable development and the goals of Agenda 2030, researchers and developers are faced with the significant challenge of making water quality monitoring available and affordable for all countries worldwide.

Recommended reading

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Figure Titles/Captions:

Figure 1 Water quality monitoring is an essential activity for society and the freshwater ecosystem. Ambient water quality directly or indirectly influences much of human society, for example, in the provision of drinking water, the production of food, and in the requirements for a stable, equitable and healthy society. It also influences the overall quality and health of our environment, biodiversity, and biogeochemical processes.

Figure 2 A. Ambient waters should be of good quality, abundant and uninfluenced by human activities. B. There is a general lack of public awareness of the criteria for good ambient water quality.

Figure 3 Typical approaches to water quality involve: A. Water sensors located in the water body that provide continuous, near real-time data; B. Making in-situ measurements with a sensor; C. Taking a grab sample for later analysis in the laboratory (Credit P. Cross); D. Examining the aquatic communities present in a sample. Images A, B, D (Credit D. Chapman, reprinted from Chapman et al., 2021