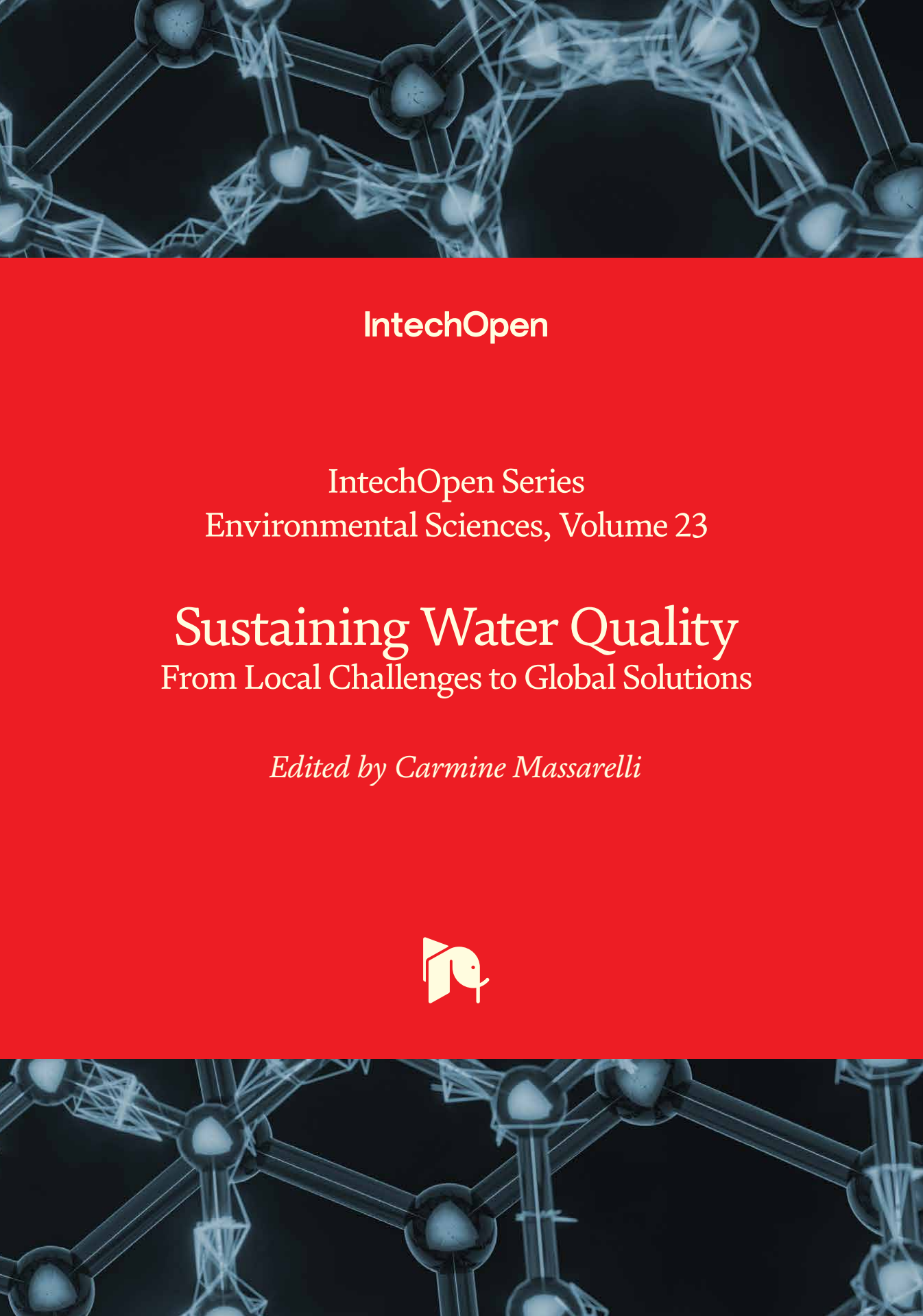


The background of the cover features a complex, blue-toned molecular structure, possibly representing a protein or a crystalline lattice, with spheres and connecting rods. This structure is visible at the top and bottom of the cover, framing the central red area.

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Sustaining Water Quality

From Local Challenges to Global Solutions

Edited by Carmine Massarelli



Sustaining Water Quality - From Local Challenges to Global Solutions

Edited by Carmine Massarelli

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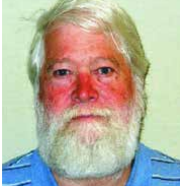
Volume 23

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers is a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He is currently working with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He leads research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editor



Dr. Carmine Massarelli is an environmental technologist at the National Research Council of Italy, Construction Technologies Institute and an expert in the design of complex monitoring programs of water and soil aimed at the correct assessment of environmental status. Expert in data analysis activities through machine learning, Dr. Massarelli specializes in advanced research on smart technologies for characterizing and monitoring contaminated and degraded sites. His work focuses on the integration of spatial data, interoperability, and data infrastructures. He is also an expert in the use of open-source software for the management of Geographic Information Systems, geo-database administration, programming and IT-related roles. He is currently coordinating several research projects for regional monitoring of pesticide residues in water bodies, pollution by nitrates of agricultural origin, understanding the dynamics of environmental illegals, and safeguarding biodiversity.

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Preface

The quality of water resources is a fundamental pillar for environmental sustainability, especially in a global context increasingly threatened by climate change, human pressure, and the ecological crisis. Monitoring water resources is an essential mission for safeguarding ecosystems and biodiversity supporting the development of resilient and sustainable communities. The ability to rapidly assess water quality and identify sources of pollution is an invaluable asset in understanding changes in the hydrological cycle and the impact of human activities.

This volume explores the most advanced monitoring systems, in situ detection methodologies, and innovative technologies for the management and protection of water resources, offering a multidisciplinary framework that ranges from pollution risks to solutions for the protection of resources. From management experience in the Chaco region to the recent challenges of the water cycle altered by global warming, to the analysis of specific contaminations such as that of Pearl Harbor, this book provides an in-depth look at the methods, regulations, and approaches applied to sustainable water management.

It offers advanced solutions for real-time monitoring and illustrates concrete case studies to address critical pollution problems, with a particular focus on the protection of water from agricultural and industrial pollution. Through these analyses, the text aims to inspire and guide the formulation of water policies and strategies that contribute to protecting one of the most vital resources on the planet and building a more sustainable future.

Carmine Massarelli

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Section 1

Global Challenges and Pressures on the Water Cycle

Chapter 1

Perspective Chapter: Challenges of Water Needs – Water Management Experiences in the Chaco Region

Araceli Clavijo

Abstract

About 2.4 billion people in the world live in water-scarce regions. Approximately half of the world's population suffers from water scarcity for at least part of the year and 52% will be severely water-stressed by 2050. These figures are expected to increase, exacerbated by climate change and population growth. In Argentina, there is a semi-arid sub-region representative of the South American biome known as Gran Chaco, in the Chaco Salteño area (northwest). Here, access to water in rural communities is a structural problem, representing the greatest constraint to the productive capacity and resilience to climate change of families. At the socioeconomic level, it is one of the regions with the worst rates of access to water and sanitation, and with the highest levels of unsatisfied basic needs. Indeed, one of the most pressing problems is the lack of water in sufficient volumes for consumption and production. In this context, it is imperative to manage access to safe water, with technical solutions appropriate to the social, cultural, and environmental context and that are sustainable over time. This document analyzes this problem in the region, presenting successful experiences of water management based on collaboration between the State and civil society.

Keywords: semi-arid Chaco, water assessment, water harvesting systems, climate change, water access

1. Introduction

Ensuring access to safe drinking water has been one of the central concerns of various state agencies, international organizations, and civil society in Latin America. In 2010, the United Nations General Assembly explicitly recognized access to water and sanitation as an essential human right [1, 2]. The Sustainable Development Goals (SDGs) included in the 2030 Agenda have as their main objective to put an end to poverty in all its forms, urging all countries to adopt strategic measures that address economic growth and social needs while combating climate change and promoting environmental protection [3–6].

Argentina began in January 2016 the process of adapting the SDGs to the national reality under the leadership of the National Council for the Coordination of Social Policies and with the participation of all the agencies of the National Executive Branch—*Poder Ejecutivo Nacional* [7]. As a result of this process, SDG 6 was declared

by the national government as one of its priorities [8]. Goal 6 aims to ensure the availability and sustainable management of water and sanitation for all, establishing that safe drinking water and sanitation are essential for human health, environmental sustainability, and economic prosperity; it is further recognized that sustainable water management not only includes achieving access to safe drinking water and adequate sanitation services (targets 6.1 and 6.2) but also implies addressing the issue in a broader context, incorporating concepts such as water for inclusive socio-economic growth; healthy watersheds and water sustainability; preventive management of water-related risks; and integrated water resource management [9].

However, the World Bank report revealed in 2021 that 17% of the population in Argentina lacks access to safely managed water and more than twice as many lack access to sanitation services [10]. The Gran Chaco region (Santiago del Estero, Chaco, Formosa, and Salta, among others) is the most affected, with 41% of households without water. This serious service gap mainly affects the poor and vulnerable in peri-urban areas. Moreover, water quality problems pose risks to public health and the environment, and climate change is increasing pressure on the resources.

1.1 Multilevel governance

In Argentina, there is no general national law regulating available water resources, but it is enshrined in international treaties of constitutional rank, and each province has its own legal-political structure for managing and administering the resource. Nor is there any public planning in the country that includes water and energy issues as part of a thematic and strategic Nexus. This situation leads, in regions such as Chaco, to the emergence of intersectoral and interjurisdictional conflicts.

However, what is established in Argentina's federal political-administrative system is that most of the legal competences for the management of natural resources correspond to the provinces. These are the owners of water resources, including interjurisdictional rivers, and they are responsible for the provision of water services within their boundaries. Thus, in Argentina, access to water poses a complex scenario since the federal governance system implies understanding that there are 24 different ways of managing this service (the 23 provinces and the Autonomous City of Buenos Aires). However, this federal structure of the country also offers opportunities for multilevel governance and locally based policies. Since, as mentioned above, there is no national law regulating the service, each of the provinces has the power to regulate it. Thus, federalism creates the possibility for the provinces to adopt specific localized measures, which can also be financially supported by the national government. This great potential for partnership at various levels can help develop a shared, forward-looking national strategic vision backed by the necessary investments in tangible and intangible infrastructure. The truth is, however, that these opportunities are currently untapped.

Law 25,688 of 2002 sought to promote a general legislative framework for water management and to establish the minimum environmental budgets for the preservation, development, and rational use of water resources. However, this norm, known as Environmental Water Management, was never regulated, operationalized, or applied directly and conclusively for the solution of concrete cases. The environmental policy coordination entity defined for this law is the Federal Environmental Council (COFEMA), which establishes special commissions to articulate and coordinate the implementation of environmental policy and management instruments. In 2003, the provinces and the national government agreed on the Guiding Principles

of Water Policy of the Argentine Republic (PRPH), which established guidelines that allow the integration of the technical, social, economic, legal, institutional, and environmental aspects of water into the concept of water resources management. This was definitely an important step toward the adoption of a more integrated water management approach.

Salta province is one of the few institutions that have a space dedicated to stakeholder participation in the decision-making process. The provincial water law passed in 1998 (Law 7.017) created the *Provincial Water Council*. The purpose of this entity is to advise the public administrations responsible for the planning and management of water resources. However, its scope today is limited. On the one hand, despite being one of the Argentine provinces with the largest number of indigenous communities, they do not have membership in the cabildo. On the other hand, there are no public information systems on the council's discussions, nor on the influence of stakeholder input in the decision-making process. However, as will be seen below, initiatives originating in civil society in these provinces become management alternatives and new governance modalities.

1.2 Water in the Chaco region

The Chaco is an ecoregion that represents the second largest natural biome in South America, second only to the Amazon region [11]. It is one of the most environmentally and biologically diverse regions on the planet. It extends from central Argentina to western Paraguay, southeastern Bolivia, and, marginally, Brazil. More than 8 million people live in the American Chaco (8% of whom are indigenous) [12, 13]. However, due to its natural conditions and human intervention, it is also one of the region's most vulnerable to the effects of the climate crisis in Latin America [14]. Soil erosion, desertification, and alteration of the hydrological regime are some of the problems that already affect this territory [15]. Despite being the second largest and most important forest in South America, the region has lagged behind other bioregions of the continent, with social indicators below the regional average, especially in terms of deficits in access to infrastructure and essential services such as health, education, and access to drinking water [16–19]. More than 60% of this area, approximately 52,000,000 hectares, is Argentine territory. Within this, the so-called *Chaco salteño* comprises about 7,000,000 hectares and corresponds to the subregion of the dry Chaco (**Figure 1A**) [20]. It is made up of the eastern departments of the province located in the Chaco plains and threshold: a strip of about 40 km wide that extends from north to south between the border with Bolivia and the northern border of Catamarca. **Figure 1B** shows in red those areas in the north of the province with high social and environmental vulnerability—this is where the departments of *San Martín*, *Rivadavia*, and *Orán* are located, part of the Chaco region [22]. The Chaco of Salta is characterized by a semi-arid climate, with an average annual rainfall of 576 mm, concentrated mostly in the summer. During the rest of the year, there is usually no rainfall, and temperatures are high (with daily highs above 40°C in summer). This scarcity of precipitation and high potential evapotranspiration (1000 and 1200 mm/year) mean that the average annual water deficiency is of the order of 500 mm. Six good quality aquifers have been identified up to a depth of 300 m, with flow rates of more than 100 m³/h [23]. Low rainfall and long months of drought make up the usual rhythm of the climate.

Considering that the region has social indicators below the regional average, especially in terms of the lack of access to infrastructure and essential services such

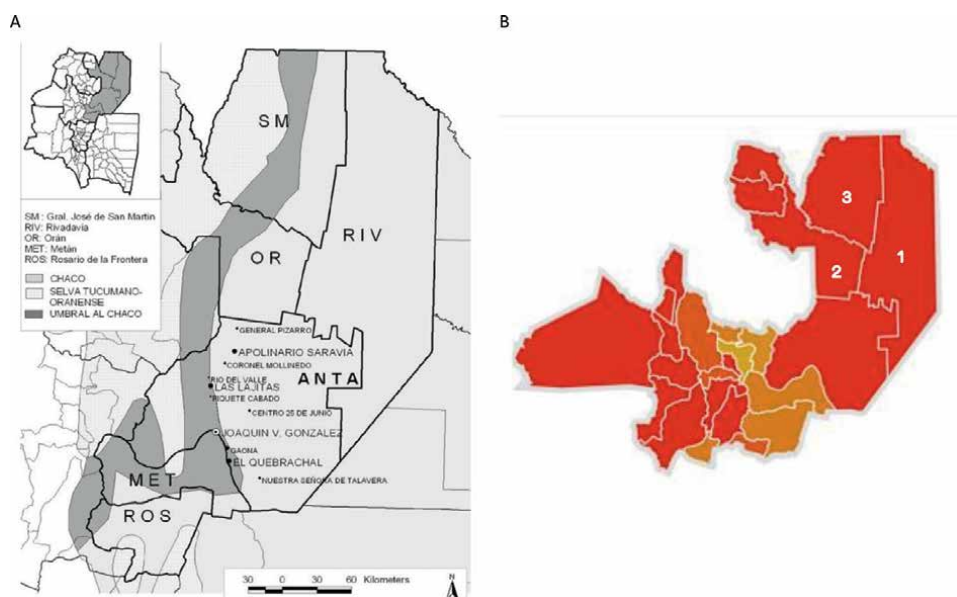


Figure 1.

*A. Study area: Chaco salteño. Source: extracted from Krapovickas, Rainer & Mikkelsen, 2019 [21] copyright B. Emergency index map for water management in the province of Salta. Source: Juárez et al., 2017, 222 copyright. Available on Plataforma del Agua (2018). *Departments: (1) Rivadavia; (2) Orán; (3) San Martín.*

as health, education, and access to drinking water, water scarcity is undoubtedly the most serious social problem. Water represents a crisis factor for both its excessive availability (flooding of the Pilcomayo River) and its scarcity (extreme droughts). Nevertheless, to understand the problem of access to safe water, it is necessary to recognize the geographical, seasonal, and governance characteristics of the province. Both in the American Chaco in general and in the Argentine Chaco in particular, indigenous communities have a very strong bond with the environment. They share a spiritual, cultural, and social relationship with their ancestral lands and ecosystems. The Argentine Chaco can be understood as a hydro-social territory, where the socio-economic, political, and cultural processes of the territory are incorporated into the natural understanding of water and determine the particular forms of control and use of water [24–30]. Today, moreover, these areas are being degraded by factors related to climate change, causing new environmental problems such as prolonged droughts, floods, and forest fires [31].

In the Chaco region of Salta, access to water in rural communities is a serious structural problem that represents the greatest limitation to the productive capacity and adaptation to climate change of producer families, being a cross-cutting problem in the region to most productive activities [32, 33]. In a large part of the province, the supply is not guaranteed, neither in sufficient quantity nor in sufficient quality, with the aggravating factor that there is an unsafe management of water since it is not stored appropriately. One of the most pressing problems for families is the lack of sufficient water for human consumption and therefore for production [19, 32]. In the area, there are more than 50,000 people without safe water service coverage, and there are areas of contaminated water associated with the presence of arsenic and high salinity. The Northwest of Argentina (provinces of Salta and Jujuy) is one of the areas most affected by the presence of arsenic in water, with high concentrations of

arsenic [34–36]. In many of these areas, groundwater is the main source of drinking water throughout the year (70% of the water distribution system is through boreholes that come from groundwater), which mainly exposes rural and dispersed populations that do not have safe surface sources to contaminants [37–39].

Access to safe water is related to other problems that have an impact on the lives of smallholder families and are factors in the uprooting and disappearance of productive units: access to safe food, lack of access to education, infant and maternal mortality, social and gender inequalities, conflicts over loss of land tenure, environmental pollution, and extreme poverty [40, 41]. It is also a violation of human rights. Today, taking into consideration the circumstances of the past COVID-19 epidemic and its economic and social consequences, the situation in the region is even more vulnerable.

2. Safety water management experiences in the Chaco region: rainwater collecting systems

To ensure water security in the Chaco region of Salta, we must emphasize water accessibility and quality. This is a key point in the management of water resources, to meet the water needs of the region in terms of quantity and quality.

Equitable access to water depends on technologies that protect, filter, and distribute water; but it also depends on social arrangements that protect the less powerful from exclusion [42, 43]. Given that in most areas of the world, water remains a common property (albeit highly contested) resource, barriers to access are often determined not so much by prices as by such things as geographic variation in supply, quality, and reliability, and ownership of (or access to) water infrastructure [44]. In Salta Chaco, in particular, the situation is not easy; wells are far away, and transporting energy requires high costs, so in some places, solar panels are used for extraction by drilling. Therefore, access to water resources is limited due to problems of availability (available flow), quality (salinity), and infrastructure (technologies) [18]. However, as already discussed, standard technological responses, such as drilling new wells or protecting community water supplies, are a key solution to water supply but do not necessarily solve water insecurity in this area. In addition, the cost of water per hectare is the same for a farmer as for an agro-industrial producer, which reinforces an inequitable relationship between the two [45, 46]. In this hydro-social territory, the main decisions continue to be made within the hegemonic development model and without the intervention of the affected populations, ignoring and/or subalternizing their knowledge and productive and reproductive practices [47]. However, social-ecological systems cannot be managed in a centralized, top-down manner, but require a new style of governance based on decentralized and cooperative networks. Achieving the goal of access to safe drinking water requires concerted action at all levels of governance and the participation of all stakeholders. One solution that has proven to be effective is the rainwater harvesting system [48–52]. But the analysis of the water issue in the context of sustainable development requires taking a long-term view, to account for some hydrological and social processes. In addition, water authorities need to consider the vulnerability of water systems to potential future climate change, not just past climate variability. Legal, technical, and economic approaches to water resource management should be re-evaluated in the face of possible climate change and future demographic changes.

Water harvesting by precipitation concentration and storage for beneficial use [53, 54], represents a key to coping with water scarcity and sustaining agricultural production [55–58]. Rainwater Harvesting cisterns are part of the so-called social technologies or technologies for social inclusion as a set of replicable products, techniques and/or methodologies developed in interaction with the community and representing effective solutions for social transformation. This type of system has the following advantages: (i) It can be covered so that there are no significant evaporation losses; (ii) it collects water during the rainy season and stores it during the rainy season; (iii) the cistern is built close to the residence, avoiding long journeys to get the daily water, taking away free time to carry out other activities; (iv) with proper care, the stored water can be of higher quality than other water from different sources; and (v) with proper care, the stored water can be of higher quality than water from other sources [59]. These systems have proven to have great potential to cope with climatic adversities, while at the same time, they represent an important contribution to the development strategies of the Semi-Arid Chaco. Rainwater harvesting cisterns are also part of the Climate Change Adaptation strategies. Indeed, the Intergovernmental Panel on (IPCC) Climate Change Report [60] names this technology as an example of sustainable development in the semi-arid tropics.

Precisely in the Brazilian semi-arid region, in 2010, the Ministry of Social Development together with several NGOs launched the “Water for All” program to build 367 cisterns to distribute drinking water and another 600 thousand for water used in food production and animal husbandry in the northeast of Brazil, a region that concentrates most of the 36.3 million poor people in Brazil (**Figure 2**). Inspired by the experience in Brazil, in 2013, this Brazilian technology of plate cisterns and rainwater storage for human consumption arrived in Argentina through an articulation between INTA and the Brazilian Semi-Arid (ASA Brazil); being a great solution to the problem of access to water for many families in several parts of the country. They have a capacity of 16,000 liters and are built near the house using a system of gutters and pipes to collect rainwater through the roof system and store it in the pool. The main objective of these systems is to give priority attention to the indigenous and Creole populations that do not have access to drinking water. Thus, it allowed the design of a rainwater collection, filtration, and storage system adapted to semi-arid regions and for people’s consumption. Accordingly, in the same year, the Latin American Semi-Arid Platform was also created [61]; for learning and exchange among leaders, farmers, technicians, and officials on innovative practices for the sustainable use and management of natural resources in the Trinational Chaco (Argentina, Bolivia, and Paraguay), Northeastern Brazil, and the Central American Dry Corridor (Honduras, Guatemala, Nicaragua, and El Salvador). In these areas, the use of cisterns has shown good results.

In 2016, a “water technical table” began to operate in the province of Salta, aimed at addressing specific issues regarding water needs, mainly in the Chaco region of Salta. The table was composed of various agencies and constituted a link between institutions to streamline procedures and provide greater response to water problems [62]. In 2017, this space was formally constituted as the “Coordination and action roundtable for water access and management in the Chaco Salta” in July 2016, based on an agreement signed between the Ministry of Indigenous Affairs and Community Development of Salta, the NGO FUNDAPAZ, the Semi-Arid Platform of Latin America, the *Tri-national Integrated Program* (*programa Integrado Trinacional* (PIT)), the *International Land Coalition* (ILC-ALC), and the *Church World Service* (CWS). This new regional roundtable was created to give priority attention to the

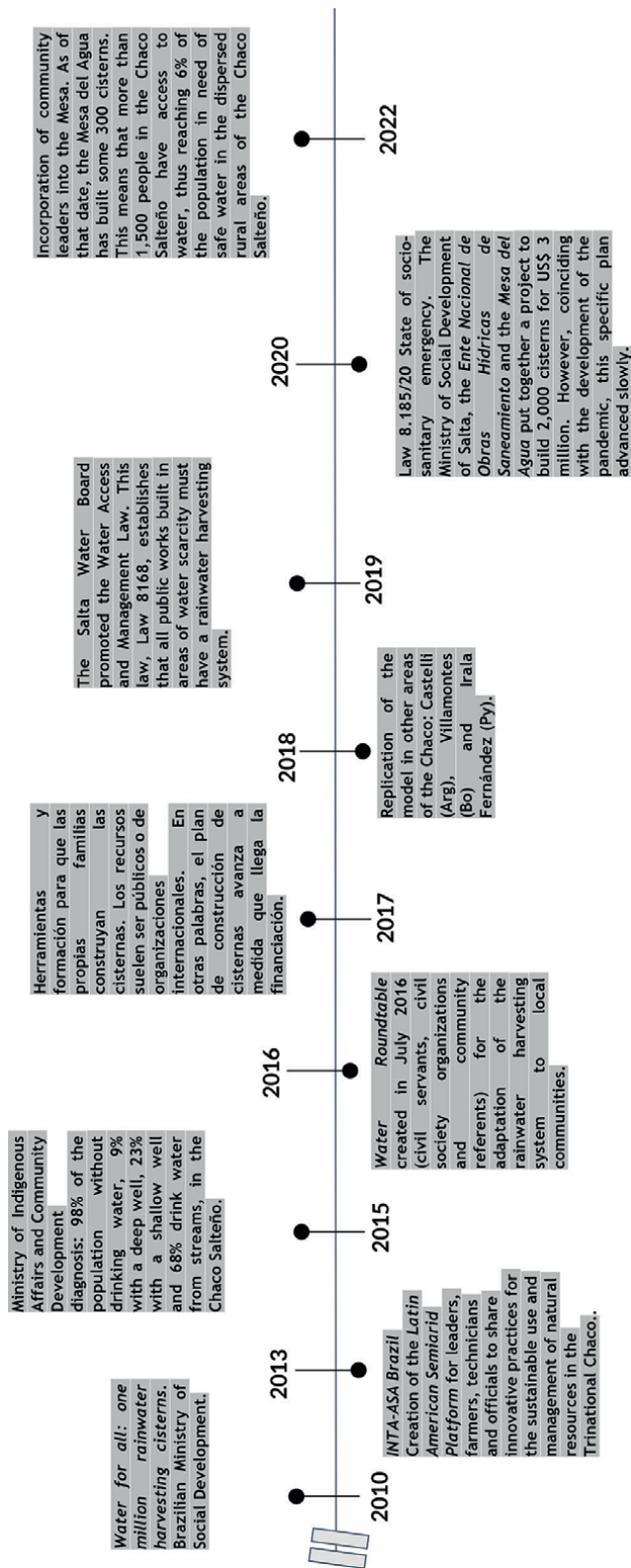


Figure 2.
Timeline of the joint plan (alliance between the state, civil society associations, and communities) for access to water in the Chaco Salteño.

indigenous and Creole population that does not have access to safe water in the Chaco region of Salta. This working space between the state and civil society represents a model for the management and construction of public policies that are still in operation today. It addresses the issues of access to water for the inhabitants of rural areas and the design of a technical and social analysis system to survey the situation of families and communities regarding access to water in order to have a database to prepare a map where the works already carried out, and those planned are identified; the level of water requirement for human consumption and production; the necessary investment, the public works required and the training to be carried out.

One of the key proposals on which the roundtable has been working is access to water through models that guarantee a solution for the dispersed rural population. This is how, through the work that has been managed in this space, the Water Access and Management Law, Law 8168, was promoted, presented to the government of the province in November 2019, and converted into law a month later (**Figure 2**). This law establishes that all public works to be built in water-scarce areas must have a rainwater harvesting system. It is estimated that this law will guarantee greater access to water for almost 8000 peasant and indigenous families, and will allow the promotion of a new form of safe water management in the *Chaco salteño*.

Indeed, the rainwater harvesting system has represented a solution for the access and supply of safe water in some parts of this region, where the drilling of water wells is not safe. These technologies are part of the so-called social technologies, which are developed in interaction with the community and represent effective solutions for social transformation.

3. Water security: from conflict to institutionality

Even if it is true that the construction of rainwater harvesting cisterns throughout this area is generating positive effects for different types of actors, they also give rise to socioenvironmental conflicts and conflicts over water management (distribution conflicts). However, water conflicts, in turn, can become a real impetus for institutional innovations. This is true both at the level of local community management and public policies.

Many mobilizations for water justice have proposed new principles of water management and have not only been active in promoting the human right to water but have also been the first to support the recognition of water, along with land and air, nature, in short, as a subject of rights. Water crises are often crises of governance, and these mobilizations should make us rethink the idea that the solutions to water problems do not come with the creation of new infrastructures, but rather with new and better governance and forms of water management to make them effective and sustainable.

In this sense, peasant and indigenous organizations can contribute to knowledge management: to the design of public policies and plans for sustainable management of natural resources. Networks of local organizations also provide an opportunity to respond to their own needs in the medium and long term.

However, the type of model we know as community water management is not always necessarily the most just and ecological. Even so, bottom-up initiatives can express ecological, subsistence, and cultural values outside markets or state power.

The search for these models of inclusive social technology such as water cisterns makes it possible to achieve a better coexistence with the entire semi-arid Chaco

region, a reduction in the impact of climate change, and the ecological vulnerability of the population, favoring environmentally sustainable human development and the basic living conditions of the population.

The Mesa space is an example of articulation between civil society and the state for the management and promotion of public policies for access to water. From these spaces, originating in the heart of civil society, progress is also made in the formalization and institutionalization of regional strategies of joint work, as was the realization in Salta of the First Trinational Meeting of Water Management and Access Tables in the Chaco Region. This was held in July 2022 with the participation of representatives of this type of space in Argentina, Bolivia, and Paraguay, with the aim of sharing experiences in similar spaces and advancing a common work plan for access to water in the Chaco region.

Based on participatory mapping, the Mesa carried out collective diagnostic exercises in which it identified critical situations, reached a consensus on the order of priority for the works, quantified the need for catchment and storage for each case, and defined the plan to offer a specific solution for the families or communities chosen.

The dynamics of dialog, collective decision-making, and articulations generated from Mesa's activities produced results beyond the construction of water harvesting systems linked to public policy advocacy strategies.

In 2019, an important milestone was that Mesa achieved the sanction of its proposed law—provincial law No. 8168—which establishes that rainwater harvesting and storage equipment be installed in buildings—mainly in rural areas—constructed by the provincial state in areas where there is a deficit in access to safe water. This initiative makes it possible that, in the future, an adequate water system will be contemplated in new buildings.

Likewise, in February 2020, in response to an event that gained national transcendence, the death from thirst and hunger of seven children and women from *Wichís* native communities in the northern area of Salta, the *Mesa Federal del Agua Social para Salta* was created, which sought to bring together authorities from national ministries and provincial officials, representatives of the UNSA and other social and scientific actors, with the aim of generating an integral response for the provision of safe water in rural areas—particularly in Indigenous communities, contemplating basic infrastructure works such as boreholes and attention to health and food [63]. However, this Federal Roundtable did not become fully operational and was quickly dismantled. In its place, the Salta Water Board consolidated itself as a valid interlocutor to bring answers to the territories [64].

After more than a year of work, the *protocol for Prior, Free, and Informed Consultation* (FPIC) for the indigenous and *creole* organizations that participate in the *Mesa de Agua del Chaco Salteño* was drafted.

The proposal for the elaboration of the Protocol took place in an Assembly of the Board, to comply with ILO Convention 169, referring to indigenous communities and the National Law 25.675 of the Nation. It was carried out by FUNDAPAZ and the Institute of Environmental Law and Sustainability of the UCASAL—Catholic University of Salta—both members of the board of directors signed an agreement to carry it out. This agreement also included the United Nations High Commissioner's Office with the support of the Argentine Resident Coordinator's Office, UN Women, and the Socio-Environmental Studies and Research Group belonging to the Non-Conventional Energy Research Institute (National Research Council). The latter organization participated with the purpose of incorporating uniformity in water quality criteria and minimum management guidelines that should be followed to have access to safe water. This project takes up the provisions of UN Resolution 64/292,

which “recognizes that the right to safe drinking water and sanitation is a human right essential for the full enjoyment of life and all human rights.”

To carry out the participatory process that would lead to the elaboration of the Protocol, during 2021, participatory workshops were held in the four areas where the Mesa del Agua del Chaco Salteño has a scope, in the departments of General San Martín and Rivadavia. There is an international, national, and provincial regulatory framework, by which free and informed prior consultation with the communities is a recognized right for indigenous peoples as an action of historical reparation. At the core of this normative set, we can mention ILO Convention 169 (1989) [65], in force in Argentina since 1992, the United Nations Declaration on the Rights of Indigenous Peoples (2007) [66], the National Constitution of 1994, and the provincial constitutions.

On the other hand, there is the *Regional Agreement on Access to Information, Public Participation, and Access to Justice in Environmental Matters* in Latin America and the Caribbean, known as the Escazú Agreement [67], which is another complementary tool to guarantee access to information, participation, and justice, understood as interrelated and interdependent terms. The protocol, which was presented to the Minister of Social Action of Salta, must be used prior to each public work or private undertaking carried out in the work areas of the *Mesa de Agua del Chaco Salteño*.

These examples of water management experiences from collaboration between the state and civil society have proven to be essential for the sustainable and participatory development of rural areas with dispersed rural marginalized populations.

4. Closing remarks

The water crisis is a global situation that will undoubtedly worsen because of climate change if adequate adaptation policies are not adopted to cushion the vulnerability of the population, particularly the poorest communities, to the risks of drought and heavy rainfall, which, according to all forecasts, will tend to increase in both intensity and frequency.

Water security will go hand in hand with optimal resource management, carried out by provincial and municipal governments, with emphasis on improving regulatory and institutional frameworks and strengthening the role of organizations; ensuring inclusive and sustainable provision of water (and sanitation) services; implementing improvements in efficient and compatible management. Strengthening water resources management will be the fundamental pillar for adaptation to climate change and growing water demand. Of course, this goes hand in hand with the urgent need to promote public policies to guarantee access to water and land, specifically in the Chaco Salteño and at the regional level. Thus, improvements in Argentina's water governance system are necessary conditions for building the environment that will enable the achievement of SDG 6.

After the crisis generated by the COVID-19 pandemic, which has highlighted the shortcomings in the supply of safe water for human use, comprehensive planning will be necessary (especially in developing countries) to design not only new infrastructures but also new management models in addition to rehabilitating and protecting existing successful ones. To this end, a robust institutional framework is essential to ensure the adaptability of the systems to future similar events. The new water management will have to revise regulatory frameworks and policy instruments to achieve the goal of generating more resilient and prosperous rural areas.

The experience of the Mesa de Coordinación y Acción para el Acceso y Gestión del Agua is a valuable example of the potential of integrating the beneficiaries of actions to support vulnerable communities in the collective process of identifying their problems and building solutions. The experience of the participation of the communities in the mapping of needs, the assignment of priorities for the implementation of solutions, and the construction and maintenance of water collection and storage systems stimulates trust and collaboration among the inhabitants, encourages the commitment of the beneficiaries with the execution of the program, broadens their management capacities and their pool of constructive skills, mobilizes resources in the area of belonging, and favors the rooting and development of productive activities. The success obtained so far in the provision of solutions for the supply of safe water to vulnerable populations of the Chaco Salteño by the Mesa can be considered for the design and implementation of public policies, increasing the probability of achieving its objectives.

These management experiences demonstrate that the solutions to water problems will come more from governance than from infrastructure. Changes in management and institutions are the key to sustainable development. In the specific case of Salta, the most successful management of water resources was promoted from the civil level. Initiatives originating in civil society, such as the Chaco Water Roundtable, become management alternatives and new governance modalities. In them, decision-making in the water sector is transparent and involves all interested parties. Ecological functions are recognized and maintained. Human use of water becomes sustainable, understanding that the solution to the complex set of water problems cannot be achieved without addressing the interrelationships between technological, demographic, economic, social, environmental, and institutional issues.

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Perspective Chapter: Shortening the Natural Altered Water Cycle by Global Warming

Jorge Garza-Ulloa

Abstract

The natural water cycle is the process that describes the continuous and endless circulation of water between natural resources on the Earth and atmosphere, transformed in different states by solar energy and magma heat energy from Earth's molten core and attracted by Earth's gravity, maintaining its constant mass of water. The natural water cycle is very complex and it is affected by changes in all of its states by many factors that, in these times, have been extremely altered by climate change and are creating altered natural water cycles that are extending on distance, duration and volume of rain. Some factors currently occurring are the result of global temperature increases reflected in severe weather changes, such as more intense heat waves and insufficient freshwater to meet human and environmental demands in many areas of almost all countries, besides sea ice loss, accelerating sea level rise, and many other threats. In this perspective chapter, we focus on the need to develop and implement plans in the near term and focus on how to mitigate damages and specify fast adaptation actions to handle the urgent situation raised by global warming, based on plans to implement steps to observe, measure, and analyze ways to shorten the natural altered water cycle by global warming.

Keywords: natural water cycles, climate changes, natural water altered cycles, shorter natural water cycles, global warming, water scarcity, water quality

1. Introduction

The general water cycle is a continuous movement and interchange of water state conversion by different processes, altered by the natural solar and Earth energy [1]. These water conversions are as follows:

- From liquid to gas, by evaporation and transpiration.
 - Evaporation is the change from liquid to gaseous state by the heat applied to surfaces of water, that is, oceans, streams, and lakes.
 - Transpiration is a natural passive process that does not require external energy for water movement through plants and its evaporation in the aerial parts, that is, leaves, stems, and flowers.

Evapotranspiration is a term for the combined processes that move water from Earth's surface (as open water, ice surfaces, bare soil, and vegetation) into the atmosphere.

- From solid to gas, by sublimation
 - Sublimation is the transition from solid to the gas state, without passing through the liquid state. It occurs due to dry winds, low humidity, and low air pressure over the mountains covered by snow.
- From gas to liquid, by condensation and deposition
 - Condensation is the process in which water vapor converts into liquid.
 - Deposition is the process of sediment being laid down, when the wind, flowing water, the sea, or ice loses its energy and cannot transport the sediments.

From gas to liquid and solid, by precipitation and deposition

The water vapor is obtained from evaporation, transpiration, and sublimation of gas molecules that come together, forming a liquid by rising in the atmosphere and receiving cool air by the natural flow from high- to low-pressure layers.

- Precipitation happens when water vapor in the form of clouds condenses into drops big enough to fall to Earth by gravitation.
- Deposition is when water vapor changes directly into ice, when clouds are colder at higher altitudes where droplets freeze, forming snow or ice falling faster. It is the opposite of sublimation.

The returning of water back into underground reserves known as aquifers is a component of the hydrological cycle by runoff, infiltration, percolation, and collection.

- Runoff is the flow of water over the land before reaching a watercourse, which is then identified as a streamflow.
- Infiltration is the water process by which the water from the ground surface enters the soil.
- Percolation is the movement of water filtered through the porous surface.
- Collection is a storage of water to conserve resources, that is, water storage in ice and snow, water storage in oceans, etc.

1.1 Earth's atmosphere

The Earth's atmosphere is structured into five layers of unique characteristics and phenomena known as troposphere, stratosphere, mesosphere, thermosphere, and exosphere [2]:

- Troposphere extends up to 5–9 miles, varying with latitude. The most important for weather events, it has about 75% of the atmospheric mass and most of its water vapor, where its temperature decreases with altitude.
- Stratosphere (from 9 to 31 miles) contains the ozone layer that absorbs ultra-violet (UV) solar radiation and moves it, causing rising temperatures in higher altitudes.
- Mesosphere (from 31 to 53 miles) is a layer where temperature decreases, reaching –130 Fahrenheit degrees on the top layer. This is the region where most meteorites burn up upon entry.
- Thermosphere (from 53 to 373 miles) is a layer where the air density is very low, with very high temperature due to the absorption of high-energy X-rays and UV from the Sun. This layer includes the ionosphere, very useful for radio communications as it reflects the radio waves back to Earth.
- Exosphere (from 373 to 6200 miles), influenced by Earth's magnetic field, contains hydrogen and helium. It protects the planet from solar wind and cosmic radiation.

1.2 Hydrosphere and general water cycle

Hydrosphere is the total amount of water in any state: gas collected in the air in the clouds, liquid collected on the surface from rain, solid collected as snow or ice, and water that is collected underground.

The general water cycle is an infinite movement through the hydrosphere, as shown in **Figure 1** and its respective Eq. (1). The process in this movement are as follows:

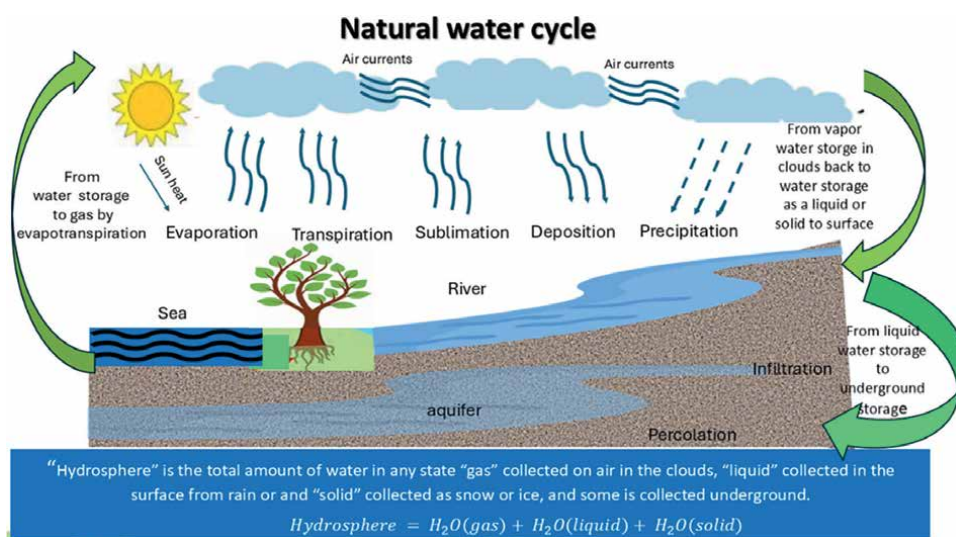


Figure 1.
 General natural water cycle and its processes for water state conversion.

- From water storage to gas: by evapotranspiration to water vapor storage in the atmosphere as clouds through processes such as evaporation, condensation, transpiration, and sublimation.
- From water vapor storage in the atmosphere, sent back to earth as liquid or solid by precipitation to water storage as liquid or solid by precipitation (through liquid or frozen water) and deposition.
- From liquid water storage to underground storage by infiltration and percolation.

The general water cycle container is the hydrosphere. Approximately 71% of Earth's surface is covered by water, but only 3% is freshwater, and a small portion of it can be used as a drinking water [3].

2. Natural altered water cycle due to global warming

Global warming is the unnatural phenomenon of increasing average air temperature near the surface of the Earth, mainly due to human overactivity altering the natural ecosystem. As indicated by the analysis of the Earth's climate data by the Intergovernmental Panel on Climate Change (IPCC), study results indicate that human activity has been responsible for a worldwide average increase from 0.8 and 1.2 centigrade degrees (1.4 and 2.2 Fahrenheit degrees), and most of the warming began over the second half of the twentieth century [4, 5]. Consequently, we need more observation and measuring in detail of the main effects of weather phenomena such as increasing temperatures, excessive precipitation, excessive dryness, storms, and follow-up changes in nature by studying ocean currents, air currents, and atmospheric chemical compositions.

The new proposed water measurement and analysis are described with easy-to-follow examples in this research to achieve a shortened natural altered water cycle by global warming.

2.1 Weather pattern alterations change the natural water cycle

Human activity is the number one cause of global warming, with burning fossil fuels emitting carbon dioxide, diminishing carbon capture, and destroying forests. Human activity is increasing Earth's natural greenhouse gases in the atmosphere, located at the troposphere layer, by heat-trapping gases such as carbon dioxide in a large proportion, with respect to other gases such as methane, nitrous oxide, ozone, and various chlorofluorocarbons [6]. These gases and other pollutants released from the earth are acting as a blanket, trapping the Sun's heat and causing the Earth to warm up. The consequences are catastrophic with the alteration of Earth's natural climate system, including lands, atmosphere, oceans, and ice. These alterations are reflected in the natural water cycle, with higher temperatures resulting in atypical weather patterns with increasing effects to an extreme value from storms, heat waves, floods, droughts, and atmosphere alterations. Each of these can be identified by their effects: storms' global frequency, for example, may decrease or remain unchanged, but hurricanes are more intense, causing more intense

rainfall and an increased coastal flood by raised seas [7]. The four main ingredients to form and strengthen hurricanes are warm ocean water, increased air moisture, low vertical wind shear, and persisting disturbance, that is, thunderstorm clusters. There are some models, although still very hard to predict, that currently focus on where the hurricane is going and how strong it will be on its path, especially when it comes ashore.

The weather pattern alterations that change the natural water cycle are expressed as: heat waves, floods, droughts, and atmosphere alterations.

- Heat waves are affected by global warming by their duration, how warm they usually are, and how frequently they occur [7].
- Floods are affected by global warming: they can surge all year round, in every region of the world. Historical data is not useful anymore, particularly for extreme, infrequent floods. Some main ingredients for flood development are river flood, when rivers', streams', or lakes' water overflows, and coastal flood, when land areas near the coast are water inundated following severe storms that collide with high tides [8].
- Droughts are when areas receive less rain or snow than expected over the course of a year, altered by more frequent patterns of drought, longer duration, and intensity. This affects all kinds of water storage on the surface of the Earth (wetlands, lakes, and rivers), aquifers, and water stored in the soil that is absorbed by dry ground as a sponge. Something similar happens with snow, which, when melted, also absorbs too quickly [9].
- Atmosphere alterations under global warming are seen as abnormal vapor storage retention on wet areas that become wetter and dry areas that become drier and, in some irregular patterns, dry areas being wetter and wet areas being dry.

All these changes in the weather patterns alter the natural water cycle, affecting plants, animals, agriculture, and ecosystems with socioeconomic and health impacts.

2.2 Natural altered water cycle due to global warming

Natural water cycle processes have changed to the natural altered water cycle in recent decades due to human activities that influence, directly and indirectly, global warming, that is, water demand, stronger winds, and others. Based on previous research, we can state that the natural altered water cycle due to global warming is observable, as summarized on the right side of the table in **Figure 2**:

- Water is moving between its states faster than expected due to various factors present in global warming [10].
- Rainwater in any region could arrive from a distant ocean in couple of days [11].
- River water or aquifer water could be from a faraway high mountaintop [12].

Representation: Shortening natural altered water cycles by global warming

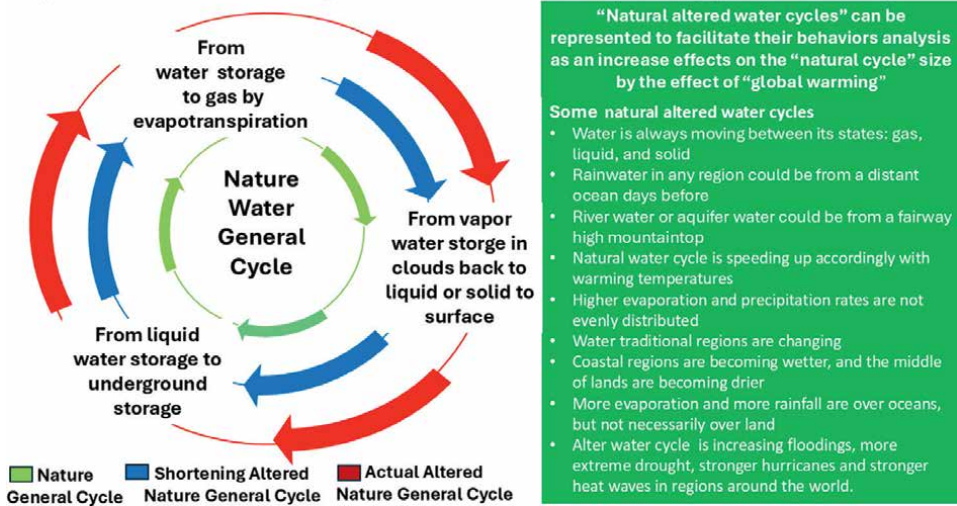


Figure 2.

The representation for altered water cycle by global warming is based on circles with a specific radius according to the alteration in the natural water general cycle.

Water cycle is the way to move the water that we need, and this cycle has been altered. There is an urgent need to analyze and measure the changes in the present altered water cycle to help nature reestablish its natural water cycle.

Based on altered water cycle due to global warming, the following are some important changes:

- Natural water cycle is speeding up accordingly with warming temperatures going up at an increasing evaporation rate. A higher evaporation rate is reflected through a higher precipitation rate.
- Higher evaporation and precipitation rates are not evenly distributed. Some regions receive heavier than normal precipitations, while other regions receive less than normal precipitations.
- Traditional water regions are changing: some regions are experiencing relatively heavy rainfall, and deserts are shifting in response to a changing climate.
- Coastal regions are becoming wetter, and the middle of lands is becoming drier.
- More evaporation and more rainfall concentrate over oceans, but not necessarily over land.
- The altered water cycle is increasing flooding, causing more extreme drought, stronger hurricanes, and stronger heat waves in regions around the world.

The natural water cycle has been altered, and it is speeding up as warming temperatures, precipitation, evaporation, and others are also increasing. Water areas have been shifted, which seems to indicate their cycle has been extended to wider areas. It is time to help nature reestablish its natural water cycle with methods and techniques to shorten the natural altered water cycles due to global warming, as explained in the next sections.

3. Charting the natural altered water cycles caused by global warming

We need to focus on how nature works and learn how to correct deviations. Nature is always moving in a circular way, as indicated by the natural water cycle represented on the left side of **Figure 2**. Many other natural circular behaviors work in this same pattern. Also, we need to recognize that the actual problem with natural altered water cycles was created due to overconsumption, with many resources being exploited to a greater extent by the industrial system. Human activities have also altered natural environment with excessive material extractions, excessive water utilization, and many other activities that generated excessive waste while disregarding the consequences. Nature is just responding to adjustment, trying to balance the global warming threats.

The natural water cycles, as shown in the left side of **Figure 2**, can be represented using a water parameter that represents many factors involved. This value is the radius of a circle representing the alteration. A circle representing the altered water cycle has the goal of facilitating the analysis of many behaviors involved. The natural general water cycle value increases accordingly with the rise of global warming effects, as explained in Section 2.2 and summarized on the right side of **Figure 2**, the actual extremely altered natural general cycle is in red. When some correction methods are applied, the radius of the circle will decrease. The altered natural general cycle is shown in blue compared with the normal natural general water cycle, which is in green.

3.1 Relation of natural water cycle, water state conversion, and energy

Generally, the natural water cycle, as indicated by green arrows in **Figure 1**, is based on water state conversion and represents the total water found in any state in the hydrosphere. To accomplish the water state conversion, it is extremely necessary to involve external energy. They are summarized using their respective equations and explained with the following descriptions:

- Hydrosphere is the total constant amount of water on Earth in any of its states:
 - Gas, collected on air in the clouds,
 - Liquid, collected from rain, on the surface in land, lakes, and stored underground, and
 - Solid, collected as snow or ice.
- Water state conversion is the process of water moving from one state to another, but it involves the need for energy that must be added to add/remove water atoms and molecules. The different water state conversions are as follows:

- Condensation (water moving from vapor to liquid state)
- Freezing (water moving from liquid to solid state)
- Deposition (water moving from vapor to solid state)
- Water droplets and ice crystals have the following properties:
 - Water droplets/ice crystals are formed in the atmosphere when it is cooled.
 - Water droplets fall when a relative humidity of 100% (dew point) is reached.
 - Ice crystals are formed in the dew point when the temperature is below 0° C.

For water droplet/ice crystal formation, an additional condition is needed: they are formed based on surfaces of microscopic particles of dust, smoke, and salt, where six-sided particles are needed in the ice crystal.

This is the reason for cloud seeding, where the substances used are silver iodide, potassium iodide, and dry ice, with hygroscopic materials like table salt dispersing into the air to attract more moisture to achieve cloud condensation.

The water state conversion, including energy needed, is represented as follows:

- Thermal energy is directly proportional to the change in temperature of the matter object. Heat absorption is a form of thermal energy when the temperature increase affects an atom's movement, and by consequence, molecules are affected.

The states of water are dependent on changes in its thermal energy. Increasing thermal energy allows water to change from solid to liquid and liquid to gas based on the increase of internal energy of its molecules and atoms.

Energy is needed for the three states of natural water conversion. Additional state, known as the fourth state, is identified as plasma or plasma-activated water (PAW) or cold atmospheric plasma. It is obtained by ionization when a lightning from air or other gases with a high voltage reacts with water, as shown in **Figure 3** with its respective Eq. (2) and processes.

Plasma, known as the fourth state of matter [13], is formed by ions, electrons, free radicals, atoms in excited and neutral states, molecules in excited states, and ultra-violet photons. PAW is an electrically expanded water state, and it is formed when a gas is ionized with a negatively charged plasma that is created when water absorbs electricity and gains an extra electron. This process in nature is the cause of thunderstorms for green rain [14]. PAW is stable for at least 3 weeks and has many applications; it picks up reactive molecules such as nitrogen oxide and hydrogen peroxide, useful in agriculture for reducing bacteria and fungi in crops, and in medicine as a disinfectant.

Water conversion processes and energy needed are shown graphically, represented with opposite cycles marked by arrows → and ←, including the fourth state, plasma, in **Figure 4**, and can be summarized as follows:

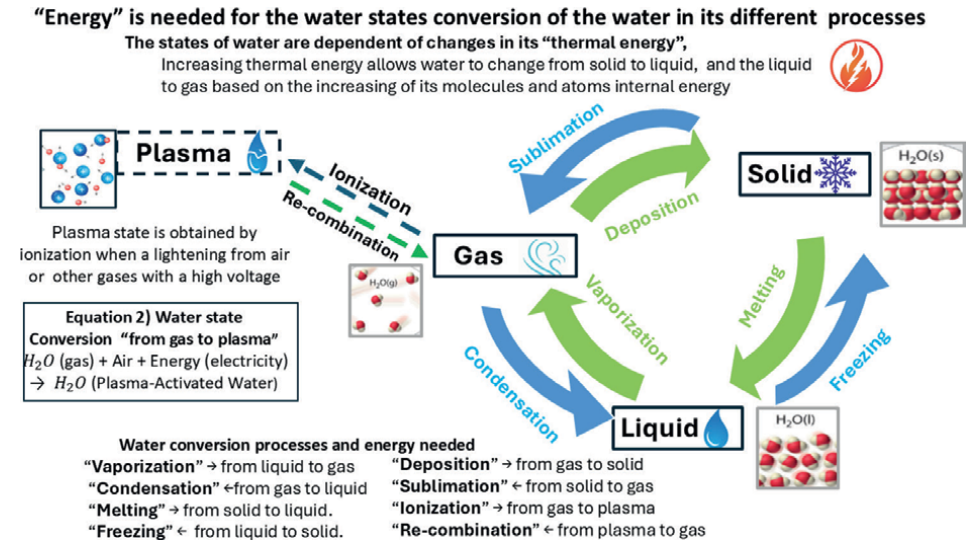


Figure 3.
 Energy and states of water conversion.

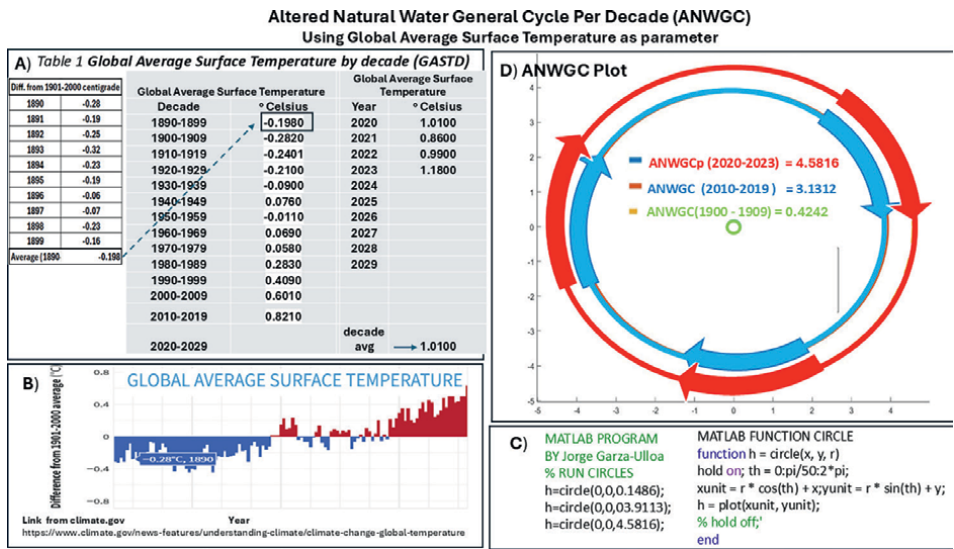


Figure 4.
 Instructions for calculating the altered natural water general cycle per decade (ANWGC) using the global average surface temperature as a parameter: A).

- Vaporization $\rightarrow$ from liquid to gas
- Condensation $\leftarrow$ from gas to liquid
- Melting $\rightarrow$ from solid to liquid
- Freezing $\leftarrow$ from liquid to solid

- Deposition → from gas to solid
- Sublimation ← from solid to gas
- Ionization → from gas to plasma
- Recombination ← from plasma to gas

Plasma-activated water showers have a temporary cleansing effect, and the water that remains contains a higher content of bound nitrogen. This is nature's way of providing nutrition for plants and trees [15].

3.2 Parameters to evaluate altered natural water general cycle

There are many ways to evaluate the natural water cycle by using different parameters as a radius for the circle representing the corrections for the altered water cycle. The most common parameters for the natural water cycle are Earth's global average surface temperature, water scarcity, precipitation, and many other indirect parameters to evaluate the natural water cycle with specific purposes. Earth's global average surface temperature is calculated by the weighted average of the temperature of Earth's surface over the land and ocean. The temperature values are measured at the surface air and at the sea surface over the ocean. The analysis of recorded data for the Earth's global surface temperature indicates the following [16]:

- It has risen by an average of 0.11° Fahrenheit (0.06° Celsius) per decade since 1850, or about 2° F in total.
- The rate of warming since 1982 is more than three times faster: 0.36° F (0.20° C) per decade.
- The 10 warmest years in the historical record have all occurred in the past decade (2014–2023).

A fraction of a degree seems to be small, but compared with the massive heat energy for raising the temperature of the ocean and land, it is very significant for nature. It causes temperature extremes, reduced snow cover and sea ice, and intensifying heavy rainfall and results in the alteration of all habitats on Earth, affecting human life, vegetation, and animals.

- Water scarcity is measured by two different types: physical water scarcity, when there is not enough water for the demand needed, and social water scarcity, when water infrastructure usually fails to meet the demand when the demand increases due to the effects of global warming. The measurement of water scarcity and water quality is frequently made by remote sensors, drones sensing temperature, and satellite imagery [17]. These are described as follows:
 - Remote sensors are used to measure water quality with parameters such as pollution, turbidity, and chlorophyll levels.

- Sensors used in drones take high-resolution images of water sources to assess the impact on water resources.
- Satellite imagery allows real-time data by monitoring water resources per region and applying spatial analysis to the geospatial data to detect regions with severe water scarcity.

The main tools to represent water scarcity are as follows:

- Water scarcity index, which combines various factors such as water stress. It is a value when the demand for water exceeds the available water, water quality, and population density in each specific region.
- Water risk filter that evaluates the risk for businesses and communities based on water scarcity and water quality.
- And others.

Water scarcity increases the need to focus on sustainability of groundwater resources, which include the water beneath the surface trapped in sediments and rock. We need to take good care of our planet to have an opportunity for adaptation in times of climate change caused by global warming.

- Precipitation is the main way for atmospheric water to return to Earth from clouds in different forms, such as rain, freezing rain, sleet, snow, or hail. It is usually measured in units of inches or millimeters over a specific time period [18]. The precipitation measurement methods that are more common are traditional physical measurement devices, ground-based weather radar, and satellite-based radiometers [19]. They are described as traditional physical measurement devices and are used *in situ* including as nonrecording cylinder container gauge, recording weighing, float gauge, and others. Gauges perform direct measurements of precipitation constituting the only device providing independent quantitative data, but gauges only provide point measurements; thus, the representativeness regarding the capture of extreme rainfall is limited.
 - Ground-based weather radar scans for echoing or by electromagnetic waves for specific atmospheric volume for precipitation particles in continuous real-time monitoring. Radar-based precipitation retrievals use the interaction of air-borne hydrometeors with the emitted electromagnetic wave of the measurement device.
 - Satellite-based radiometers are from two categories: geostationary Earth-orbiting satellites that monitor the same limited region of the Earth at a high frequency and low Earth-orbiting satellites that provide global information, in the case of polar-orbiting satellites, or at least up to a maximum latitude, although they give only temporal snapshots at each location.

Weather radars, in combination with gauge data, provide high-quality precipitation data with blanket coverage. Satellite-based measurements help provide a global view of precipitation and precipitation monitoring, especially in areas without ground-based radar coverage, such as oceans.

- Other indirect parameters to evaluate the natural water cycle with specific purposes that include climate adaptation, water management, water quality, soil management, and many others, are as follows:
 - Climate adaptation parameters such as air temperature or thermal climate index that describes the physiological comfort of the human body to the surrounding environment under specific meteorological conditions based on humidity, wind, and radiation [20].
 - Water management, with a main objective of strengthening development outcomes for people, production, and the planet while reducing disaster-related risks such as water scarcity, hydrological uncertainty, and extreme weather events.

The following are some of the facts about water:

- There are 2.5 billion people worldwide depending on ground water.
- 276 transboundary basins are shared by 148 countries that account for approximately 60% of the global freshwater flow, and 300 aquifer systems are transboundary in nature.
- The most frequent parameters for water management are water security, flood peak reduction, and EPIC perspective response (managing hydroclimatic risks), which describe floods and droughts not as independent events but rather as different ends of the same hydroclimatic spectrum [21].
- Water quality, which measures the suitability of water based on physical, chemical, and biological parameters based on a particular use under standard types: potable water, safe to drink, palatable water, the presence of chemicals, not a threat to human health, contaminated water, unfit for drinking or domestic use, and infected water, contaminated with pathogenic organisms [22]. The most frequent parameters for water quality are physical, chemical, and biological:
 - Physical water characteristics include temperature, turbidity, electrical conductivity, salinity, total dissolved solids, color, taste, odor, and chemical-biological characteristics.
 - Chemical water characteristics include pH, acidity, alkalinity, hardness, chlorine, and dissolved oxygen chemicals.
 - Biological water characteristics include biological oxygen demand and pollutant presence.
- Soil management that applies treatments and practices for protecting soil with the goal of enhancing performance on soil conservation, amendment, and optimal health. Soil conservation includes measures for preventing erosion and degradation. Soil amendment is aimed at improving quality by adding nutrients and organic matter. Lastly, optimal soil health aims at balancing human needs

with environmental conservation [23]. Some of the most common parameters are soil biological activity, soil water infiltration, soil contamination, chemical fertility, and others [16].

- Many other indirect parameters.

3.3 Evaluation of the natural altered water cycle by global warming

The most recommendable initial parameter to evaluate the natural altered water cycle by global warming is the global average surface temperature (GAST), which includes the land and marine environments. Unfortunately, the planet's average temperature is on a continuous rise, and all the values throughout the years are well documented on the website climate.gov [16]. They plotted the difference of GAST per year from the reference value before industrial years, which was approximately 59°F (15°C).

The GAST changes over the years in °C can be found at the website climate.gov, specifically the bar chart found on the section Climate Change: Global Temperature section [16], where the bar chart compares the annual GAST value against the trend from 1901 to 2000 average [16]. In this research, they have summarized the average temperatures per decade as shown in Table 1 of **Figure 4A**. For example, the average temperature for the decade 1890–1899 is obtained by the average for the bar chart [16] for 1890 value = −0.28 to 1899 value = −0.16, obtaining the result −0.198 for the decade 1890–1899, where:

- global surface temperatures per decade (GASTD) from 1890–1899 to 2020–2029 are on the left side of table 1 in **Figure 4A** and
- global surface temperatures per year (GAST) for the actual decade from 2020 to 2029 are on the right side of table 1 in **Figure 4A**.

3.3.1 General equation for altered natural water general cycle (ANWGC)

For calculating the altered natural water general cycle for any decade represented as ANWGC(D), we apply the general equation for the altered natural water general cycle as shown in Eq. (3).

General equation for altered natural water general cycle:

$$ANWGC(D) = ABS \left(\frac{GASTD(To\ Evaluate) - GASTD(Ref)}{GASTD(Ref)} \right) \quad (1)$$

Where: ABS () is a mathematical function to obtain a nonnegative value regarding its sign, ANWGC(D) is the general equation for altered natural water general cycle applied for a specific decade D, GASTD (To Evaluate) is the global average surface temperatures for the decade to be evaluated, and GASTD (Ref) is the global surface temperatures for the decade used as a reference.

3.3.2 Calculation of ANWGC for the decade 1900–1909

To obtain the value of the altered natural water general cycle by global warming for the decade 1900–1909, which is represented in Eq. (2) as ANWGC

(1900–1909), we take the GASTD values from the left side of table 1 in **Figure 4 A**. These are as follows:

- $GASTPD(D) = GASTPD(1900–1909) = -0.2820^{\circ}C$
- $GASTPD(Ref) = GASTPD(1890–1899) = -0.1980^{\circ}C$

Applying these values in Eq. (1), we obtain Eq. (2):

Altered natural water general cycle evaluated for the decade 1900–1909 using 1890–1899 as reference:

$$ANWGC(1900–1909) = ABS\left(\frac{-0.2820 - (-0.1980)}{-0.1980}\right) = 0.4242 \quad (2)$$

The resulting value for $ANWGC(1900–1909) = 0.4242$ is plotted in **Figure 4D**, represented as a small circle with a radius of 0.4242 in green. This is going to be used as comparative values for other decades in this example.

Note*: We used the MATLAB© program [24] shown in **Figure 4C**.

3.3.3 Calculation of ANWGC for the decade 2000–2009

To obtain the value of altered natural water cycle by global warming for the next decade from 2000 to 2009, represented as $ANWGC(2000–2009)$, we take the GASTD values from the left side of table 1 in **Figure 4A**. These are as follows:

$GASTPD(\text{to evaluate}) = GASTPD \text{ by year } (2000–2010) = 0.6010^{\circ}C$

$GASTPD(Ref) = GASTPD(1900–1909) = -0.2820^{\circ}C$

Applying these values in Eq. (1), we obtain Eq. (3).

Altered natural water general cycle for the decade $ANWGC(2000–2009)$ using as reference 1900–1909:

$$ANWGC(2000–2009) = ABS\left(\frac{0.6010 - (-0.2820)}{-0.2820}\right) = 3.1312 \quad (3)$$

The resulting value, $ANWGC(2000–2009) = 3.1312$, is plotted in **Figure 4D** as a circle with a radius of 3.1312 in blue. This circle indicates an altered natural general circle, where the last hundred years (last century) had a big increase by global warming from $(1900–1909) = 0.4242$ to $(2000–2009) = 3.1312$. The ratio of increase in global temperature in one century analyzed per decade can be calculated by applying Eq. (4).

Ratio of increased global temperature in twentieth century:

$$RGT(20th\ century) = \frac{ANWGC(2000–2009)}{ANWGC(1900–1909)} = \frac{3.1312}{0.4242} = 7.38 \quad (4)$$

3.3.4 Calculation of ANWGC for the decade 2010–2019

The altered natural water cycle by global warming for the decade from 2010 to 2019 is represented as $ANWGC(2010–2019)$. We take again the GASTD values from the left side of table 1 in **Figure 4A**. These are as follows:

- GASTPD (to evaluate) = GASTPD by year (2010–2019) = 0.8210°C
- GASTPD (Ref) = GASTPD (1900–1909) = −0.2820° C

Applying these values in Eq. (3), we obtain Eq. (7).

Altered natural water general cycle for the decade ANWGC(2010–2019) using as reference 1900–1909:

$$ANWGC(2010-2019) = ABS\left(\frac{0.8210 - (-.2820)}{-.2820}\right) = 3.9113 \quad (5)$$

The ratio of the increase in global temperature in one century +20 years analyzed per decade can be calculated applying Eq. (4), as shown in Eq. (6).

Ratio of increased global temperature in a century +20 yrs:

$$RGT(a\text{ century} + 20\text{ yrs}) = \frac{ANWGC(2010-2019)}{ANWGC(1900-1909)} = \frac{3.9113}{0.4242} = 9.22 \quad (6)$$

RGT (20th century) = 7.381 indicates that the altered natural water general cycle increased more than 7 times in 100 years. And indicates the increase of the altered natural water general cycle on 120 years was 9.22 times.

3.3.5 Calculation of ANWGC for the current decade (2020–2029)

The altered natural water cycle by global warming for the current decade 2020–2029 can be calculated as a partial decade represented as ANWGC_p (2020–2029). We take again the GASTD values from the right side of table 1 in **Figure 4A**. These are as follows:

- GASTPD (to evaluate) = GASTPD by year (2020–2023) = 1.0100°C
- GASTPD (Ref) = GASTPD (1900–1909) = −0.2820°C

Applying these values to Eq. (1), we obtain Eq. (7).

Altered natural water general cycle for decade (ANWGC) partial decade 2020–2023 using as reference 1900–1909:

$$ANWGC_p(2020-2023) = ABS\left(\frac{1.0100 - (-.2820)}{-.2820}\right) = 4.5816 \quad (7)$$

The resulting value ANWGC (2020–2023) = 4.5816 is plotted in **Figure 4D** as a circle with a radius of 4.5816 in red. This circle indicates that the altered natural general circle for the partial decade of 2020–2023 has one more time an accelerated increase in global warming.

To calculate the ratio of increase in global temperature in one century +24 years, we apply Eq. (6) as indicated in Eq. (8).

Ratio of increased global temperature in one century+24 yrs.

$$RGT(2020-2023) = \frac{ANWGC(2020-2023)}{ANWGC(1900-1909)} = \frac{4.5816}{0.4242} = 10.80 \quad (8)$$

The ratio of the increase in global temperature in one century plus 24 years is 10.80; this means almost eleven times!

4. Conclusions for the calculation of altered natural water general cycle (ANWGC) and future research directions

The steps to calculate the altered natural water general cycle per decade (ANWGC), using global average surface temperature as a parameter, are shown in **Figure 5** and summarized in Table 2 in **Figure 5A**. These are as follows:

1. Use data from Table 1 in **Figure 4A** for global average surface temperature by decade from the left side and by year for the actual decade on the right side of the table.
2. Apply the general Eq. (1) altered natural water general cycle per decade ANWGC(D) indicated at Eq. (1) and obtain the results for each decade to evaluate in your analysis. Run the MATLAB® [24] code shown in **Figure 4C** to plot the different decades for the altered natural water general cycle; this program calls the function circle also shown in **Figure 4C**.
3. Analyze the resulting plotted ANWGC per decade evaluated, as shown in **Figure 4D**, the altered natural water general cycle for decade and calculate the ratio of the increase in global temperature.

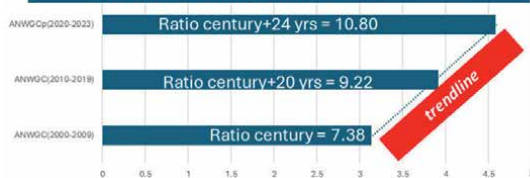
A) Table 2: Calculation & Analysis for "Altered Natural Water General Cycle"

Eq.	Decade evaluated GASTD (ref) for 1900 - 1909	ANWGC	Ratio Increase decade Nature process	Ratio of global warming increase
7)	(1900 - 1909) ref (1890-1899)	0.4242	-	Ref Value
8)	(2000 - 2009) ref (1900-1909)	3.1313	7.38	More than 7 times
10)	(2010 - 2019) ref (1900-1909)	3.9113	9.22 (9.22-7.38-1.84)	More than 9 times
12)	P(2020-2023) ref (1900-1909)	4.5816	10.80 (10.80-9.22-1.58)	Almost 11 times

C) These result obtained agrees with

The comments and observations of the data shown at climate.gov [17]: "In 2023, nearly half of the days were more than 1.5°C above the 1850–1900 average," and reports of the "European climate agency Copernicus" said July 2024's average heat just missed surpassing July of last year [25], and some scientists say this sets a dangerous precedent [24].

B) Altered Natural Water General Cycle Per Decade (ANWGC) "ratio global warming increase" and its "trendline"



D) Final remark

The calculation for the "altered natural water general cycle (ANWGC)" and charting it as a circle representing its alterations is an easy way to understand how global warming is increasing. It is a practical way to evaluate, measure, and analyze the need for "shortening the natural altered water cycle by global warming."

Figure 5. Calculations and final remarks for shortening altered natural water general cycle.

4. Place all the resulting values in a table and analyze the trend tendency, as shown in Table 2 in **Figure 5A** and obtain a bar chart as shown in **Figure 5B**.

Analysis results shown in **Figure 5A** table 2 indicate the following:

- The ratio for global warming increase per decade values shows a very clear trend line of increase for accelerated global warming, as shown in **Figure 5B**.

The difference in increment in ratio increased decade as shown column 4, Table 2 on **Figure 5** calculated as the difference between ratio $9.22-7.38=1.84$ and the difference in the last 4 years calculated $10.80-9.22=1.58$. This means that in only 4 years from 2020–2023 the global warming has now grown close to the value obtain in 10 years from 2010–2019 representing exponential growth values!

- The result agrees with the comments and observations of the data shown on climate.gov [16]: “In 2023, nearly half of the days were more than 1.5°C above the 1850–1900 average,” and some reports and the European climate agency Copernicus said that July 2024’s average heat just missed surpassing July of last year [16, 25, 26], and some scientists say this sets a dangerous precedent [16] as shown in **Figure 5C**.

The calculation for ANWGC as well as charting it as a circle representing its alterations is an easy way to understand how global warming is increasing. It is a practical way to evaluate, measure, and analyze the need for shortening the natural altered water cycle by global warming.

4.1 Future development to evaluate and correct the altered natural water general cycle

We will focus the future of this research on the altered natural water general cycle in three main directions:

1. Integration with other water parameters beside global surface Earth temperature as water scarcity, precipitation, and many other indirect parameters to evaluate the natural water cycle with specific purposes as climate adaptation, water management, water quality, soil management, and many others. All of them were introduced in Section 3.2.
2. Evaluation of altered natural water general cycle in water cycle by region to have an easy measurement to detect changes, and the goal is to optimize the ecosystem and have more control over its evolution. Water cycle by region must be based on a well-defined landscape and represented by its specific natural water cycle, integrating the variations on the altered natural water cycle.
 - a. Water cycle by region representation must be in a natural logical way, allowing us to do continuous evaluations based on historic readings of normal, stable values for that specific region compared to actual reading values in the same region. Evaluation of water cycle by region must allow pondering each method and technique applied for shortening the natural altered water cycle and detecting the values for water scarcity available in that region for adequate time periods.

- b. Water cycle by region will use different methods and techniques to help restore the natural general cycle. Restoration must be based on replicating nature general water cycle by region, but in some special cases, artificial based on human design to help resolve the water scarcity problem faster.
- c. The shortening natural altered water cycles will be explained in future research, with the goal of helping nature to be reestablished and following up the water cycle. Water cycle by region that is based on landscape types is

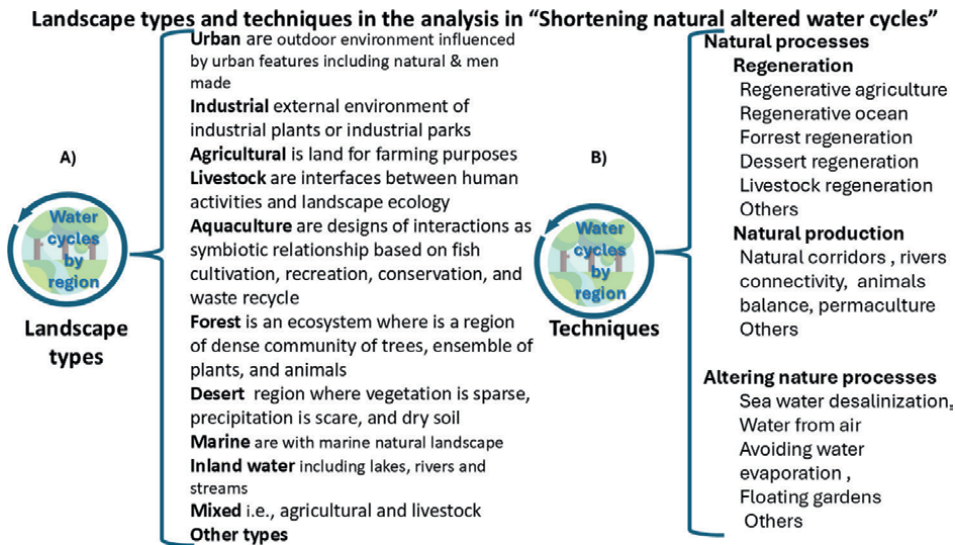


Figure 6.
Proposed landscapes and techniques in the analysis of shortening natural altered water cycles.

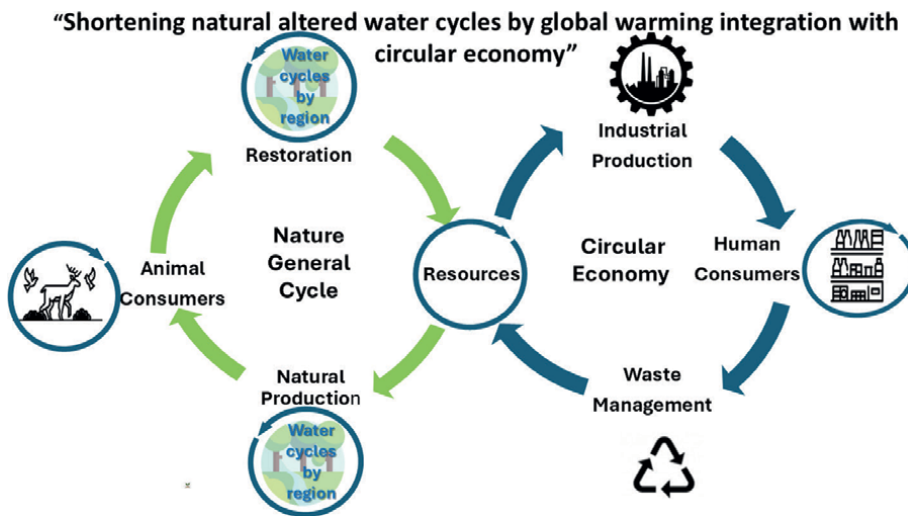


Figure 7.
Proposal for the integration of water cycles for region in the natural general cycle and circular economy evaluated by shortening natural altered water cycles.

summarized as shown in **Figure 6A**, and the techniques are summarized as shown in **Figure 6B**.

- d. New proposals with examples based on the integration of evaluated measurements of shortening natural altered water cycles, applying different methods and techniques for region for the Natural General Cycle and Circular Economy as indicated at **Figure 7**.

Notices

Knowledge and best practices in this field are constantly changing as new research and experience broaden our understanding. Changes in research methods, professional practices, or medical treatment may be necessary. To the fullest extent of the law, neither the publisher nor the authors, contributors, or publishers assume any liability for any injury and/or damage to persons or property as a matter of product liability, negligence, or otherwise, or for any use or operation of any method, product, instruction, or idea contained herein.

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The Impact of Red Hill Fuel Leaks on Water Quality: A Case Study of Pearl Harbor's Contamination in O'ahu

Patricia Yu

Abstract

Water quality monitoring is crucial for maintaining the sustainability and safety of water resources, especially in areas vulnerable to industrial activities and environmental hazards. This paper explores the 2021 fuel leak incident at Pearl Harbor, O'ahu, involving the Red Hill Bulk Fuel Storage Facility, which led to significant environmental contamination. Approximately 19,000 gallons of jet fuel leaked into the Pearl Harbor aquifer, impacting around 93,000 individuals reliant on this water source. This study assesses the contamination's extent and its effects on the local ecosystem and public health. Key findings reveal severe and ongoing social, economic, and health impacts, underscoring the need for robust monitoring systems, effective response measures, and sustainable water management practices. This paper also emphasizes the importance of adaptive management, collaborative efforts among stakeholders, and the integration of advanced technologies to mitigate environmental risks and ensure water quality.

Keywords: water quality monitoring, Red Hill fuel leak, water contamination, sustainable water management, advanced monitoring technologies, public health impact

1. Introduction

Water quality monitoring is essential for ensuring the sustainability and safety of water resources, especially in regions prone to industrial activities and environmental hazards. The 2021 fuel leak at Pearl Harbor, O'ahu, involving the Red Hill Bulk Fuel Storage Facility, represents a significant case of environmental contamination, showing the need for robust monitoring and rapid response systems.

1.1 Background

Pearl Harbor has been a strategic military location for the United States since World War II, hosting significant naval activities. This harbor's infrastructure includes the Red Hill Bulk Fuel Storage Facility, which poses potential environmental risks. On November 20, 2021, the Red Hill Bulk Fuel Storage Facility leaked approximately

19,000 gallons of jet fuel into the Pearl Harbor aquifer, the primary source of Oahu's drinking water. This event directly contaminated the Red Hill well, affecting the Navy Water System, which provides water to about 93,000 people. Following this contamination, the State of Hawai'i Department of Health (HDOH) urged Navy Water System users to stop using tap water on November 30, 2021. As a result, approximately 93,000 individuals were potentially exposed to jet fuel for at least 10 days before transitioning to an alternative water source. The HDOH and Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry (CDC/ATSDR) conducted surveys to assess the immediate physical and mental health impacts, revealing that 86% of respondents reported new or worsening symptoms since the spill. A follow-up survey in September 2022 indicated that 80% continued to experience symptoms. These findings demonstrate the severe and ongoing social, economic, and health impacts of the fuel leak, raising significant concerns about long-term consequences and the effectiveness of response measures [1]. The Environmental Protection Agency (EPA), in conjunction with the HDOH, mandated comprehensive environmental monitoring and remediation actions to address the contamination. Their efforts include the installation of groundwater monitoring wells, soil and water sampling, and the implementation of treatment systems to remove contaminants [2].

1.2 Location

Figure 1 shows that the Red Hill Fuel Storage Facility is located on the island of O'ahu, Hawaii. It is situated inland from the southern coast, relatively close to the central part of the island, and is marked within a circled area on the map. This facility is positioned in proximity to key transportation routes, reflecting its strategic importance for fuel storage and distribution. According to **Figure 2**, the Red Hill Fuel Storage Facility comprises 20 tanks sitting on end, connected by an upper and lower access tunnel. These tanks were constructed from 1940 to 1943, with each tank being

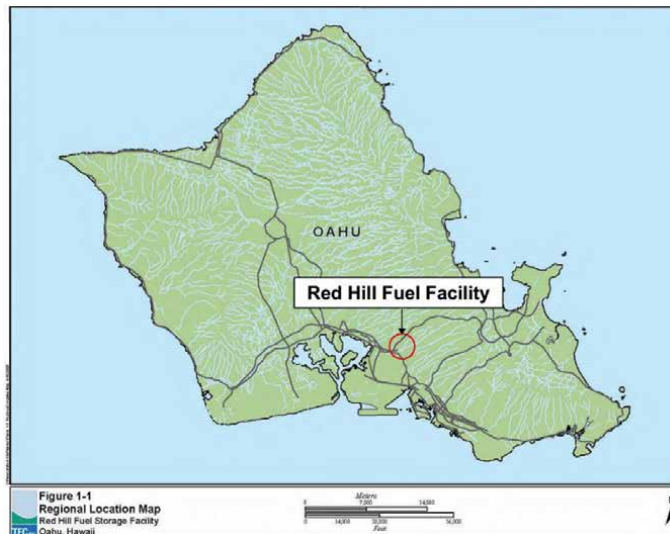


Figure 1. Red Hill Fuel Storage Facility map. Source: City and county of Honolulu Board of Water Supply. (<https://boardofwatersupply.com/bws/media/redhill/briefings/red-hill-ocr-community-informational-briefing-2020-01-10.pdf>).

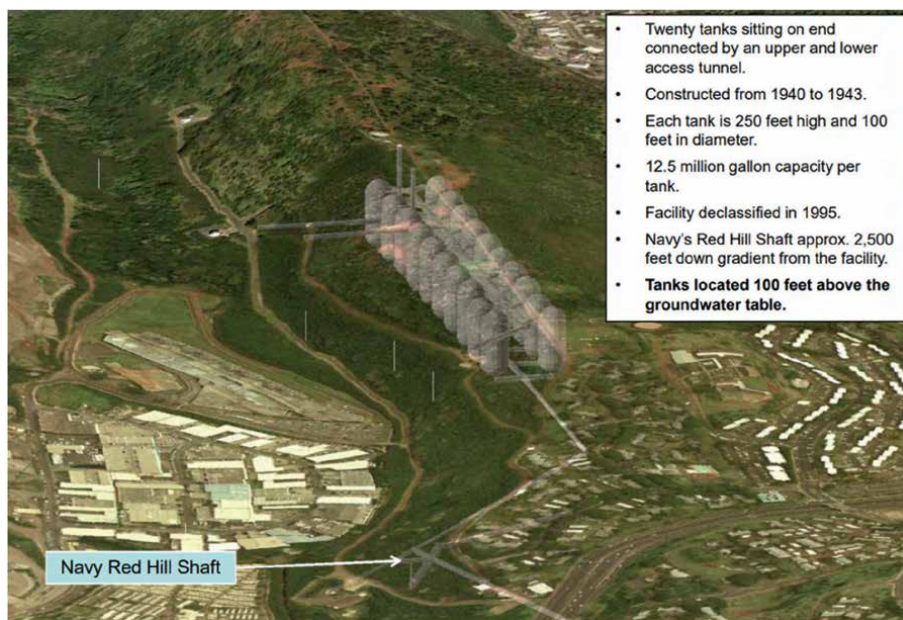


Figure 2.
 Red Hill Fuel Storage Facility details. Source: Red Hill Bulk Fuel Storage facility final technical report, 2007, Figures 1-3, p. 1-15. (<https://boardofwatersupply.com/bws/media/redhill/briefings/red-hill-ocr-community-informational-briefing-2020-01-10.pdf>).

250 feet high and 100 feet in diameter and having a capacity of 12.5 million gallons per tank. This facility was declassified in 1995. The Navy's Red Hill Shaft is located approximately 2500 feet down gradient from the facility. Notably, the tanks are positioned 100 feet above the groundwater table.

Figure 3 shows that the Red Hill Bulk Fuel Storage Facility is located adjacent to the Red Hill Shaft and near the Halawa Shaft. This facility is situated above the Moanalua Aquifer and the Waimalu Aquifer, with Moanalua Wells located further south. It also includes the boundary of the aquifers, water supply wells, and the distribution of Red Hill tanks within the storage facility. The inset map provides a regional context like **Figure 1**, showing the facility's position relative to other areas on the island of Oahu, underscoring the significance of the facility's location in relation to crucial water resources.

Figure 4 depicts the hydrologic units and sustainable yield of aquifer systems on Oahu, as managed by the State of Hawaii Commission on Water Resource Management. Oahu is divided into several regions, each labeled with its respective aquifer system and sustainable yield in million gallons per day (MGD). Major areas include Windward with 87 MGD, Pearl Harbor with 166 MGD, and Honolulu with 48.5 MGD. Other regions such as North, Central, and Waianae have yields of 56 MGD, 23 MGD, and 13 MGD, respectively. This figure shows the diverse aquifer systems across the island, showing the importance of water resource management for sustainable development and environmental protection. The Red Hill fuel leak poses a significant threat to the aquifer systems in Oahu, particularly those in the Pearl Harbor and Honolulu regions, which have high sustainable yields of 166 MGD and 48.5 MGD, respectively. Contamination from the fuel leak could jeopardize the island's water supply, affecting both the quantity and quality of available water resources, and

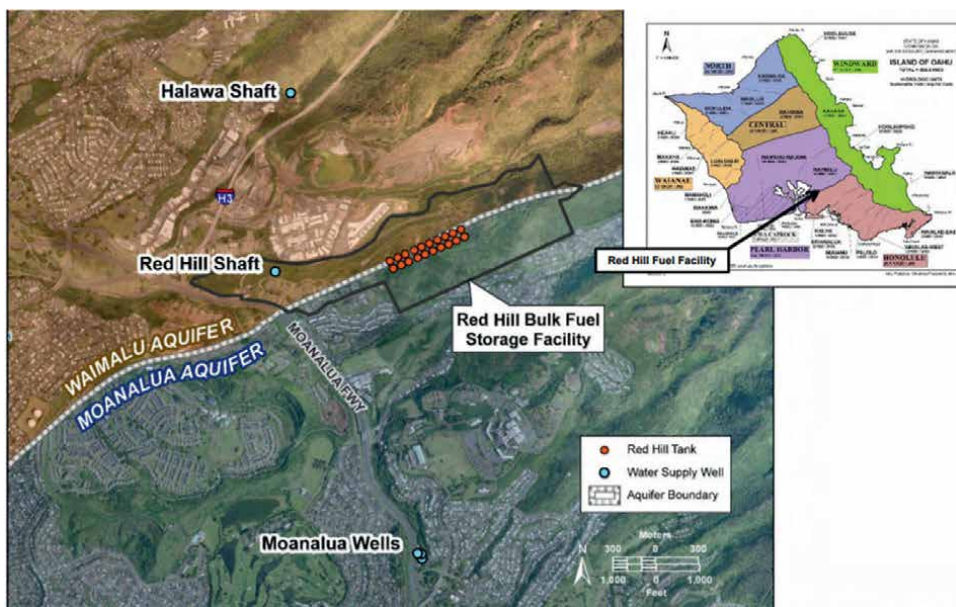


Figure 3. Red Hill tank and water supply wells. Source: City and county of Honolulu's Board of Water Supply. (<https://boardofwatersupply.com/bws/media/redhill/briefings/red-hill-ocr-community-informational-briefing-2020-01-10.pdf>).

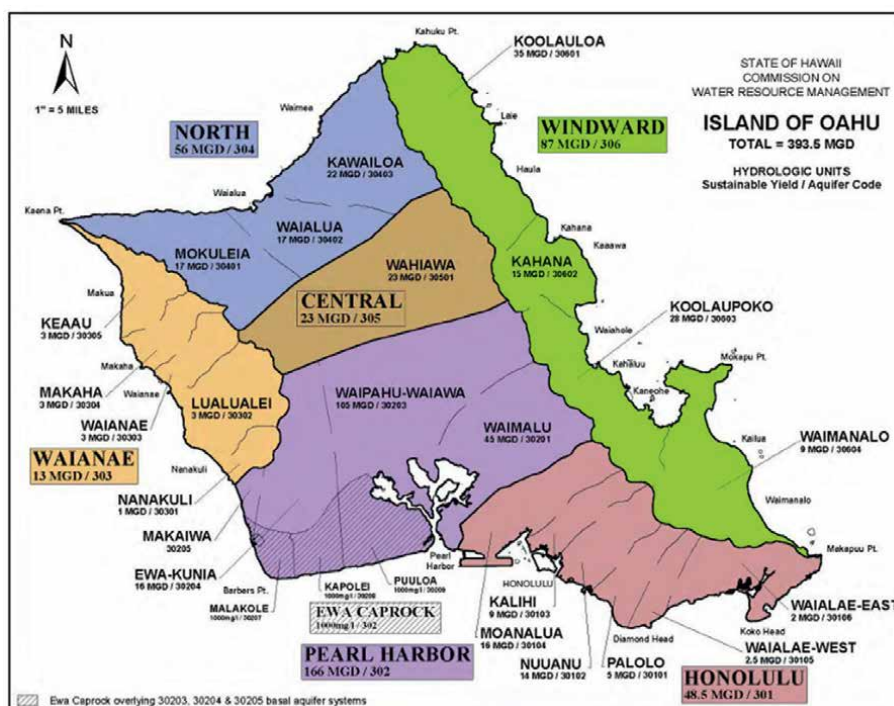


Figure 4. The inset map of **Figure 3**. Source: City and county of Honolulu's Board of Water Supply. (<https://boardofwatersupply.com/bws/media/redhill/briefings/red-hill-ocr-community-informational-briefing-2020-01-10.pdf>).

necessitating urgent measures for mitigation and cleanup to protect public health and the environment. This paper examines this incident's impact on water quality, reviewing advanced monitoring technologies and methodologies to analyze the extent of contamination and its effects on the local ecosystem and public health.

2. Literature review

Water quality monitoring is critical for detecting pollutants, assessing environmental health, and guiding water management policies. Acioly et al. [3] examines the water quality of the Tocantins River, a crucial water body located at the interface of the Brazilian savanna and Amazon biomes. This study focuses on the levels of potentially toxic and essential elements in the river's water and assesses the associated human health risks. Their findings indicate that elements like aluminum, copper, iron, magnesium, and selenium frequently exceed legal standards, particularly in urban areas. This research uses various indices, including the Weighted Arithmetic Water Quality Index (WAWQI) and the Water Quality Index (WQI), to evaluate the water quality comprehensively. Despite seasonal fluctuations and occasional exceedances, the overall water quality is rated from excellent to good, with no immediate health risks detected. This reveals the importance of ongoing water quality monitoring to protect public health and ensure the sustainability of the river's ecosystem.

Olugbenga et al. [4] presents a comprehensive review of the application of biomass-derived biochar in wastewater treatment within the framework of a circular economy. Their study highlights the efficacy of biochar as an adsorbent for removing various contaminants, including organic pollutants, heavy metals, and nutrients from wastewater. The authors emphasize the environmental and economic benefits of using biochar, particularly in promoting resource efficiency and sustainability. This paper is significant as it provides insights into innovative and sustainable water treatment solutions, emphasizing the role of biochar in addressing environmental challenges and advancing circular economy principles. Kesari et al. [5] provides a review of wastewater treatment and reuse, emphasizing its critical role in addressing water scarcity and environmental health. This study demonstrates various sustainable wastewater treatment methods, including the use of biochar, nanotechnology, and advanced oxidation processes, which enhance the removal of contaminants. The authors also discuss the health risks associated with untreated wastewater and propose a model for its safe reuse in agriculture. This work is important as it underscores the potential of treated wastewater as a resource for sustainable water management, improving soil fertility, and reducing environmental pollution. By integrating innovative treatment solutions, this study aims to mitigate the adverse health effects and promote the reuse of wastewater in an eco-friendly manner.

Silva [6] conducts a systematic literature review on wastewater treatment and its role in sustainable water resources management. This study shows the importance of wastewater treatment in extracting pollutants, removing coarse particles, eliminating toxicants, and killing pathogens, thus making treated water safe for various uses. It emphasizes the connection between waste management and sustainability, highlighting how wastewater treatment minimizes water waste, reduces pressure on natural water sources, and contributes to clean energy production. This review is significant as it provides a thorough evaluation of how wastewater treatment can lead to economic and environmental sustainability, offering valuable insights for policymakers and researchers in the field of sustainable water management. The author also emphasizes

that sustainable wastewater treatment solutions are vital for addressing global water scarcity and ensuring the availability of clean water. These solutions involve advanced treatment processes that not only purify water but also recover valuable resources such as biogas and fertilizers. Silva shows the multifaceted benefits of wastewater treatment, including the protection of natural water sources from depletion, the provision of a sustainable water supply for domestic and industrial use, and the reduction of environmental pollution. By integrating innovative technologies and promoting efficient water reuse, wastewater treatment plays a crucial role in achieving sustainable water resource management and supporting overall environmental sustainability.

Historical data on fuel leaks, such as the Exxon Valdez oil spill (1989) and the Deepwater Horizon oil spill (2010), provide insights into the long-term environmental impacts of such incidents. Beyer et al. [7] provides a comprehensive review of the environmental impacts of the Deepwater Horizon oil spill, which constituted an ecosystem-level injury in the northern Gulf of Mexico. This study details how oil contamination affected deepwater habitats, coastal areas, and a wide range of marine organisms. The use of dispersants, in situ burning, and other response measures helped mitigate some of the impacts, but long-term effects on species like deep-sea corals, large fish, sea turtles, and cetaceans remain a concern. This paper emphasizes the need for continued monitoring and research to understand the full extent of the spill's impact and to guide future oil spill response strategies. Wiens [8] provides an extensive examination of the environmental impact of the Exxon Valdez oil spill, drawing on nearly 25 years of scientific research. The Exxon Valdez oil spill released approximately 11 million gallons of crude oil into Prince William Sound, Alaska, severely affecting wildlife, including seabirds, sea otters, and fish populations. This book offers a multidisciplinary perspective, discussing the spill's effects on various biota and ecosystems, the successes and failures of post-spill studies, and ongoing areas of disagreement. It covers the fate of the oil in the environment, including its behavior in the water column and on shorelines, the use of bioremediation, and the broader ecological risks and recovery processes. Bioremediation and other cleanup efforts were employed to mitigate the damage, but recovery has been slow, with some habitats and species still showing signs of distress decades later. This comprehensive analysis is crucial for understanding the importance of water quality monitoring and effective spill response strategies to manage and mitigate the impacts of such environmental disasters.

3. Methodologies for water quality monitoring

3.1 Sampling techniques

In the case of the Pearl Harbor fuel leak, various sampling techniques were employed to assess water quality. These included grab sampling, which involves collecting water samples at specific locations and times [9], and composite sampling, which aggregates multiple samples over a period to provide an average concentration of pollutants [10]. Grab samples were collected using sterilized bottles to ensure no contamination, while composite samples were taken using automatic samplers that combine water at regular intervals. Both methods were crucial in obtaining accurate and representative data on the extent of contamination. Analytical instruments such as gas chromatographs and mass spectrometers were used to detect and quantify the presence of hydrocarbons and other contaminants in the water samples [11]. These rigorous methodologies ensured the reliability and validity of the water quality assessment.

Schaeffer et al. [12] provides a detailed comparison of grab and composite sampling methods used in effluent monitoring. This paper discusses the theoretical and practical aspects of both techniques, showing the advantages and limitations of each. Grab sampling involves collecting individual samples at specific times, providing snapshots of water quality that can reveal variability and extreme values. Composite sampling, on the other hand, aggregates multiple subsamples over a period, offering an average that is useful for understanding overall process conditions but can obscure short-term fluctuations. The authors argue that while composite samples are economically favorable for routine monitoring and regulatory compliance due to lower analytical costs, grab samples offer superior information on process variability and are better suited for detecting extreme values and immediate issues. This study underscores the importance of selecting the appropriate sampling method based on the monitoring objectives and the specific environmental context.

3.2 Field equipment and remote sensing technologies

Advanced field equipment, such as portable water quality meters and spectrophotometers, were used to measure parameters like pH, dissolved oxygen, and hydrocarbon concentrations. Remote sensing technologies, including satellite imagery and drones, provided spatial data on the spread of contaminants, helping to identify affected areas and guide remediation efforts. Ahmad [13] provides an in-depth overview of the application of smart remote sensing networks in disaster management. This paper explores the critical role of remote sensing technologies in monitoring various environments, predicting disasters, and aiding in mitigation and recovery efforts. This study discusses the layered framework of remote sensing technology, which includes the sensing layer, network layer, data processing layer, and application layer. It shows the importance of advancements in each layer to enhance the overall intelligence and effectiveness of remote sensing systems. The integration of emerging technologies like the Internet of Things (IoT), cloud computing, and low-power wireless networks is highlighted as essential for the evolution and sustainability of remote sensing applications. This comprehensive analysis underscores the significance of remote sensing in providing timely and accurate data for disaster management, making it an invaluable resource for researchers and practitioners in the field. Vijayaraghavan et al. [14] provides an extensive review of the application of remote sensing and GIS technologies in disaster management. This paper discusses how these technologies have been used over the past five decades to manage natural disasters such as floods, earthquakes, and tropical cyclones, as well as man-made disasters like nuclear accidents and oil spills. It shows the advantages of using geospatial technologies for effective disaster management, including improved data collection, real-time monitoring, and enhanced decision-making capabilities. This review also identifies challenges related to data interoperability and visualization for decision-makers. This paper is important as it shows the critical role of remote sensing and GIS in mitigating the impacts of disasters, improving emergency response, and facilitating recovery efforts.

3.3 Artificial intelligence

Using Artificial Intelligence (AI) to monitor water quality is essential for several reasons. AI models, such as Artificial Neural Networks (ANN) and Long Short-Term Memory (LSTM), can handle large volumes of data quickly and accurately, identifying patterns and trends that may be missed by traditional methods. This capability

allows for real-time monitoring and early detection of water quality issues, enabling prompt intervention and management. Rana et al. [15] explores the application of AI techniques in monitoring and evaluating surface water quality. This study focuses on the use of machine learning models, specifically ANN and LSTM models, to predict and assess water quality parameters such as temperature, pH, dissolved oxygen, and turbidity. The authors demonstrate how these AI models can process large datasets efficiently, providing accurate predictions and real-time monitoring capabilities. This research is significant as it highlights the potential of AI to enhance traditional water quality monitoring methods, offering a more efficient and scalable approach to managing and protecting water resources. Shiri et al. [16] explores the development and application of various AI models for simulating groundwater quality parameters. This study evaluates several AI techniques, including Support Vector Machine (SVM) and ANN, and their hybrid forms combined with optimization algorithms like the Firefly Algorithm (FFA). This research demonstrates the effectiveness of these AI models in accurately predicting key water quality indicators such as electrical conductivity, sodium adsorption ratio, total dissolved solids, and sulfate concentrations. This paper is significant as it shows the potential of AI to enhance the precision and efficiency of water quality monitoring, providing valuable tools for environmental management and decision-making. Strobl and Robillard [17] provides an insightful overview of the application of various AI technologies in the monitoring of surface water quality. This paper reviews the potential of expert systems, ANNs, genetic algorithms (GAs), and fuzzy logic systems in enhancing the design and operation of water quality monitoring networks. These AI technologies are shown to offer significant advantages in terms of optimizing sampling locations and frequencies, handling large datasets with missing or uncertain data, and providing real-time, accurate water quality assessments. The authors highlight the importance of integrating AI techniques with traditional monitoring methods to achieve more efficient and cost-effective water quality management.

4. Impact of the fuel leak

4.1 Extent of water contamination

The primary source of contamination was identified as a ruptured underground fuel storage tank at Red Hill, which leaked thousands of gallons of fuel into the surrounding soil and groundwater. The contamination spread through subsurface pathways, affecting nearby water bodies and threatening drinking water supplies. Analysis of water samples revealed elevated levels of hydrocarbons, particularly benzene, toluene, ethylbenzene, and xylene (BTEX compounds). These contaminants exceeded safety thresholds set by the EPA, indicating severe pollution.

Jedra [18] reports on the discovery of extensive contamination at the Navy's Red Hill fuel complex, showing a broader issue beyond a notable 2022 firefighting foam spill. State and federal regulators found that the Per- and Polyfluoroalkyl Substances (PFAS) levels in soil and groundwater around Red Hill exceeded EPA standards in multiple monitoring wells. These "forever chemicals" are persistent in the environment and pose significant health risks even in small amounts. The contamination affects an interconnected aquifer that supplies drinking water to both military and civilian populations. Regulators are calling for more frequent and comprehensive testing, as well as immediate investigations to address the widespread contamination, which may stem from both recent and historical chemical releases at the site

Figure 5 illustrates the proximity of the Red Hill Fuel Storage Facility to crucial water sources on O’ahu. Located just 100 feet above the Waimalu/Moanalua Aquifer, the facility comprises 20 massive fuel tanks connected by a system of underground tunnels and pipelines. The Red Hill Shaft, a key water source for the Joint Base Pearl Harbor-Hickam (JBPHH), lies a mere 2600 feet from the tanks, while the Halawa Shaft, providing water to urban Honolulu, is 5000 feet away. The historical and ongoing fuel leaks from the Red Hill facility pose a significant threat to these water supplies. Contaminants from the leaks can migrate through the porous volcanic rock into the aquifer, leading to drinking water contamination problems. The presence of fuel-laced water in the aquifer indicates that the contamination can travel and impact a broader area, putting at risk the health of approximately 400,000 residents who rely on this water source.

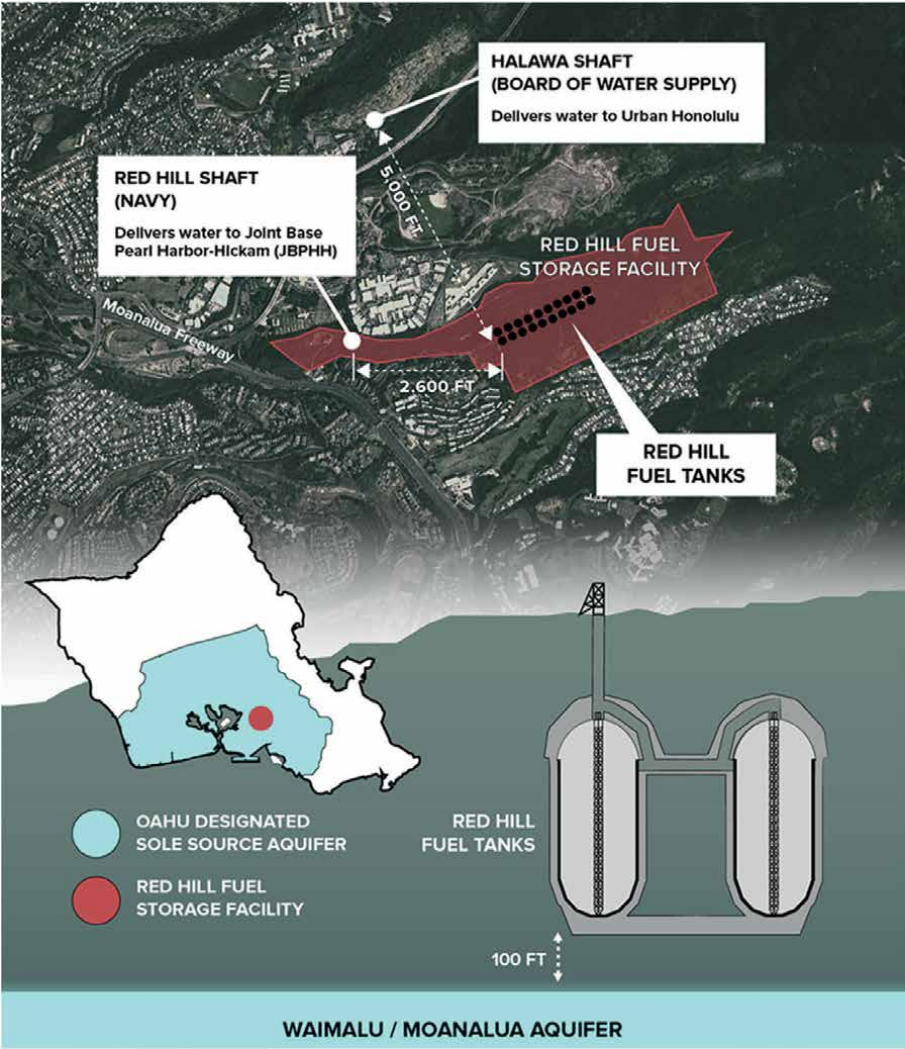


Figure 5. Impact of Red Hill Fuel Storage Facility on Oahu’s drinking water. Source: City and county of Honolulu Board of Water Supply ‘Red Hill Bulk Fuel Storage Facility Community Information Briefing, 2020,’ ACE Library/map data: Google maps.

4.2 Public health implications

Exposure to contaminated water posed significant health risks to the local population. Residents reported symptoms such as nausea, headaches, and skin rashes, prompting public health advisories and water use restrictions. Long-term health studies were initiated to assess potential chronic effects, particularly in vulnerable populations such as children and the elderly. Coveney [19] demonstrates the reported health problems included seizures, kidney failure, migraines, burns, rashes, brain injuries, and the death of pets from the Red Hill fuel leak. This contamination affected around 93,000 individuals, with 2000 reporting health issues and 17 requiring hospitalization. Children were particularly affected, with 77% of those surveyed showing symptoms linked to petroleum-contaminated water. Initially, the Navy denied the severity of the contamination but later confirmed hazardous levels of petroleum hydrocarbons in the water. This incident shows the necessity for strict oversight and maintenance of military fuel storage facilities to prevent environmental disasters and safeguard public health.

4.3 Socio-economic impacts on local communities

The contamination had significant socio-economic repercussions for local communities, particularly those dependent on fishing and tourism. The closure of affected water bodies for fishing and recreational activities resulted in economic losses and reduced livelihoods. Public distrust in water quality management also increased, highlighting the need for transparent and effective communication strategies. Arjun [20] details the socio-economic and environmental impacts of the Red Hill Fuel Leak on Oahu's local communities. The Red Hill Fuel Leak incident caused significant health problems, displacement, and financial strain among residents. The delayed response and poor communication from the US Navy and Department of Defense eroded public trust and highlighted ongoing issues of US militarism in Hawaii, including environmental degradation and indigenous displacement. Efforts led by the O'ahu Water Protectors, a coalition of community members and activists, focus on raising awareness, organizing protests, and advocating for stricter regulations. Arjun emphasizes the need for robust preventive measures and greater accountability to protect Oahu's water resources and community well-being.

The incident management faced several challenges, including limited access to contaminated sites, the complexity of subsurface contamination pathways, and the need for rapid and effective communication with the public. These challenges underscored the importance of preparedness and robust monitoring systems in managing environmental disasters.

5. Recommendations for future monitoring and management

5.1 Enhancing early detection and rapid response systems

To improve future response efforts, it is essential to enhance early detection systems using advanced monitoring technologies such as remote sensing and real-time data collection. Rapid response protocols should be established, ensuring timely and effective action to contain and mitigate contamination incidents. Trogrlić et al. [21] discusses the crucial role of Early Warning Systems (EWS) in disaster risk reduction,

emphasizing the importance of preparedness and robust monitoring systems. This chapter outlines an integrated approach to EWS, which includes hazard monitoring, risk assessment, forecasting, communication, and preparedness activities tailored to community needs. The authors show that effective EWS requires technological advancements in monitoring and forecasting, combined with educational drills, early alerts, and strong governance. They advocate for a holistic strategy that involves both top-down and bottom-up approaches, ensuring community engagement and leveraging local knowledge. Continuous monitoring, accurate risk communication, and regular drills are essential for significantly mitigating the impacts of environmental disasters. Vermiglio et al. [22] provides a comprehensive analysis of the impact of emerging technologies (ETs) on disaster management (DM) processes, particularly in improving performance across the preparedness, response, recovery, and mitigation phases. This study employs a systematic literature review, analyzing 69 publications using VOSviewer software for text mining and cluster visualization. Their findings reveal the significant role of ETs in enhancing preparedness and resilience in DM systems. Simulation and disaster risk reduction are identified as major fields where ETs can be effectively applied. The authors emphasize the importance of robust monitoring systems and preparedness measures enabled by ETs. Technologies such as big data, IoT, machine learning, AI, and remote sensing are shown to provide transformative potential for disaster management by improving data collection, decision-making, and performance measurement. These technologies facilitate timely and accurate information dissemination, which is crucial for effective preparedness and response, thereby enhancing the resilience and efficiency of systems to mitigate the impact of catastrophic events on communities and economies.

Khan et al. [23] conducts a comprehensive review of disaster management systems, focusing on flood control while addressing other natural disasters such as earthquakes and wildfires. This study advocates for the development of model-driven engineering approaches to simulate disaster scenarios and improve response planning. The authors underscore the necessity for continuous improvement and innovation in disaster management practices to mitigate the impacts of natural disasters effectively. This paper highlights the significance of incorporating interdisciplinary approaches and leveraging technological advancements to create resilient and adaptive disaster management systems. The authors suggest that future research should focus on developing integrated systems that combine various data sources and analytical techniques to enhance predictive capabilities and decision-making processes.

5.2 Implementing sustainable water use practices

Sustainable water use practices should be promoted to reduce the risk of contamination and ensure the long-term availability of clean water resources. This includes measures such as water conservation, pollution prevention, and the protection of natural water bodies from industrial activities. Santos et al. [24] examines sustainable water management practices in Brazil and Portugal, focusing on the integration of socio-economic and cultural dimensions. Key strategies include establishing robust legal frameworks, addressing socio-economic disparities to ensure inclusive water access, integrating cultural practices into modern management techniques, promoting efficient agricultural water use, and encouraging public participation. This article also highlights the role of digital transformation in optimizing water resource management through real-time monitoring and data analytics and emphasizes the need for adaptive strategies to enhance climate change

resilience. Elleuch et al. [25] discusses strategies for achieving environmental sustainability through pollution prevention, showing the importance of reducing waste and using non-toxic materials. Key approaches include increasing process efficiency to minimize pollution at its source, adopting new business tools and materials, and fostering a cultural shift toward anticipating and internalizing environmental costs. This article demonstrates the significance of sustainable practices in managing soil, water, and air pollution, and calls for comprehensive programs to reduce, reuse, or prevent pollution.

5.3 Policies for better environmental protection and resource management

Effective policies and regulations are crucial for protecting water resources and managing environmental risks. Policymakers should focus on strengthening environmental protection laws, enhancing regulatory oversight, and promoting community engagement in water resource management. Collaborative efforts between government agencies, industry stakeholders, and local communities are essential for achieving sustainable water management outcomes. In alignment with Sustainable Development Goal 6 (SDG 6), which aims to ensure availability and sustainable management of water and sanitation for all, comprehensive frameworks such as the OECD (Organization for Economic Co-operation and Development) Council's "Recommendation on Water" [26] provide valuable guidance. Key policies include managing water quantity through demand management and efficient allocation, improving water quality by setting standards and controlling pollution at the source, and addressing water risks and disasters via risk assessment and integrated emergency responses. The recommendation also emphasizes enhancing water governance by clarifying roles, ensuring policy coherence, and promoting stakeholder engagement. Sustainable financing and investment are supported through principles like Polluter Pays, diverse revenue streams, and appropriate water tariffs, aiming to balance economic, social, and environmental objectives. These guidelines aim to foster sustainable growth, social inclusion, and resilience against climate change, ultimately supporting the targets set by SDG 6.

Orr et al. [27] discusses the critical importance of effective policies and regulations in managing water scarcity and protecting water resources. They emphasize that water scarcity is primarily a governance issue rather than a mere physical shortage. Effective water management policies must address social, economic, and environmental factors, involving stakeholders at all levels—local, national, and international. The authors argue that robust regulatory frameworks are essential for sustainable water use, advocating for the enforcement of environmental laws, investment in water-efficient technologies, and the preservation of freshwater ecosystems. They stress that both governments and businesses must collaborate to mitigate water-related risks, ensuring long-term water security and environmental sustainability.

Reilly and Schindler [28] demonstrates the critical role of local governments in supplementing state and federal regulations to protect water resources. They stress that local governments can proactively address gaps through zoning and preventative measures, which are not always covered by state laws that often react to issues after they occur. Effective local policies include coordinated efforts to protect entire watersheds and integrate measures for groundwater, surface water, and wetlands, considering their interconnected nature. Examples of successful local initiatives include zoning ordinances that prevent groundwater contamination, wellhead

protection programs, and shoreline management practices. This article argues that no single level of government can manage water resources alone, and a collaborative approach involving local, state, and federal levels, as well as community stakeholders, is essential for comprehensive water protection. Gerlak et al. [29] provides a comprehensive review of effective policies and regulations crucial for protecting water resources and managing environmental risks in the United States. They highlight the importance of adaptive management, which involves implementing policies on a trial basis, collecting data, and revising strategies based on the lessons learned. This approach encourages flexibility and responsiveness to new information and changing conditions. This document emphasizes the necessity of collaborative and integrated management of water resources, involving multiple agencies, stakeholders, and the public to achieve ecological and sustainable outcomes. Key policies such as the Clean Water Act (CWA), Safe Drinking Water Act (SDWA), and the Total Maximum Daily Load (TMDL) process are noted for their roles in setting national standards and promoting holistic environmental management. Overall, the integration of adaptive management principles, ecological restoration, and cross-agency collaboration are identified as critical elements for the future success of U.S. water policy.

6. Conclusion

The 2021 fuel leak at Pearl Harbor, O'ahu, from the Red Hill Bulk Fuel Storage Facility serves as a stark reminder of the critical importance of robust water quality monitoring and effective environmental management. This incident, which led to the leakage of approximately 19,000 gallons of jet fuel into the Pearl Harbor aquifer, significantly impacted the local water supply, public health, and the surrounding ecosystem. There are several key takeaways and recommendations for future environmental protection and water resource management. Firstly, the immediate and long-term health impacts observed among the affected population, including symptoms such as nausea, headaches, and skin rashes, indicate the urgent need for rapid response systems and thorough health monitoring. Long-term health studies are essential to understand the chronic effects of exposure, especially in vulnerable populations such as children and the elderly. Secondly, this fuel leak incident has shown the critical role of advanced monitoring technologies. The use of portable water quality meters, spectrophotometers, and remote sensing technologies proved invaluable in assessing the extent of contamination and guiding remediation efforts. These technologies enable real-time monitoring and early detection of water quality issues, allowing for prompt and effective response measures. The integration of AI techniques further enhances monitoring capabilities by efficiently processing large datasets and identifying patterns that may be overlooked by traditional methods. To prevent future incidents, it is essential to implement sustainable water use practices and strengthen regulatory frameworks. Promoting water conservation, pollution prevention, and the protection of natural water bodies from industrial activities are vital steps. Effective policies and regulations, such as the CWA and the SDWA, play a crucial role in setting national standards and ensuring compliance. Policymakers must focus on enhancing regulatory oversight, promoting community engagement, and fostering collaboration among government agencies, industry stakeholders, and local communities. Lastly, the concept of adaptive management emerges as a critical approach for environmental protection and resource management. This involves implementing policies on a trial basis, collecting data, and revising strategies based

on the lessons learned. Adaptive management encourages flexibility and responsiveness to new information and changing conditions, making it an effective strategy for dealing with complex environmental challenges.

In conclusion, the 2021 Red Hill fuel leak incident underscores the necessity of robust water quality monitoring, advanced technologies, effective communication, and strong regulatory frameworks to protect water resources and manage environmental risks. By adopting these measures and fostering collaborative efforts, we can do our best to ensure the sustainability and safety of our water resources, safeguarding public health and the environment for future generations.

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Section 2

Technologies and Methods for Water Quality Monitoring

In-Situ Contaminant Detection by Portable and Potentially Real-Time Sensing Systems

*Giuseppe Emanuele Capuano, Roberta Agata Farina,
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Maria Anna Coniglio and Sebania Libertino*

Abstract

This chapter aims to provide information on the progress of research into water quality analyses, providing an overview of the state of the art, including novel research achievements, in the detection of water contaminants. After a brief introduction to the main sensing systems' characteristics, the attention will be devoted to two different classes of pollutants: organic and inorganic. Microbiological analyses concerning the monitoring of bacterial load in water and chemical analyses with a special focus on mercury, related to heavy metal pollution, and nitrogen compounds, i.e. nitrate ion and ammonium ion, are discussed. Particular attention will be devoted to all sensing systems that are in principle portable and able to make real-time measurements in situ.

Keywords: water quality, bacteria, heavy metals, nitrogen compounds, silicon photomultiplier, biosensors, electrochemical sensors, conductive polymers, metallic nanoparticles, catalysis

1. Introduction

Water is essential for life and its quality is crucial for human health and environmental sustainability. Regular analysis of water is important to ensure its safety and purity. Microbiological analysis is fundamental for detecting harmful bacteria such as, for example, *Escherichia coli*, *Legionella*, and *Salmonella*, or dangerous chemical presence, i.e. heavy metals or hydrocarbons, which can cause serious waterborne diseases if present in drinking water [1]. Chemical analysis, on the other hand, helps prevent environmental problems, such as eutrophication due to excessive nitrogen compounds, or human health problems that can arise from contamination by heavy metals such as mercury. For these reasons, a careful analysis of water samples is crucial for human health and environmental protection. The different contamination issues must be investigated separately to determine the best detection strategies. This chapter aims to describe the various sensory detection systems (design and manufacture) of bacteria, mercury (as an example of heavy metal), and nitrogen compounds in water.

Monitoring bacteria in water is essential to ensure public health and prevent waterborne diseases such as cholera, typhoid fever, and other types of waterborne diseases. Contaminated water can lead to serious epidemics, especially in communities with limited access to clean water. In many developing countries, water is still known as “black” [2]. These countries are characterized by high population density and should have good water quality for the population to survive. Bacterial indicators may differ among countries, e.g. total coliforms, fecal coliforms, heterotrophic microorganisms, *Clostridium perfringens*, etc. [3]. This monitoring allows us to evaluate the effectiveness of disinfection systems already in use within the Water Safety Plans [4, 5] and to test and develop antibiofilm methods to further contribute to improving water quality [6, 7]. Regular monitoring helps to detect bacterial contamination early, enabling timely intervention and treatment to prevent the spread of the disease. Among traditional monitoring methods, such as bacterial culture and membrane filtration, new techniques have been developed such as polymerase chain reaction (PCR) and next-generation sequencing (NGS), advanced methods that sequence DNA from water samples, providing comprehensive data on bacterial communities, and in the case of NGS allowing the identification of known and unknown pathogens.

Innovative methods of bacterial monitoring have been developed using a Silicon PhotoMultiplier (SiPM) [8]. This device is a highly sensitive pixelated photon detector, each pixel being a silicon photodiode operating in avalanche mode [9]. It has a high sensitivity to detect even individual photons, a wide dynamic range for varying light intensities, and a rapid response to light signals [10]. It was also employed for monitoring heavy metals, such as mercury by using engineered bacteria as a sensing element emitting a light signal in its presence, which is then transduced into an electrical signal.

Mercury is one of the most difficult heavy metals to detect and the most dangerous element of the periodic table, excluding the radioactive ones. It exists in three forms with different properties and toxicity: elemental or metallic mercury (Hg^0), inorganic mercury, and organic mercury compounds (Hg^{2+} and Hg^+ , respectively). Each one can be converted into other forms through oxidation, reduction, methylation, and demethylation that occur due to the presence of chemical compounds or through the metabolic process of fishes or plants [11].

Long exposure to mercury can cause neurological disturbances, memory problems, skin rash, and kidney abnormalities. In addition, when combined with other chemical elements, such as sulfur or oxygen, it can lead to severe digestive system corrosion, and when mercury is combined with carbon, especially in fresh and seawater, it accumulates in the food chain and, during pregnancy, it can pass through the placenta, causing developmental abnormalities and cerebral palsy to infants [12, 13].

It is worth noting that Hg^{2+} can accumulate in biofilms in pipes of main water and be converted into other toxic forms. Mercury toxicity depends on the form and its water concentration is expected to be very low. The tolerance value is 1 $\mu\text{g/L}$ for water intended for human consumption and contact recreation and thus revealing water contamination can result essential in avoiding risks to human health [14, 15].

Finally, other chemical species must be monitored to provide a meaningful water analysis and we focused our attention on nitrogen compounds. Nitrogen plays a critical role in the structure and function of life-essential biomolecules, in the cycling of elements in nature, and in the provision of nutrients to plants, significantly contributing to the development and maintenance of life on Earth. Plants absorb nitrogen from the soil mainly in inorganic forms: nitrate and ammonium. Specifically, nitrate ions are absorbed by plants through their roots primarily via an active process that

requires energy as it involves specific cell membrane carriers. In contrast, ammonium ions can be absorbed by plants either through an active process or passive diffusion across cell membranes [16, 17]. Under excessive irrigation, plants are unable to absorb all the nitrate and ammonium ions present in the soil, allowing them to percolate through the soil and enter groundwater or surface water bodies. An excessive presence of these nutrients in groundwater or water bodies can lead to eutrophication which can damage aquatic ecosystems [18]. Furthermore, nitrogen can be produced as the result of disinfection of water with chlorine dioxide or monochloramine. An excessive presence of nitrogen compounds (the so-called disinfection by-products) in drinking water is harmful to humans as nitrates convert to nitrites, which bind to hemoglobin, making it incapable of transporting oxygen to tissues in the body.

Several chemical methodologies exist to monitor the concentration of nitrogen compounds and mercury in water, such as flow injection analysis, spectrophotometry, chemiluminescence, capillary electrophoresis, ion chromatography, FTIR spectroscopy, colorimetric pH detection, ion-selective electrodes, and other optical methods [19–24]. Although these techniques are sensitive and specific, they require sophisticated, expensive, time-consuming systems, and the necessity for sampling campaigns.

Despite the fact that the contaminants to be detected are very different (microorganisms, mercury, and nitrogen compounds), a common demand can be inferred: the need for portable systems to perform in-situ measurements that should be precise, simple to be made, and the devices should provide a detection limit at least within the World Health Organization defined limits [25].

The rest of this chapter reviews the three examples of contaminants and the most investigated detection system to infer their concentration in water samples.

2. Microbiological analysis

The main methods for bacteria detection in water samples employ different techniques, such as bacterial cultural growth, immunological, genetic, physical, and chemical methods. Hereafter, all of them are briefly reviewed.

2.1 Cultural methods

One of the most used methods to detect microorganisms' presence in water is the Heterotrophic Plate Count (HCP). It allows for estimating the total aerobic heterotrophic bacteria charge (organisms taking energy from organic carbon) in each sample. The water specimen is collected using a sterile container and spread over a solid culture medium in Petri dishes to provide nutrients for bacterial growth (**Figure 1**). After dish incubation, the formed bacteria colonies are counted in terms of Colony-Forming Units per milliliter of water (CFU/mL) [26]. However, this technique is usually limited to bench-top equipment.

2.2 Enzyme/substrate methods

These methods are based on colorimetric or fluorometric assays concerning specific enzymatic activities. During bacterial growth, the bacterial enzymatic activity allows the fluorophore to be cleaved from the substrate, increasing the fluorescence signal. The sensitivity is strictly related to the time of analysis. Immunological methods are based on the interaction between a specific antibody (Ab) and a specific antigen (Ag). Ab is



Figure 1.
Escherichia coli growth on agar medium.

mounted onto a support system, such as nylon supports, cantilevers, magnetic beads, nanoparticles, graphene quantum dots, electrospun nanofibers, and polymers [27]. The most important immunological techniques are Enzyme-Linked Immunosorbent Assay (ELISA) [28], lateral flow tests (immunochromatographic assays) [29], SPR (Surface Plasmon Resonance) [30], and electrophoresis [31]. However, in most cases, these methods suffer from poor specificity, sometimes returning false-positive results, contributing to issues of low sensitivity [32, 33]. The sensitivities and the specificities of immunological methods depend on the antibody, with a minimum limit of detection (LoD) of 10^5 cells/mL employing ELISA [34]. Finally, the analysis can last from several hours for ELISA to some minutes for lateral flow.

2.3 Genetic methods

Genetic methods are highly specific due to their affinity to specific nucleic acid sequences. The polymerase chain reaction (PCR) [35] is the most used technique employing appropriate short nucleic acid sequences (primers) for DNA sequence amplification relative to bacterial strains. It is characterized by the execution of several steps at different temperatures (see **Figure 2**). The fluorescence phenomenon can be coupled with PCR to monitor bacterial DNA amplification in real time, to obtain quantitative information about the initial amount of DNA contained in the sample under analysis; this technique is known as “quantitative PCR” or “qPCR” [36, 37], which is easy to automate and can be used when pathogens concentration is below the LoD of other assays. Recently, researchers developed an “isothermal technique” to obviate the shortcomings of PCR, which employs in the same way the nucleic acid-based method for bacteria strain identification by amplifying nucleic acids at a fixed temperature [38]. In particular, the loop-mediated isothermal amplification (LAMP) technique has gained popularity due to its specificity, sensitivity, and stability [1, 39]. The disadvantages of these methods are the quality of the sample, which remarkably impacts the sensitivity of the detection, and the presence of inhibitors which create limitations in the analysis of samples. Immuno-PCR (IPCR) exceeds these limits since it combines ELISA with qPCR. Such a combination allows the ELISA to enhance the LoD about 100–1000 times using qPCR to amplify the system signal [40].

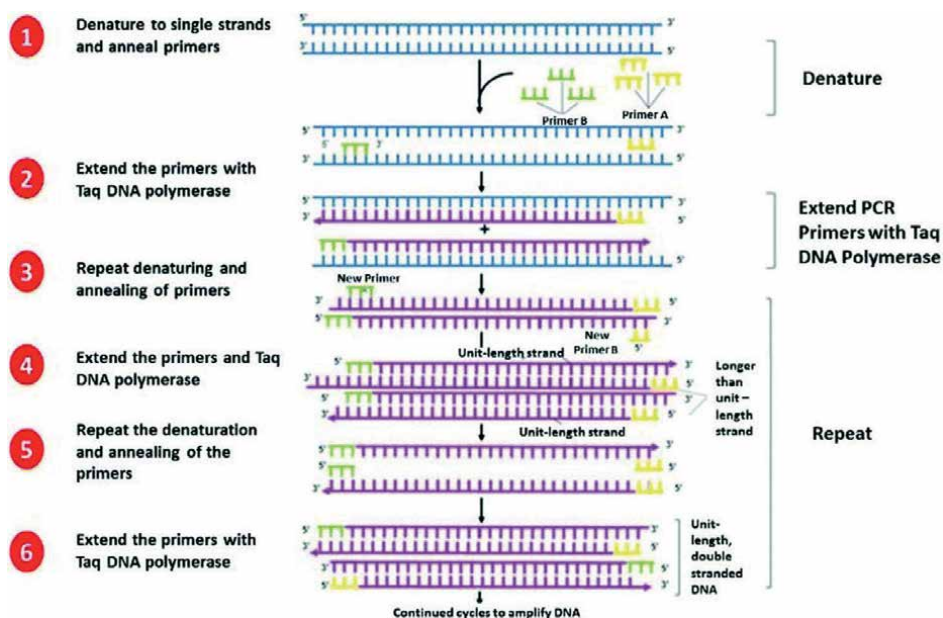


Figure 2.
 Scheme representing PCR cycle. Reprinted with permission from Rajapaksha et al. [35].

2.4 Mass spectroscopy methods

Mass spectroscopy techniques are indicated for their accuracy, selectivity, reproducibility, and high Signal-to-Noise Ratios (SNR). Tandem Mass Spectrometry (MS/MS) [41], nanoscale Liquid Chromatography coupled with MS/MS (nano LC-MS/MS) [42], and Matrix-Assisted Laser Desorption-Ionization Time Of Flight mass spectrometry (MALDI-TOF) [43, 44] are the most used techniques for detection and identification of bacterial proteins peptide sequences by comparing the obtained mass spectra to associated databases. The limitation linked to these methods concerns the similarities between organisms and the limited number of spectra in the databases, which can lead to poor discrimination between species or misidentifications [44]. Furthermore, these techniques are not indicated for quantitative analysis.

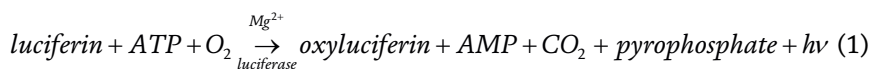
2.5 Fourier transform infrared (FT-IR), raman spectroscopy, and laser-induced breakdown spectroscopy (LIBS)

Fourier Transform Infrared (FT-IR) is a rapid tool indicated for the investigation of the total composition of all components of the bacterial cells under analysis by using infrared spectroscopy [45], although precise identification with this technique remains to be developed. Raman spectroscopy is currently used for the classification of complex biological samples, due to its fast and non-destructive methodology [46]. Finally, Laser-Induced Breakdown Spectroscopy (LIBS) is a rising spectroscopic method based on atomic emission, in which elemental composition is determined by placing samples in a laser plasma and observing the resulting spectra. For example, LIBS is used to differentiate different types of bacteria and their metabolic state [47]. The main advantages of LIBS-based bacterial detection technology are the speed of analysis (some minutes) and the ability to detect pathogens on all types of surfaces.

However, all the described techniques require the presence of skilled human operators for sample preparation, treatment, processing, and results interpretation.

2.6 Methods based on ATP-luciferin-driven chemiluminescent reaction

Currently, chemiluminescent reaction based on the interaction between adenosine triphosphate (ATP) and luciferin is one of the most sensitive methods for bacterial load detection [48]. It allows obtaining quantitative information about viable cell concentration in a sample [49–51] by employing the internal ATP after appropriate lysis procedures. This reaction is catalyzed by the enzyme luciferase, to obtain luciferyl adenylate that combines with oxygen to produce oxyluciferin and a photon at 560 nm. The reaction is reported in the following [52]:



Some commercial readers based on ATP-luciferin-driven reactions reach low limits of detection, such as BioThema ATP Kit SL [53], Luminultra Quench-Gone Aqueous (QGA) Test Kit [54], Hygiena handy type luminometer [55], with LoDs reaching values down to 10^{-12} M, corresponding to about 5×10^2 cells/mL if a mean amount of ATP equal to 1 fg for the single viable cell is considered (see Microbial Equivalent definition [56]).

Hu et al. [57] developed a low-cost and portable device based on the ATP-luciferin-driven chemiluminescence reaction taking place in test tubes for bacterial charge detection, employing a SiPM as a detector. The system reaches a LoD for ATP concentration of 3.6×10^{-11} M, corresponding to about 1.8×10^4 cells/mL.

The described devices also require skilled human operators and long sample treatment times. To overcome such an issue, Santangelo et al. [8] designed and developed a prototype of a low-cost, miniaturizable, real-time, and remote-sensing microfluidic SiPM-based sensor for bacterial ATP detection, which does not require the presence of human operators, allowing to reach a LoD for bacterial charge of about 4×10^6 cells/mL (8×10^{-9} M for ATP).

Recently, Capuano et al. [58] developed an optimized low-cost, miniaturizable, real-time, and remote-sensing SiPM-based sensor based on static ATP-luciferin chemiluminescent reaction measurements (**Figure 3**), allowing the detection of water total bacteria concentration down to about 10^5 cells/mL (2×10^{-10} M for ATP).

It is worth noting that, although the described devices return detailed information about the concentration of the total bacterial load, these systems are not selective,

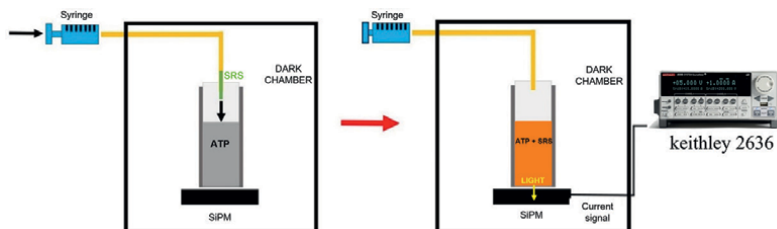


Figure 3. Schematic layout of the ATP detection system developed by Capuano et al. [58] (reprinting permitted). The chemiluminescent reaction takes place when the reactants contained in the standard reaction solution (SRS) interact with ATP. The light emitted during the reaction is acquired through a SiPM, obtaining a current signal proportional to ATP concentration.

since ATP is contained in similar quantities in all viable cells, and discrimination among different bacterial species is not achieved.

3. Heavy metals detection in water: mercury (Hg^{2+})

Many techniques have been developed for detecting mercury in water samples providing high-performance quantification. The traditional analysis systems need bulky and costly laboratory instruments, require specialized personnel, and are not suitable for in-situ monitoring.

Chromatographic and spectrometric methods are the most used in mercury analysis and these powerful techniques can be coupled with other monitoring systems. Sanchez-Rodas et al. [59] coupled chromatographic and non-chromatographic separation with Atomic Fluorescence Spectrometry (AFS). The latter is a technique based on the absorption of radiation of characteristic wavelengths by an atomic vapor with subsequent detection of radiationally deactivated states via emission in a direction orthogonal to the excitation source. This method is extremely sensitive and selective in determining environmentally and biomedically important elements such as mercury, arsenic, lead, and cadmium. The separation of the mercury species can occur either by Gas Chromatography (GC) or High-Performance Liquid Chromatography (HPLC). Cold Vapor (CV) is employed with liquid chromatography to convert inorganic Hg to its elemental state. Using liquid chromatography combined with AFS detection (HPLC-CV-AFS) leads to detection limits of 0.2 $\mu\text{g/L}$ for methylmercury (MeHg), 0.07 $\mu\text{g/L}$ for Hg (II), 0.06 $\mu\text{g/L}$ for phenylmercury (PhHg), and 0.12 $\mu\text{g/L}$ for ethylmercury (EtHg) [59]. Gas chromatography has been more widely used than liquid chromatography for Hg detection with AFS. In this case, pyrolysis has been employed as an intermediate step for Hg species oxidation [60]. Detection limits of GC-pyro-AFS have been improved over time reaching 0.13 ng/L for Hg (II) and 0.01 ng/L for MeHg [59].

Other strategies have been developed without chromatographic separation using AFS as a detection process. These include various types of CV-AFS using different chemicals for Hg revealing. In particular, a hydrostatically modified electro-osmotic flow and a newly developed interface have been used for AFS exploitation, detecting Hg(I), MeHg, EtHg, and PhHg in the range of (6.8–16.5 $\mu\text{g/L}$) [61], while conjunction of flow injection with AFS using a modified flow-through chamber as the interface was employed for fast separation of Hg(II) and MeHg with detection limits of 0.1 and 0.2 $\mu\text{g/mL}$ when applied to water samples [62].

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is an analytical technique with LoD lower than ng/L and great linearity in revealing elements. The requirement of elemental forms leads to coupling versatile separation techniques like HPLC, GC, and Capillary Electrophoresis (CE) with a highly sensitive detector, such as ICP-MS, for ultra-trace elemental speciation analysis [63]. Employing the HPLC-ICP-MS method LoD of 0.07 ng/L for inorganic mercury and 0.02 ng/L for MeHg⁺ was reported in investigating mercury in seawater samples [64]. Analytical features, such as low detection limits and wide linear calibration ranges, make AFS and ICP-MS great atomic detectors in the speciation and detection process. Compared to ICP techniques, AFS provides additional advantages: low acquisition and running costs, robustness, and ease of operation [59].

In the last decades, many efforts have been made to develop alternative miniaturizable systems to achieve inorganic mercury analysis in water samples. Lots of sensors

based on electrochemical techniques and optical methods employing colorimetry, fluorimetry, and Surface-Enhanced Raman Scattering (SERS) have been designed revealing extremely promising thanks to their high sensitivity and selectivity, fast results, and cost-effectiveness [65, 66].

Electrodes modified with biochemical or chemical compounds raised great attention. The advantages of using them are the large surface area, high electrical conductivity, biocompatibility, heterogeneous electron transfer, and mechanical strength. Many types of electrodes revealing mercury have been designed. Among them, it is worth mentioning the following: polymer-based electrodes which use conductive polymers that contain functional groups binding toward mercury; Ion-Imprinted Polymers (IIP) modified electrodes that have high binding capacity, selectivity, and stability [67]; electrodes based on complexing agents forming complexes with mercury ions [68]; DNA-modified electrodes in which oligonucleotides that contain T-T mismatches can selectively bind mercury with a LoD lower than 0.5 µg/L [69]; finally, nanoelectrodes that show high surface area with higher working electrode surface, adsorption capacity, and catalyzing electron transfer.

Nanomaterials have been widely used in biosensing and various strategies have been developed for mercury detection. Carbon nanomaterials have higher sensitivity, and, among them, carbon nanotubes have raised attention. Specifically, Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs) have more advantages. Metal nanoparticles show higher response in the field of electroanalysis compared to unmodified electrodes and in some cases, increase the transfer of electrons between electroactive substances and electrodes [70]. Lastly, there is a growing interest in hybrid nanomaterials formed by metallic and carbon structures, such as gold nanoparticles coupled with Carbon Nanotubes (AuNPs/CNTs) [71, 72].

Biosensors have received widespread attention for their relatively low cost, miniaturization, and easy-to-use characteristics. A biosensor is made of two main parts: a biorecognition element that specifically binds to the analyte to be detected. It can be a nucleic acid, antibody, a whole-cell, aptamers, enzymes, or biomimetic receptors; a transducing element that transduces biological response in an electrochemical, optical, magnetic, or acoustic signal [73].

Some drawbacks can occur when using biorecognition elements such as enzymes, biomimetic receptors, or antibodies. Enzymatic-based biosensors are not specific in binding mercury leading to poor selectivity because various heavy metals may cause cross reactivity. In addition, antibody-based biosensors also show some limitations due to reaction conditions, like temperature, pH, and ionic strength affecting antibody activity [74].

Whole cell-based biosensors are based on cells, in most cases microorganisms which can be natural or recombinant [75], that act like biorecognition elements. There are many advantages to using whole-cell biosensors. Firstly, cells can be easily cultivated compared to enzymes making whole cell-based biosensors cheaper than enzyme-based ones. Moreover, microbial sensors are more selective than enzyme ones, thanks to pathways used in microorganisms [76]. Lastly, whole cell-based biosensors usually do not require sample preparation or preconcentration [77] and, compared to antibody-based biosensors, present higher resistance to environmental conditions (e.g. changes in pH, temperature, etc.) [78].

Sciuto et al. [12] developed a miniaturized optical system for inorganic mercury (Hg^{2+}) detection in water, combining engineered *E. coli*, capable of emitting light in the presence of mercury, with a Silicon PhotoMultiplier (SiPM) used as a detector (**Figure 4**). The sensing element used for revealing Hg^{2+} was a strain of *E. coli* modified

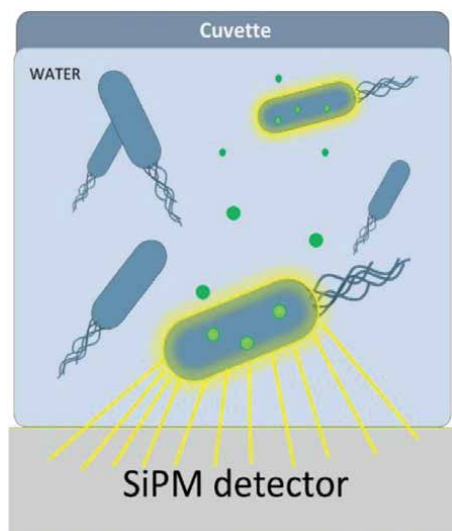


Figure 4.
 Design of detecting system. The upper part stands for cuvette with a water sample containing mercury and bacteria emitting light detected by the SiPM (lower part of the figure). Reprinted with permission from Sciuto et al. [12].

with the recombinant plasmid containing a fusion between the gene *merR*, coding for transcription repressor of mercury resistance operon, and genes *luxCDABE*, that encode for bacterial luciferase and its substrate, all regulated by the *PmerT* promoter. Expression of *lux* genes is induced when Hg^{2+} enters bacteria cells from the water sample and binds to MerR protein, causing the release of its repression on the promoter. This triggers the expression of luciferase and its substrate whose interaction causes 490 nm blue-green light emission that can be detected by SiPM (**Figure 5**).

Bioluminescence intensity was related to a mercury concentration in water samples ranging from 0.25 to 200 $\mu\text{g/L}$, with a LoD of 0.15 $\mu\text{g/L}$ and providing results in only 20 minutes.

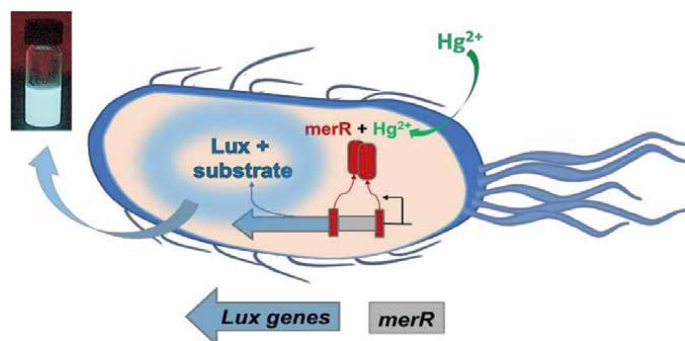


Figure 5.
 The mechanism for *Lux* genes transcription. Mercury binds to protein MerR that provides the de-repression of promoter regulating transcription of luciferase and its substrate. Reprinted with permission from Sciuto et al. [12].

4. Nitrogen compounds detection in water: nitrate and ammonia ions

4.1 Electrochemical sensors

Electrochemical sensors are composed of three electrodes: the working electrode (WE), the reference electrode (RE), and the counter electrode (CE). They can be manufactured using screen-printing technology, by printing the electrodes on a low-cost solid substrate with reproducible chemical performance (**Figure 6**).

The inks used for printing electrodes determine the properties of the electrochemical cell. The appropriate functionalization of the WE surface plays a key role in the development of sensitive and selective chemical sensors and biosensors. This involves modifying the electrode surface with specific chemical molecules, metal nanoparticles, or biological molecules that have a high affinity for the target analyte. For example, enzymes can be bonded to the electrode to selectively interact with certain chemicals; gold nanoparticles can be used to improve electrical conductivity and sensitivity. The functionalization process increases the specificity and efficiency of the sensor, enabling accurate and reliable detection of various substances in a sample. The miniaturized design allows these electrochemical cells to be portable and suitable for real-time analysis and on-site measurements due to their linear output, low power demand, rapid response, high sensitivity, and capacity to operate at room temperature [79, 80].

The electrochemical sensors undergo an electrochemical reaction on the WE, resulting in changes in current, potential, charge, conductivity, or impedance, that can be measured using different electrochemical techniques. The most used electrochemical techniques are voltammetry, amperometry, potentiometry, and impedance spectroscopy.

In voltammetry, the current as a function of applied potential is measured. By varying the potential at the working electrode, information on redox reactions, kinetics, and thermodynamics of species in solution can be obtained. The most common types of voltammetry include Cyclic Voltammetry (CV), Linear Sweep Voltammetry (LSV), Differential Pulse Voltammetry (DPV), and Square-Wave Voltammetry (SWV).

Amperometry measures current at a constant applied potential. It is often used for the detection and quantification of analytes in solution. The current is directly proportional to the concentration of the electroactive species, allowing for sensitive detection limits. In contrast, chronoamperometry measures current as a function of time at a fixed applied potential. It is often used to study reaction kinetics, electrode processes, and diffusion-controlled processes.

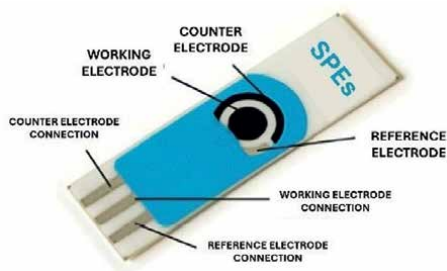


Figure 6.
Scheme of screen-printed electrodes (SPEs).

Potentiometry measures the potential of an electrochemical cell without current flow. It is commonly used in pH and ion-selective electrode measurements. Potentiometric sensors can be selective for specific ions using ion-selective membranes.

Impedance spectroscopy is a technique that measures the electrical impedance of an electrochemical system as a function of frequency. It can provide information on the kinetics of electrode processes, charge transfer resistance, bilayer capacitance, and diffusion processes.

These electrochemical techniques offer valuable insights into the behavior of chemical species at electrode interfaces and are widely used in environmental analysis and biochemistry [81, 82].

4.2 Nitrogen compounds detection in water

To date, various types of electrochemical sensors have been developed to detect NO_3^- [64–66]. Generally, nitrate ion electrochemical sensors are developed using specific nitrate ionophore molecules deposited on the working electrodes, or by exploiting the reduction reaction of nitrate using metal particles. Copper (Cu) is one of the most effective metals to catalyze the electroreduction of NO_3^- due to its high conductivity ($5.8 \times 10^7 \text{ S/m}$), which improves charge transfer [83–85], compared to platinum (Pt), silver (Ag), and gold (Au). Researchers showed that Cu deposition, increasing the electroactive surface area of the working electrode, lowers the LoD of electrochemical NO_3^- sensors. For instance, Inam et al. [86] developed a flexible screen-printed amperometric NO_3^- sensor, functionalized with copper nanoclusters deposited via cyclic voltammetry on silver WE. The obtained copper nanocluster morphology and size were uniform all over the Ag surface (**Figure 6a**). The device showed a high capability to detect NO_3^- in water in a dynamic concentration range from 50 to 5000 μM (**Figure 7b**) with a LoD of 0.207 nM using LSV.

Farina et al. [87, 88] developed an electrochemical amperometric NO_3^- sensor, functionalized with Cu micro-flowers electrodeposited via CV on Carbon WE (**Figure 8a**). The flower-like structure of the crystals favors a greater catalytic effect for nitrate reduction since increases the mass transport and the electron transfer

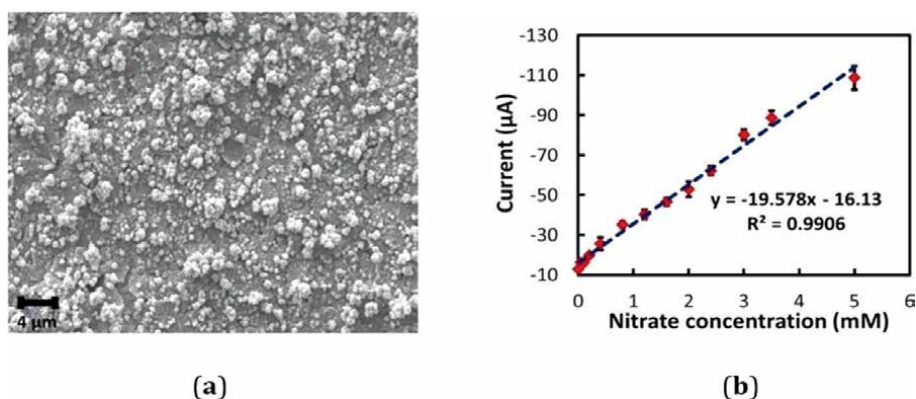


Figure 7. (a) SEM micrograph of Cu/Ag surface characterized by a uniform deposition of Cu nanoclusters; (b) Calibration curve of the Cu/Ag sensor for NO_3^- detection in water. Reprinted with permission from Inam et al. [86].

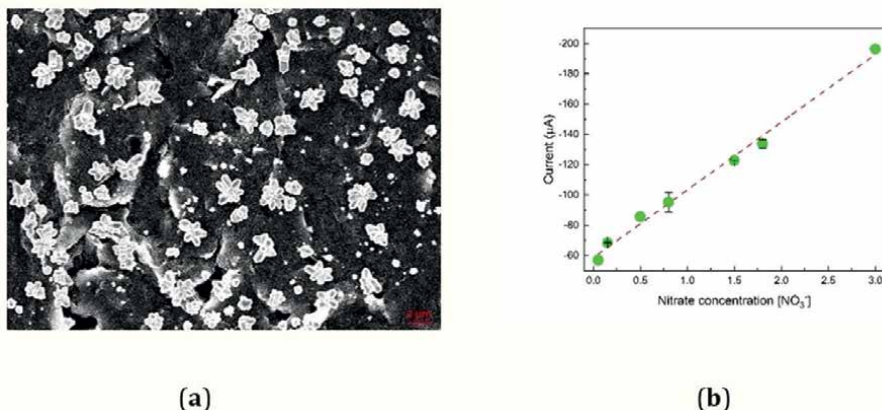


Figure 8. (a) SEM micrograph of Cu/C surface characterized by a Cu micro-flowers deposition; (b) Calibration curve of the Cu/C sensor for NO₃⁻ detection in water. Reprinted with permission from Farina et al. [87].

process. The obtained sensor showed a LoD of 0.87 μM for NO₃⁻ in water and a wide dynamic concentration range from 0.05 to 3.00 mM using LSV (**Figure 8b**).

Nitrate detection was investigated by Hyusein et al. [89] using commercial carbon nanofibers (CNF) and single-walled carbon nanotube (SWCNT) electrodes modified with Cu and Pd-Cu in sulfuric acid solution via LSV. The data (**Figure 9b** and **d**) show a higher sensitivity of the reductive currents for the Pd-Cu modified CNF and SWCNT electrodes than for the Cu modified ones. In particular, the electroanalytical response of the Pd-Cu modified SWCNT electrode shows an extended concentration range of non-linear electroanalytical response. Instead, Pd-Cu modified CNF electrode remains linear but in a restricted concentration range. Therefore, the SWCNT modified with Cu and bi-metallic Pd-Cu particles showed a high sensitivity in a larger concentration range of 0.1 to 7.8 mM with a LoD of 52 μM.

This behavior can be traced back to the morphological composition of the electrodes. Specifically, the Pd-Cu modified CNF electrode shows individual well-separated Pd particles where the deposition of Cu resulted in nucleation and growth of well-separated Cu particles with larger sizes (**Figure 9a**). Instead, Pd-Cu modified SWCNT electrode shows a dense population of overlapping Pd particles that decreased the C surface available for the nucleation and growth of Cu. Therefore, the Cu deposition formed micrometric crystals in the defects of the C structure (**Figure 9b**). Probably, the contact between Cu and Pd in areas populated by Pd NPs led to a sensitive and stable electroanalytical signal for nitrate reduction.

Conducting polymers are suitable for the detection of ammonium ions in water due to their electrical conductivity, ion exchange capacity, high sensitivity, and selectivity toward specific ions such as ammonia (NH₄⁺). They can be easily functionalized or modified to increase their affinity toward target ions, improving sensor performance in terms of detection limits and response time. When NH₄⁺ reaches a conductive polymer-based sensor, it can undergo ion exchange reactions with the polymer, resulting in changes in the electrical conductivity of the material that can be correlated with the analyte concentration. Their compatibility with microfabrication techniques also allows the development of miniaturized sensors for real-time

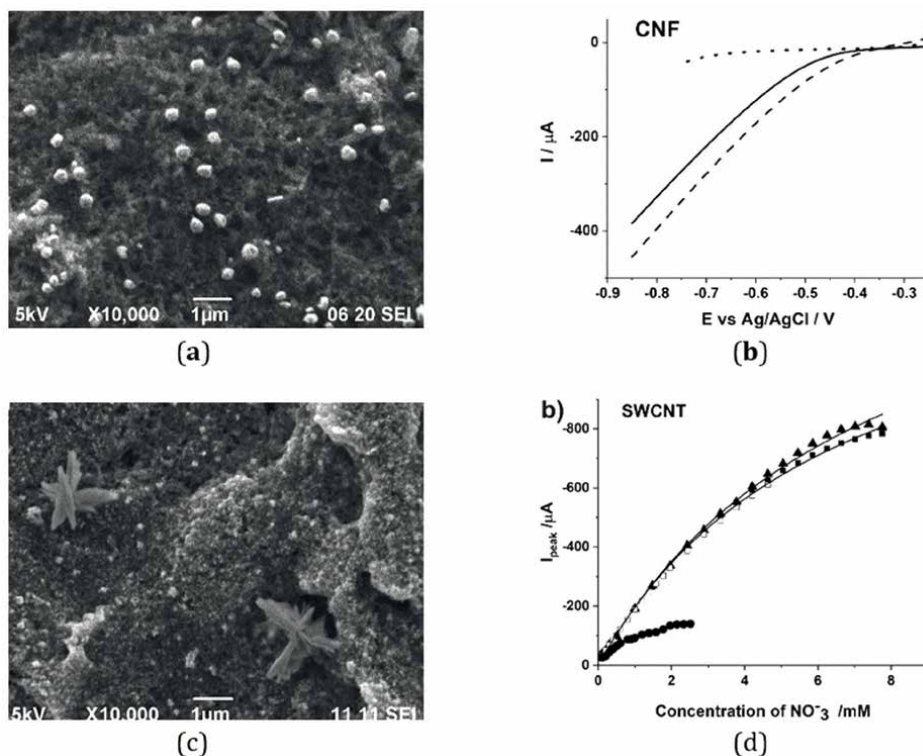


Figure 9. (a) SEM micrograph of Pd-Cu/CNF surface; (b) Calibration curve of Pd-Cu/CNF sensor for NO_3^- detection in water; (c) SEM micrograph surface of Pd-Cu/SWCNT; (d) Calibration curve of Pd-Cu/SWCNT sensor for NO_3^- detection in water. Reprinted with permission from Hyusein et al. [89].

monitoring applications. A key aspect of the conductive polymers' behavior is doping, which involves the introduction of dopant molecules or ions into the polymer matrix to increase its electrical conductivity. Dopants for conducting or semiconducting polymers include inorganic and organic acids. Doping can significantly alter the electronic structure of the polymer, leading to an increase in the concentration and mobility of charge carriers [90].

Furthermore, the conductive properties of polymers can be improved by metal nanoparticles. When conducting polymers interact with metallic nanoparticles, such as gold or silver nanoparticles, their conductivity can be further enhanced due to the synergistic effects between the two materials. The presence of metal nanoparticles provides additional pathways for charge transport, which can lead to a significant increase in conductivity compared to pristine conducting polymers.

Farina et al. [90] developed two detection electrodes for NH_4^+ detection. The first uses PANI electro-polymerized (PANIep) via CV on commercial screen-printed carbon electrodes and the second uses commercial PANI screen-printed carbon electrodes, both modified with electrodeposited Au NPs. Functionalizing the PANI with Au NPs enhanced the conductivity and performance of the system. The sensing mechanism of the devices is based on the deprotonation reaction of PANI, the oxidation of NH_4^+ , and the subsequent reduction and oxidation of PANI. The results show

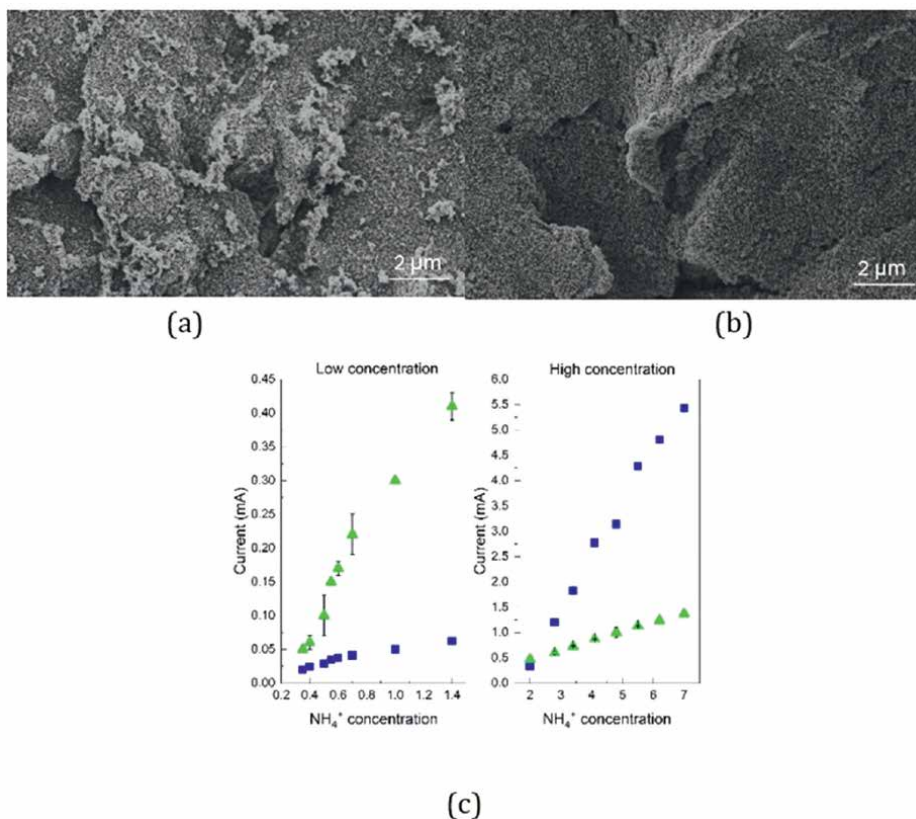


Figure 10.

(a) SEM micrograph of Au/PANlep/C surface; (b) SEM micrograph surface of Au/PANI/C; (c) Calibration curve of Au/PANlep/C (green triangles) and Au/PANI/C (blue squares) sensor for NH₄⁺ detection in water. Reprinted with permission from Farina et al. [90].

that the Au/PANI/C electrode performs better for high NH₄⁺ concentrations (0.34 μM LoD) and worse for low NH₄⁺ concentrations (0.01 μM LoD) than the Au/PANlep/C WE, which shows an opposite trend (0.03 μM LoD for low NH₄⁺ concentration and 0.07 μM LoD for high NH₄⁺ concentration) (**Figure 10c**). This phenomenon can be explained by considering the distribution of polyaniline on the carbon electrode, which can significantly influence the sensitivity and dynamic range of sensors for amperometric detection of ammonium ions in water (**Figure 10a** and **b**).

Wang et al. [91] developed an electrochemical biosensor for monitoring ammoniacal nitrogen in aquaculture water. A SPEC/AuNPs/PMB modified electrode was prepared by electrodeposition and electro-polymerization using Au NPs and methylene blue. The electrochemical behavior of reduced nicotinamide adenine dinucleotide (NADH) on the surface of the modified electrode was studied by CV. An α-Ketoglutarate substrate and glutamate dehydrogenase were coated on the modified electrode to form a functional enzyme membrane (**Figure 11a**). The ammonia nitrogen in the water sample could be calculated indirectly by measuring the consumption of NADH in the reaction (**Figure 11b**). The biosensor exhibited a linear range from 0.65 to 300 μM with a detection limit of 0.65 μM NH₄⁺.

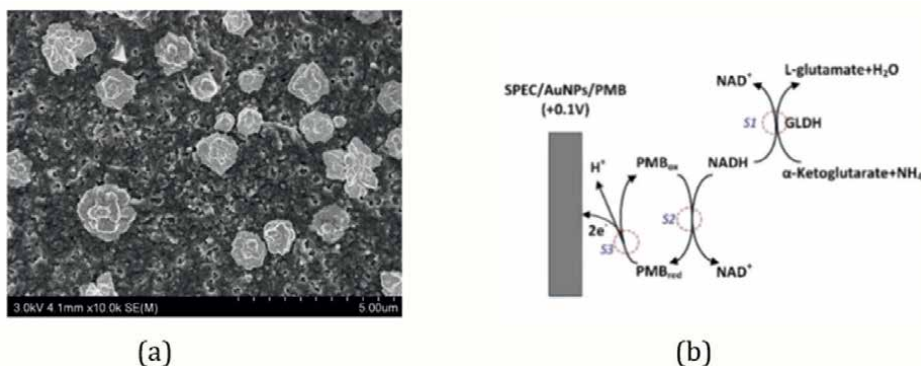


Figure 11.
 (a) SEM micrograph of modified electrode surface; (b) Schematic illustration of NH_4^+ detection. Reprinted with permission from Wang et al. [91].

5. Conclusions

In conclusion, ensuring the quality of water through regular microbiological and chemical analyses is essential for safeguarding human health and promoting environmental sustainability. Detecting harmful bacteria like, for example, *E. coli*, *Legionella*, and *Salmonella* prevents serious waterborne diseases while monitoring nitrogen compounds and heavy metals, such as mercury, helps prevent environmental degradation and health issues. The development of advanced techniques, including electrochemical sensors, and optical methodologies using SiPM, enhances our ability to detect and respond to contaminants promptly and accurately. By integrating these innovative methods into Water Safety Plans, we can achieve more effective monitoring, ensuring safe and clean water for all uses and protecting public health and ecosystems.

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Conflict of interest

The authors declare no conflict of interest.

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Perspective Chapter: Physicochemical Parameters and Water Quality

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Abstract

Water is an indispensable requirement of the ecosystem and an essential component of life. Living organisms require water to sustain life. The required water must be of high quality and also free from all forms of pollutants either chemical or biological. Pollutants tend to decrease the quality and safety of water, leading to numerous diseases and sometimes death. These pollutants are on the increase due to increased industrialization, heavy agricultural practices, improper sewage systems, and many more. The pollutants found in drinking water constitute a serious environmental and public health problem, as the presence of contaminants in water is of great concern due to the level of hazard they cause to consumers and their contribution to the reduction of water quality. This study reviews the types of chemical pollutants found in water and correlates how physicochemical parameters are affected by these pollutants and in essence the quality of water. This important concept highlighted shows how living organisms are in constant threat provided contaminants from industries, agricultural practices are not controlled properly, and how physicochemical parameters indicating water quality will be affected continuously and a consequent continued decrease in water quality if proper environmental practices are not implemented.

Keywords: physicochemical parameters, water quality, living organisms, safety, drinking water

1. Introduction

Water is an essential component of life, which is mainly derived from the ground as a renewable source or from water bodies. Human beings and animals strive to get water in order to sustain life. This is because humans and animals take up essential metals from water to maintain normal metabolism [1], an activity that sustains life on earth. WHO estimates that 844 million do not have basic drinking water and that 230 million people spend more than 30 min per day collecting water which includes piped water, boreholes, protected wells and springs, rainwater, and packaged/delivered water [2]. The water that is suitable for human utilization should be safe and of high quality, i.e. odorless, colorless, and tasty, just like normal water, and also free from dangerous chemical agents and pathogens [3]. The quality of water being used is,

however, an important issue as a decrease in the quality of water reduces its utility for a human being and other organisms [4].

Physical and chemical parameters of water are significant relative to the quality and safety of water. These parameters can be used as measures to improve the quality of water samples suitable for survival and consumption for living organisms [5]. Water is significant for numerous human applications. An increase in pollution and population affects the water quality used for drinking. Any alteration in the physical, chemical, and biological features of water that has a destructive consequence on human health and living creatures can be expressed as water pollution [2]. Polluted water has less value, as utilization may translate into various diseases. A strong relationship exists between human health and water [6]. Physicochemical parameters can serve as indicators of water pollution which can either be due to natural or artificial causes. Unsafe water has been known to cause various disease conditions [7]. WHO report for 2022 recorded that about 1.7 billion people were using contaminated water for drinking purposes that pose a threat to drinking water safety [8]. Safe drinking water is important for maintaining peoples' lives and preventing diseases [9]. Temperature, pH, electrical conductivity, total dissolved solids, dissolved oxygen, sodium, chloride, potassium, carbonate, and bicarbonate can be checked for water safety. Standard methods can be used to determine these parameters. The parameters have various functions in the living systems depending on their respective levels. Human activities, soil, and rock chemistries can affect water properties [10].

2. Quality of water

All living organisms require water for various reasons including drinking. Drinking water needs to be safe in order to maintain a healthy condition. It should have a pleasant taste and can be of domestic use. Polluted water is one that is not suitable for drinking and contains chemical, physical, and biological substances that are unwanted [10, 11]. These pollutants get into water bodies through natural or anthropogenic means. Natural means are somewhat less disastrous and are due to rainwater runoffs from one point to another.

Quality of water is a function of the physical, chemical, and biological parameters, and is influenced by natural and anthropogenic effects, including local climate, geology, and irrigation practices [12].

Anthropogenic activities causing pollution can be classified into industrial, agricultural, and domestic [13]. These are generally attributed to the intense application of farming pesticides and manures, mining activities, industrial effluents, waste dumping locations, and so on [14]. Some prominent industries known to cause water pollution through their effluents are sugar mills, thermal power plants, distilleries, fertilizer, and cement industries, oil refineries, paper, and pulp industries, tanneries, pesticides, pharmaceuticals, and textiles with dye and dye-intermediates [15]. Usually, these manufacturing units release their wastewater into the nearby sewage system, water bodies, and some abandoned lands which are in close proximity to them, these activities originate the environmental crisis [16, 17]. These activities usually affect the physicochemical parameters of water, either by changing the color, odor, pH, and concentration of dissolved solids, or leading to the accumulation of substances in water such as heavy metals, organic pollutants, and many more.

2.1 Water quality index (WQI)

Water Quality Index (WQI) is a comprehensive indicator of water quality. It incorporates various physicochemical parameters to assess the suitability of water for different purposes [12, 18–21]. These parameters include dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, ammoniacal nitrogen (AN), suspended solids (SS), temperature, electrical conductivity (EC), chloride, sulfate, calcium, magnesium, phosphate, total hardness, nitrate, lead (Pb), cadmium (Cd), copper (Cu), iron (Fe), turbidity, nitrates, and fecal coliform, which are essential for determination of water quality index (WQI) and overall water quality [21–25].

Water quality index calculation involves a series of sub-index calculations, with each parameter playing a significant role in the final index value. Determination of WQI will help in evaluating pollution levels, making informed decisions on water quality management, and categorizing pollution sources in waters. It is assumed that understanding and monitoring WQI will ensure effective water quality management, through facilitating compliance with environmental regulations and safeguarding public health.

Studies have shown that the WQI can vary over time and across different locations, reflecting changes in water quality due to factors like human activities, seasonal variations, and pollution levels. By utilizing the WQI, researchers can effectively monitor water quality, identify areas of concern, and implement targeted remediation strategies to ensure the availability of safe and clean water for various uses.

2.2 Calculating water quality index

Water Quality Index (WQI) is a comprehensive measure that consolidates various physical, chemical, and biological parameters of water into a single numerical value, allowing for a straightforward assessment of water quality. A variety of methods have been developed to calculate the Water Quality Index, each with its own advantages and suitability for specific applications.

One approach is known as the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), which evaluates water quality based on the frequency and magnitude of water quality guideline excursions [26]. This method offers flexibility in selecting the parameters to be included and the ability to modify the objectives for each variable based on the intended use of the water [27]. According to the CCME, water quality index can be calculated as follows:

$$WQI = 100 - \sqrt{(F_{12} + F_{22} + F_{32}) / 1.73} \quad (1)$$

Where,

F_1 = [Water variables that do not meet objectives/Total number of water variables]*100.

F_2 = [Number of tests that do not meet objectives/Total number of tests]*100.

F_3 = $nse / 0.01 nse + 0.01$.

Nse (normalized sum of excursions) = Σ^n departure/number of tests [28].

Another technique, the Universal Water Quality Index, was developed by studying the supranational European Community Standard and has the advantage of reflecting the appropriateness of water for specific purposes, such as drinking water supply, rather than just general supply [27]. This index proposes three

classification schemes for surface water quality assessment, providing a more nuanced evaluation. The use of water quality indices has also been explored in the context of groundwater, where they can be applied to indicate the suitability of water for various applications [29].

The National sanitation foundation (NSFWQI) developed in 1970 by the National Sanitation Foundation (NSF) of the United States [30] has been widely field tested and is used to calculate and evaluate the WQI of many water bodies [30]. It represents a general water quality and does not take into account the water's use capacities, furthermore, it ignores all types of water consumption in the evaluation process [31].

The NSFWQI has been widely applied and accepted in Asian, African, and European countries [32], and is based on the analysis of nine variables or parameters, such as BOD, DO, Nitrate (NO₃), Total Phosphate (PO₄), Temperature, Turbidity, Total Solids(TS), pH, and Fecal Coliforms (FC).

The mathematical expression for NSFWQI is given as: [33].

$$\text{NSFWQI} = \sum_{i=1}^n Q_i W_i \quad (2)$$

Where, Q_i = sub-index for i th water quality parameter; W_i = weight associated with i th water quality parameter; n = number of water quality parameters [33].

The Oregon Water Quality Index (OWQI) is a single number that creates a score to evaluate the water quality of Oregon's stream and in other geographical regions that wish to apply the method [30, 32]. Its mathematical expression is represented as [34]:

WQI Value	Rating of Water Quality
<i>National Sanitation Foundation Water Quality Index (NSFWQI)</i>	
91	100 Excellent water quality
71	90 Good water quality
51	70 Medium water quality
26	50 Bad water quality
0	25 Very bad water quality
<i>Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI)</i>	
95	100 Excellent water quality
80	94 Good water quality
60	79 Fair water quality
45	59 Marginal water quality
0	44 Poor water quality
<i>Oregon Water Quality Index (OWQI)</i>	
90	100 Excellent water quality
85	89 Good water quality
80	84 Fair water quality
60	79 Poor water quality
0	59 Very poor water quality

Table 1.
Water Quality Rating as per different Water Quality Index methods [33].

$$OWQI = \frac{n}{\sqrt{\sum_{i=1}^n \frac{1}{SI^2}}} \quad (3)$$

where n is the number of parameters ($n = 8$) SI_i is the value of parameter i .

The application of water quality indices has also been enhanced through the integration of emerging technologies, such as the use of IoT (Internet of Things) sensors. This allows for more extensive water monitoring on a national and global scale, facilitating the development of innovative water quality indices that can provide the public with consistent and easily understandable information about water quality [35].

As these indices continue to evolve, researchers have also explored the potential of artificial intelligence techniques, such as machine learning, to further improve the assessment and management of water quality [29]. These approaches have the capacity to integrate diverse data sources, identify complex patterns, and provide more accurate and nuanced evaluations of water quality that can inform decision-making processes.

These calculations provide a numerical value that represents the overall water quality, usually on a scale of 0–100. The higher the value, the better the water quality. The choice of method and parameters may vary depending on the specific context and requirements (**Table 1**).

3. Types of water pollutants

There are two major forms of water pollutants

1. Chemical pollutants and
2. Biological/pathogenic pollutants

This write-up will discuss more about chemical pollutants with respect to water quality. These chemical pollutants comprise

- i. Inorganic pollutants
- ii. Organic pollutants
- iii. Heavy Metals

3.1 Inorganic pollutants

Inorganic pollutants are considered one of the major pollutants of water bodies, these include nitrates, phosphates, halogens, and heavy metals. This contamination is due to agricultural activities and released municipal/industrial sewage. Nitrates in the body will increase the level of the toxic compound ammonium, which is also considered carcinogenic, increasing the risk of stomach, liver, and esophageal cancer [36]. Developing countries monitor these chemicals in drinking water as a means of assessing water quality.

3.1.1 Nitrates and phosphate (NO_3 and PO_4^{3-})

Nitrates are found in fertilizers and are important for plant growth. Phosphate is a vital nutrient for plants, animals, and humans. It is available in three forms: organic phosphorous, orthophosphate, and polyphosphates. Sources of nitrates in water bodies can be due to application of fertilizers that cannot be taken up by plants due to an imbalance between plant uptake and nitrate availability leading to excess availability of fertilizer not used by plant, which may get concentrated during evaporation and later contaminate the water bodies [37]. Other human-induced actions such as the use of nitrogenous manure, community wastewater, sewage ejection, industrial effluents, polluted ground, polluted sanitation performs, landfills, animal waste, and soluble nitrogen compounds contained by geologic materials—make worse the nitrate pollution [38]. Phosphates are found as sedimentary, igneous, and metamorphic rock in the earth's crust. In a few water bodies, phosphorus levels are low enough to limit the growth of algae and aquatic plants. Consequently, monitoring phosphorus levels is crucial for understanding and managing eutrophication and water quality [39].

The urine and dung of farming animals like cows and buffaloes have also been associated with nitrate pollution in shallow groundwater [40]. Higher nitrate contaminating the human body via water can cause birth imperfections and gastrointestinal diseases [41]. NO_3 goes to reaction with amines and amides in the human body and forms cancer-causing nitroso compounds [23, 42, 43]. Nitrate toxicity in humans increases by frequent boiling of nitrate-rich water for drinking, preparation of dry milk powder with high nitrate-containing water, and weaning with nitrate-rich vegetables [44].

Phosphorus enters water bodies from various sources: natural weathering of rocks and minerals, agricultural runoff, erosion, sedimentation, and animal contributions (non-point sources), as well as sewage wastewater and industrial discharges (point sources). Even a small increase in PO_4 concentration can promote the growth of algae and aquatic plants, leading to eutrophication of aquatic ecosystems. This can result in algal bloom in water bodies [27].

3.2 Organic pollutants

Organic pollutants also constitute a class of water pollutants, these include all forms of synthetic pesticides, dyes, paints, synthetic fibers, plastics, detergents, food additives, solvents, volatile organic compounds, and some pharmaceuticals. These pollutants originate from industrial wastewater, agricultural activities/waste, sewage, and urban wastewater.

Pesticides are organic pollutants of public health concern. They are not easily degradable, so they accumulate in soil and are washed away by water into the water bodies after application in agricultural fields. Some of these persistent compounds that have been traced into various water bodies include organochlorine pesticides, perfluorooctanoate, perfluorooctane sulfonate polybrominated diphenyl ethers, polychlorinated dibenzo-pdioxins, and polychlorinated biphenyls [45]. Owing to their persistent nature, these compounds, when washed into water bodies, bioaccumulate in food webs and cause significant damage to the body [46]. These facts are justified by the findings of [47], stating that an approximate amount of 2.5 million tons of pesticides is applied in the world yearly, 0.1% of these pesticides used arrive at the objective organisms, and the residual 99.9% go away through air, soil, and water, therefore consequential in the pollution of natural ecosystems and water bodies.

The consumption of pesticides in food leads to their long-term accumulation, thereby increasing the concentration of these toxins inside the body organs and leading to chronic diseases such as neurotoxicity, cancer, necrosis, asthma, reproductive disorder, cardiac disease, and diabetes [48]. Pesticides such as organochlorides and carbamates inhibit the acetylcholinesterase activity and are used as a biomarker of neurotoxicity [49]. Organophosphorus compounds (such as malathion and parathion) are associated with breast cancer and are found to affect cellular growth and proliferation [50].

Another organic pollutant of public health concern is the dyes. Dyes are extensively used in industries in conjugation with some water-soluble toxic chemicals. They give color codes for products and are therefore generally used in textile, food, paper, leather, and tanning industries [16]. The untreated effluents of these industries are released contaminants in water bodies and soil. Humans may get affected by consuming vegetables, fruits, and grains that have been sown in soil and irrigated by water contaminated by dyes.

3.3 Heavy metals

Heavy metals are inorganic pollutants of health concern; they are considered as metals having higher densities. Water bodies are highly contaminated by heavy metals due to increased industrialization, increased agricultural practices, and many more. Other sources of contamination by heavy metals include sewerage discharge, municipal and industrial wastes, and effluents. Many researchers have indicated/traced the presence of heavy metals in water, this includes but not limited to countries such as Bangladesh [51], Nigeria [52], and Saudi Arabia [53], to mention but a few. The contamination of water by heavy metals could be due to natural or anthropogenic means with anthropogenic means being the most important means of contamination. Anthropogenic means include processes such as mining, industrial emissions (both in elemental or compound form), roadside and automobiles, fertilizers used in agricultural activities, and discharge of industrial effluents, etc., which are important contributors to heavy metal contamination in water [54]. Whereas, natural means include chemical weathering of rocks with their constituent minerals, decomposing vegetation and animal matter, and also atmospheric dry or wet deposition. Some heavy metals (such as copper, iron, chromium, and nickel) play an important role in biological systems in trace amounts, and are therefore essential, whereas some (such as cadmium and Lead) have no biological role and are toxic, even in trace amounts [55]. Some heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are widely dispersed in the environment. These elements have no beneficial effects on humans, and there is no known homeostasis mechanism for them [56]. Heavy metals like chromium contaminate soil, sediments, and groundwater [57]. Water from the tanning industry has increased levels of chromium. The concentration of chromium through anthropogenic discharge in water bodies is 3550 mt [58]. Industrial wastes aid in the accumulation of toxic contaminants into the soil, affecting the food quality and also posing adverse effects on human life.

3.4 Causes of heavy metal contaminations

3.4.1 Mining

Copper enters ecosystems mainly due to industrial and mining activities. The mining and smelting of copper ores contribute to copper contamination in the soil. Farmland has elevated mercury levels, which contaminate the food chain. Lead in the

soil also results from mining and smelting activities. Additionally, cobalt, which is naturally found in the Earth's crust in minerals like cobaltite, erythrite, and smaltite, contributes to soil contamination. Increased mining activities have led to high levels of nickel in the soil and consequently into the water bodies [59]. Water contamination is further exacerbated by the use of fertilizers, sewage sludge, and other human activities, introducing copper and zinc as pollutants. Despite this, heavy metals like copper act as micronutrients for soil and play a role in ATP synthesis [60].

3.4.2 Automobile emission

Automobile emissions contribute significantly to metal contamination in nearby roadside ecosystems. Metals like lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) are released from vehicle engines, tires, and fuel, accumulating in the topsoil, water bodies, and vegetation near roads. Research indicates heavy metal contamination in water, soil, and vegetables with Zn, Pb, Ni, Cd, and Cr. Atmospheric deposition during transport and marketing also raises heavy metal levels in vegetables.

3.4.3 Other means

Long-term use of phosphate-based fertilizers, dust from smelters, sewage sludge application, and industrial waste deposited into water bodies contribute to heavy metals contamination of ground and surface water.

Below are some heavy metals of public concern.

3.4.4 Lead (Pb)

The rising levels of lead (Pb) in water can be attributed to the release of Pb from marine sediment adsorption, atmospheric dust transfer, chemical weathering of continental shells, and the deposition of airborne aerosols containing Pb [61, 62]. Lead enters the environment primarily through commercial products such as storage batteries, electroplating, construction materials, ceramics, dyes, paints, glassware, and gasoline [63]. Even low concentrations of lead can be harmful to humans over time, as it accumulates in bones. Lead is non-biodegradable and a teratogen, posing severe health risks including cardiovascular diseases and damage to the central and peripheral nervous systems. Lead poisoning can be acute or chronic. Acute exposure can lead to loss of appetite, headache, hypertension, abdominal pain, kidney dysfunction, fatigue, insomnia, arthritis, hallucinations, and dizziness. Chronic exposure may cause intellectual impairment, birth defects, mental disorders, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis, muscle weakness, brain damage, kidney damage, and potentially death [64, 65].

3.4.5 Cadmium (Cd)

Cadmium is one of the non-essential heavy metals that plays no role in biological systems. It is widely dispersed in the environment and can be found in sources such as paints, stabilizers, and coatings. Their alloys are used as coatings on iron, steel, aluminum, and other non-ferrous metals. They have a variety of applications in industries due to properties such as good conductance, low coefficient of friction, good corrosion resistance in alkaline or salt solutions, and are readily solderable. These properties make them suitable for industrial applications requiring a high degree of safety or

durability (e.g. aerospace industry, industrial fasteners, electrical parts, automotive systems, military equipment, and marine/offshore installations) [66, 67]. Cadmium contaminates water bodies and high concentrations in body organs can cause renal dysfunction, kidney damage, and gastrointestinal disorders. And in pregnancy, Cd exposure can lead to premature birth and reduced birth weights [68].

3.4.6 Mercury

Mercury has been known to contaminate water bodies and is in essence carried over to aquatic organisms. Consumption of mercury has been shown to have a detrimental effect on aquatic life and ultimately the consumers, i.e. Humans. Mercury exists in two major forms: inorganic mercury and organic mercury. Inorganic Hg is transformed to organic compounds, like CH₃Hg, which are extremely stable and accumulate in the food web. Organic mercury is a neurotoxic compound, which causes microtubule damage, lipid peroxidation, mitochondrial harm, and the gathering of neurotoxic molecules like serotonin, aspartate, and glutamate [69, 70].

3.5 Biological/pathogenic pollutants

Are pathogenic microbes that enter water bodies through sewage discharge, industrial wastewater, capable of disrupting water quality. Disposal of untreated sewage and human excreta into water body has induced the high level of pathogens in the water ecosystem. These pathogenic microbes are principally Virus and bacteria such as Cryptosporidium, Campylobacter, Salmonella that are found to be the causes of various water borne diseases. Cholera, typhoid, dysentery, polio, hepatitis are some of the common diseases which are seen in human beings caused by the water pollutants.

3.6 Contaminants of emerging concern (CEC)

These are substances that contaminate water and have been recently detected or suspected to be harmful to human health and the environment but are yet to be regulated or usually monitored. These substances include Pharmaceuticals and personal care products (PPCPs), Endocrine-disrupting compounds (EDCs), Nanomaterials, Microplastics, Cyanotoxins, and Algal toxins. These contaminants can interfere with and alter the physicochemical parameters of water, such as pH, turbidity, conductivity, dissolved oxygen, and nutrient levels [71, 72]. They can also affect the overall water quality, leading to outcomes such as:

- Changes in aquatic life and ecosystems [73, 74];
- Increased risk of waterborne diseases [73];
- Cancer, reproductive issues, neurological problems, suppression of the immune system, and Gastrointestinal disorders [75].

Therefore, effective management of emerging contaminants of water requires prompt action with regard to regulation, monitoring, and creation of public awareness [76].

Having discussed the pollutants that cause changes in water and affect its quality, next are the physicochemical parameters involved in the determination of the quality of water.

4. Physicochemical parameters

4.1 Physical parameters

4.1.1 Color

The color of a water sample can show the presence of organic matter: humic compounds or algae in a given water sample. It can also be used as a quantitative assessment index indicating the presence of potentially toxic or harmful organic substances in water [77]. The color of water is also attributed to decay from organic substances like inorganic and vegetation substances such as stones, soil, and rocks. Color is measured by comparison of the sample to standard color solution [78]. The color of water should be transparent indicating the absence of impurities.

4.1.2 Turbidity

This measures the ability of light that passes through water, it occurs due to suspended substances like organic material, silk, clay, etc. in water. It is also referred to as the cloudiness of water [78, 79], and it comprises colloidal and suspended substances [77]. Suspended particles in water can give a place for hiding harmful microorganisms, and can also give adsorption media for heavy metals such as lead, mercury, chromium, cadmium, and other harmful organic pollutants like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and many others [80]. Increased turbidity raises water temperature due to the fact that the suspended substances absorb more heat from the sun. In contrast, the level of dissolved oxygen (DO) might be decreased due to the fact that warm water takes less DO than cold water [81]. Nephelometric turbidimeter is used to measure turbidity; the measured values of turbidity are expressed as Nephelometric Turbidimetric Unit (NTU) or (TU). A TU is approximated as 1 mg/L of silica in suspension, turbidity of more than 5 NTU can be seen but that of more than 100 NTU makes water muddy [78].

4.1.3 Temperature

Temperature affects solubility, viscosity, chemical reactions [78], density, surface tension, specific conductivity, solubility of dissolved gases, etc. The rate of reactions is usually doubled with rise in temperature of 10°C [7]. The biosorption process of dissolved heavy metals in a given water sample is temperature dependent [82], biological oxygen demand (BOD), chlorination, and sedimentation processes also depend on temperature [83]. Further analysis indicated that temperature is among the major variables contributing to differences in pH. Optimum temperature is important for microbial growth [84]. The temperature of a water sample is referred to as a measure of the coldness or warmth of water, usually expressed in degrees Celsius (°C) or a time in degrees Fahrenheit (°F). Temperature is among the major physicochemical parameters used in obtaining water fitness for drinking [85]. High temperatures of water above the WHO acceptable limits can result in preventing oxygen dissolution, creating thermal pollution, and speeding up chemical reactions, even without observing the presence of contaminants [86].

4.1.4 Taste

The taste of water can be affected by foreign substances like organic and inorganic substances as a result of domestic, natural, or agricultural practices. A good water sample should be transparent indicating the absence of suspending particles. The water sample should have no taste and odor [87].

4.1.5 Electrical conductivity

The electrical conductivity of a water sample is referred to as a measure of the capacity of a given solution to conduct or carry an electrical current [88]. EC increases as the concentration of ions in a given solution increases due to the fact that electrical current is conveyed by ions in the solution [78]. EC is affected by many factors including temperature, salts, and total concentration [89]. EC is measured with the following units: U.S. units = microhms/cm. The TDS concentration is linked to EC or specific conductance [78]. Conductivity gives primary relationship with ten parameters such as pH, temperature, total dissolved solids, total hardness, total solids, alkalinity, chemical oxygen demand, calcium, iron, and chloride concentrations of water samples [90, 91].

4.2 Chemical parameters

4.2.1 pH

pH gives the degree of acidity or alkalinity of the water sample [92, 93]. pH is known as the hydrogen ion concentration's negative logarithm, it is among the most significant parameters of water quality [94]. pH is used in the determination of the corrosiveness; it was strongly linked to electrical conductance of water sample quality [69]. Many factors including variations in physicochemical conditions change the pH of the water sample. Acidic water is said to have more hydrogen ions (H^+) and alkaline/basic water contains excess hydroxyl ions (OH^-) [79]. pH starts from 0 to 14, with the middle pH of 7 as neutral. It measures the level of hydrogen ions in the water sample and specifies if a water sample is acidic, neutral, or alkaline. Pollution from industries, acid rain, and plant decomposition are among the possible causes of the acidity of water samples [93].

4.2.2 Total dissolved solids (TDS)

Total Dissolved Solids (TDS) is regarded as the measure of all organic and inorganic components that dissolve in liquid samples [95]. TDS of less than 500 mg/L is referred to as good while that which has about 1000 mg/L and above is known to be unsafe for drinking. TDS can change the color, taste, and clarity of water [8].

4.2.3 Total suspended solids (TSS)

Total Suspended Solids (TSS) of a water sample is known as a measure of materials and solid particles suspended in water that includes many substances like clay, organic substances, etc. not dissolved but suspended in a water sample [96]. Dissolved Oxygen (DO) is the oxygen level found in water [89]. DO serves as a significant measure of organic waste broken down by both anaerobic and aerobic organisms [97] (**Table 2**).

Parameter	WHO Standards
pH	6 to 8
Conductivity (µS)	200 to 400
T.D.S (mg/l)	500 to 1000
Water Temperature (°C)	—
D.O (mg/l)	>4
Chloride (mg/l)	< = 250
Sulfate (mg/l)	< =250
Nitrate (mg/l)	<=10
Calcium (mg/l)	< = 100
Magnesium (mg/l)	< = 50
Total Hardness (mg/l as CaCO ₃)	100 to 500
Sodium (mg/l)	< = 20
Potassium (mg/l)	< = 10
Aluminum (µg/ml)	< 0.1–0.2
Cadmium (µg/ml)	< 0.003
Chromium (µg/ml)	< 0.05
Copper (µg/ml)	< 2
Manganese (µg/ml)	< 0.5

WHO: World Health Organization.

Table 2.
WHO Acceptable Values of Physicochemical Parameters of Water [98].

5. Current challenges and future prospects of water quality research

Water quality research is a critical field that aims to understand the physical, chemical, and biological characteristics of water resources, as well as the factors that affect their quality and suitability for various purposes, such as human consumption, agricultural irrigation, and industrial applications. The research on water quality faces several challenges, particularly concerning the detection, analysis, and mitigation of pollutants. One major challenge is the development of advanced and cost-effective methods for detecting contaminants at very low concentrations. Traditional methods are often expensive and time-consuming, limiting their practical application, especially in developing regions.

One of the significant challenges in water quality research is the increasing pollution and contamination of water bodies due to human activities, such as industrial waste, agricultural runoff, and improper wastewater management [99]. These pollutants can have detrimental effects on the environment, ecosystems, and human health, and addressing these challenges requires a comprehensive and multidisciplinary approach. Another challenge is the variability and complexity of pollutants. Emerging contaminants such as pharmaceuticals, personal care products, and microplastics present new challenges for water quality monitoring and treatment. These contaminants are not fully understood, and their long-term impacts on ecosystems and human health are still being studied. Furthermore, there is a need for continuous

monitoring and assessment of water quality, which can be resource-intensive and time-consuming, especially in remote or hard-to-access areas [99]. Furthermore, the scarcity of water resources and the growing demand for clean water, particularly in developing countries, add to the complexity of water quality research [100]. Climate change also poses a significant challenge to water quality. Changes in precipitation patterns, temperature, and extreme weather events can alter the distribution and concentration of pollutants in water bodies [101]. This variability complicates the prediction and management of water quality.

Despite these challenges, there are promising prospects for the future of water quality research. Advances in technology, such as the development of low-cost Internet of Things (IoT) sensors, remote sensing techniques, artificial intelligence, and machine learning, can enable more efficient and widespread water quality monitoring. Additionally, the integration of data from various sources, including satellite imagery and social media, can provide real-time data, predictive analyses, and a more comprehensive understanding of water quality issues and guide decision-making processes [102]. Furthermore, interdisciplinary collaborations between scientists, policymakers, and community stakeholders can lead to the development of innovative solutions that address the multifaceted nature of water quality challenges.

6. Conclusion

Physical parameters and chemical pollutants found in water and how they affect the quality of water were reviewed in this study. The study highlighted how living organisms are in constant threat provided contaminants from industries, agricultural practices are not controlled properly, and how physicochemical parameters indicating water quality will be affected continuously and a consequent continued decrease in water quality if proper environmental practices are not implemented.

Conflict of interest

The authors declare no conflict of interest.

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Emerging Trends in Real-Time Water Quality Monitoring and Sanitation Systems

Preeti Verma and Pankaj Mehta

Abstract

Water, sometimes referred to as the ‘matrix of life’, highlights the fundamental significance of life’s ecosystem. However, water pollution creates substantial worldwide concerns, jeopardising access to safe drinking water and impeding progress towards the Sustainable Development Goals (SDGs). Real-time monitoring (RTM) systems, which use modern sensor technology and data analytics, present a possible answer to these issues. The study examines the challenges presented by worldwide water issues such as scarcity, pollution and insufficient sanitary infrastructure. This emphasised the function of RTM in water management, emphasising its benefits for improving water quality monitoring, supporting effective water management strategies and protecting water resources. Furthermore, it investigates the use of Internet of Things (IoT) devices and remote sensing techniques in water quality detection, emphasising their ability to give real-time data, increase monitoring capabilities and promote informed decision-making. The chapter also examines the use of advanced sensors (chemical sensors, smart sensors, satellite sensors), data analytics and visualisation approaches for enhanced decision-making and resource management. Overall, RTM, when combined with IoT and remote sensing technologies, provides a holistic strategy to addressing water pollution, mitigating its effects and promoting sustainable water management practices.

Keywords: SDG, sanitation, real-time monitoring, sensor networks, internet of things (IoT)

1. Introduction

Szent-Györgyi defined water as the ‘matrix of life’, claiming that life cannot exist without it [1]. Liquid water on the surface is a distinguishing trait that distinguishes Earth as a special planet, and it is frequently seen as necessary for a planet to host life [2, 3]. The total volume of water in the universe is around 1386 million cubic kilometres, distributed haphazardly throughout the Earth’s surface, depths and above it [4]. Freshwater on the surface accounts for slightly more than 1.2% of all water on Earth, meeting almost all of the requirements for life [5]. Humans rely

on the earth's principal freshwater resources, which are atmospheric water, surface water and groundwater. Freshwater is distributed over the world in a variety of ways, including rivers, lakes, ponds, dams, groundwater reservoirs, glaciers and clouds. Whilst water is required for drinking, residential, agricultural and industrial purposes, much of it remains inaccessible to humans [4]. According to UNESCO's 2021 World Water Development Report, worldwide freshwater consumption has increased sixfold over the last century, rising by about 1% per year since the 1980s [6]. Access to safe drinking water is a fundamental right for all people, regardless of nationality, religion, race, financial situation or beliefs [7, 8]. The increased demand for water has created considerable issues in ensuring water quality. Factors like industrialisation, agriculture and urbanisation have all led to environmental degradation and pollution, particularly in critical water sources like rivers and oceans [8]. These challenges endanger human health and impede progress towards long-term social development [6].

Water is extremely sensitive to pollution due to its outstanding ability to dissolve a wide range of compounds, surpassing any other liquid on the globe. Toxic substances from agricultural areas, urban centres and industrial facilities easily dissolve and combine with water, resulting in pollution [9]. Water contamination is a serious threat to both human health and the environment. Pollutants in water sources, combined with inadequate sanitation facilities, impede attempts to alleviate severe poverty and prevent disease in the poorest countries. For example, insufficient water sanitation is a major cause of death in many nations, with hazardous water and poor sanitation increasing the incidence of many ailments amongst the population [10]. Approximately 80% of industrial and municipal wastewater is released into the environment without first being treated, which has a negative impact on both human health and ecosystems. This percentage is significantly higher in the least developed countries, where sanitary facilities and wastewater treatment capacity are severely lacking [6]. Over the last decade, the World Economic Forum has continuously highlighted freshwater depletion as one of the top ten global concerns. Poor water quality due to pollution reduces its utility for agriculture, industry and household purposes, reducing the overall accessible water in the region [11]. Water quality arises as a key challenge for societies globally in the twenty-first century. Due to this problem, almost 1.2 billion people consume contaminated water, and by 2025, nearly 2.7 billion people will be compelled to consume polluted water [12]. Failure to address this huge challenge is expected to have serious ramifications for several sustainable development goals (SDGs) [13].

2. Focus on sustainable development goals (SDGs)

The SDGs are centred on particular goals aimed at attaining prosperity, benefiting people, safeguarding the planet, fostering peace and enhancing partnership, often known as the five Ps, with time-bound targets [14]. At present, the background materials consist of 17 goals, 169 targets and 247 indicators [15]. Globally, there is an apparent pattern in the indicators associated with environmental Sustainable Development Goals (SDGs). In 2022, 38% of the 92 environmental indicators showed positive changes, indicating better environmental circumstances, whilst 21% showed limited or negative moves. The indicators predominantly demonstrating positive trends were those linked with Sustainable Development Goal 9 (infrastructure), Sustainable Development Goal 7 (energy) and Sustainable Development Goal 6

(freshwater) [16]. Integrated water management is critical not only for reaching different SDGs but also for meeting SDG 6's goal of guaranteeing universal access to sustainable water and sanitation [17, 18]. There are certain issues in proper implementation of these SDGs due to various problems as discussed. Whilst many developing countries in Asia, Africa and Latin America confront issues due to a lack of water resources and infrastructure, several European countries, including as Italy, France and the Netherlands, have legally mandated water access. In contrast, in other European countries and the United States, local governments are responsible for ensuring this right, and they must find a balance between supporting immediate needs and making long-term infrastructure expenditures [19]. Sustainable Development Goal 7 strives for clean and affordable energy; however, reaching it can be difficult due to the considerable energy consumption required for wastewater treatment. With total electricity requirements ranging from 250 to 500 kWh per million litres of wastewater treated, this is a significant demand that affects municipal energy expenditures, which currently account for 30–60% of overall costs in the United States [20].

Meeting the goals of SDG 6 is difficult because India's top six domestic water-consuming states, including Uttar Pradesh, Bihar, Maharashtra, West Bengal, Madhya Pradesh and Andhra Pradesh, consume more than 8 billion cubic metres of water combined. Despite a consistent increase in India's total yearly water demand, both the total internal renewable water resource and the overall renewable water resource are expected to drop due to population growth, aggravating the reduction in per capita available renewable water resources [21]. Some causes [22] of delay in achieving SDGs are shown in **Figure 1**.

Achieving this goal requires a diverse approach that includes regulatory frameworks, technical advances and community engagement [23, 24]. Real-time monitoring emerges as a critical instrument in this endeavour, providing insights into water quality dynamics and allowing for prompt interventions [25].

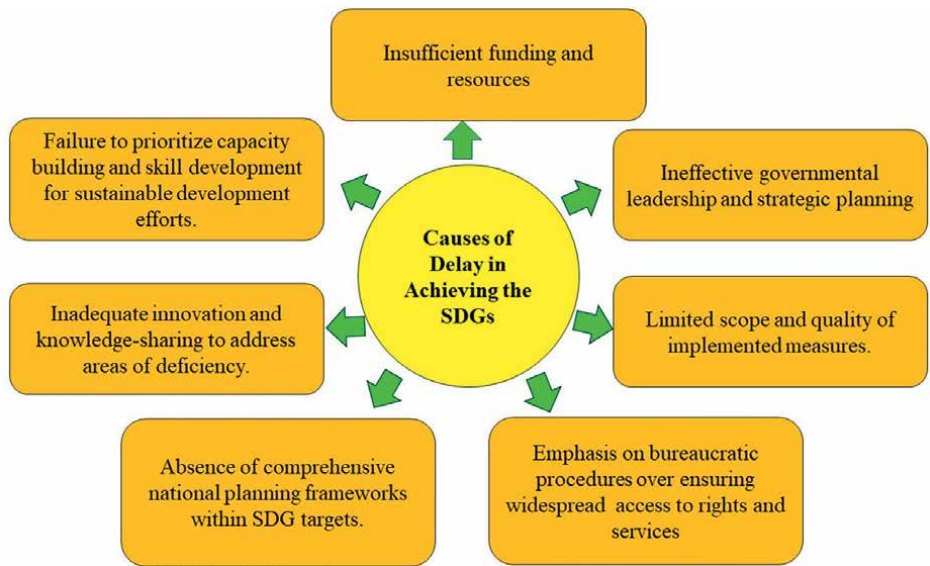


Figure 1.
Causes of delay in achieving SDGs.

3. The role of real-time monitoring (RTM) in water management

The global stress over the rising demand for clean water over a variety of activities, including household consumption, industrial production, agriculture, recreation and environmental preservation, is increasing. Right now, water parameters are assessed using chemical or laboratory tests using stationary equipment and samples brought to testing facilities. As a result, the current water quality monitoring system is operated manually, which is a labour-intensive and time-consuming process. To increase monitoring frequency, one potential approach is to insert testing equipment directly into river water, allowing for remote detection of contamination [26]. Across all water management scenarios, there is an increasing need for current data to support successful water management techniques [27]. Integrated Water Resources Management (IWRM) is a plan of action that includes the coordinated development and long-term management of groundwater and surface water systems, coastal areas, river basins and marine environments whilst taking into account land use patterns and communities' ability to use and benefit from this critical natural resource [28]. Wireless sensing devices have the potential to drastically reduce costs whilst simultaneously providing improved, continuous monitoring capabilities. These systems have the advantage of delivering accurate, real-time insights into changing environmental conditions and water quality, yielding more usable data for successful management [29]. The real-time monitoring system alerts operators, encouraging them to stop water flow in order to preserve water and reduce risks as needed. An advanced RTM and Supervisory Control and Data Acquisition (SCADA) system monitors and manages Antalya City's Water Distribution System (WDS). This integrated RTM-SCADA system monitors and adjusts both hydraulic and water quality parameters, hence improving the WDS's operational efficiency. The system allows for automated control of pumps and valves, as well as security alarms that trigger when any monitored water quality metrics deviate from drinking water quality criteria. This function protects the WDS from potential negative effects caused by purposeful or accidental activities [30]. Benefits of water quality measurements are:

- Water quantity and quality measurements are critical for implementing efficient drought and flood management techniques.
- These metrics aid in determining the availability of water resources for municipal, industrial and agricultural applications.
- Assessing the overall health of a watershed requires quantifying pollution loads in surface waters.
- These metrics also help to determine whether a watershed is suitable for supporting living resources and providing ecological services.
- Furthermore, water quantity assessments aid in the identification of potential human health risks connected with water quality issues [31].

4. Leveraging advanced sensor technologies and data analytics

The Internet of Things (IoT) dramatically improves water quality monitoring by allowing for real-time data collection, analysis and management [32]. IoT devices

outfitted with various sensors can continually monitor crucial water characteristics including pH, temperature, dissolved oxygen, turbidity and conductivity [33]. These sensors send data to centralised systems, where it may be analysed to detect pollutants, forecast contamination occurrences and assure compliance with environmental regulations [34]. Smart sensors in water bodies, for example, can detect and alert authorities to chemical spills or biological contamination, allowing for faster response and mitigation actions [35]. Furthermore, IoT-enabled devices can improve water treatment operations by providing real-time insights into the performance of the filtration and purification phases, ensuring the delivery of safe drinking water. The use of IoT in water quality monitoring not only enhances the accuracy and efficiency of water management methods, but it also promotes environmental sustainability and public health [36].

Sensors used to detect the velocity of flowing surface water: These technologies include water level sensors built for ongoing stage measurements at the surface level, as well as acoustic Doppler technology, utilised for tracking both discrete and continuous water velocity, allowing discharge to be calculated. Shaft encoders, submersible pressure transducers, noncontact RADAR systems and bubbler systems are common types of sensors used for continuous water level measurement as shown in **Table 1**.

Sensors to detect water quality: Water quality sensors detect indications of water degradation and provide diagnostic information for pollution control. They range from physical, chemical, and biological sensors to multiparameter data sondes, allowing both discrete and real-time monitoring [38].

Physical sensors: Physical sensors detect and measure physical features or changes in the environment, transforming them into readable electrical impulses [39]. These

Type of Sensors	Shaft encoders	Submersible pressure transducers	Noncontact RADAR systems	Bubbler systems	Source
On-site installation	Detects water level variations using a weight, float and pulley system to track the rise and fall of water.	Detects water level variations by analysing pressure changes caused by variations in water level.	Microwave energy propagation is used to monitor water level, which is then calculated using pulse travel time.	Determines the pressure required to drive air through the water and uses this information to calculate the water level.	[31, 37]
Operational mechanisms	A stilling well pipe is introduced into the water, and a shaft encoder is installed within.	A pressure sensor is positioned at a constant depth in the water.	Mounted atop a bridge or other fixed structure across the river, with a mounting arm.	An airline orifice tube is placed at a certain depth in the water, whilst the bubbler, pressure sensor electronics and DCP are mounted above it.	[31, 37]
Accuracy	±0.073	±2	±2	±3	[32]

Table 1.
Sensors for continuous water level measurement and accuracy.

sensors are vital in a variety of applications, including industrial automation, environmental monitoring, healthcare and ordinary consumer electronics. Some important parameters are discussed like:

- a. Temperature is an important characteristic in water quality assessment since it directly influences chemical reactions, biological processes and gas solubility in water. Temperature sensors, which are often made of thermocouples, thermistors or resistance temperature detectors (RTDs), monitor the thermal status of water [40]. These sensors detect changes in electrical resistance or voltage in response to temperature swings. For example, thermocouples produce a voltage that varies with temperature, whereas RTDs change resistance as temperature changes.
- b. Turbidity sensors detect the cloudiness or haziness of water, which is caused by suspended particles such as silt, algae and bacteria [41]. These sensors typically use optical methods to determine turbidity levels. Nephelometry, a frequent method, projects a light beam into the water and measuring the scattered light at a given angle. More levels of dispersed light indicate more turbidity [42]. Turbidity monitoring is critical for determining sediment load, contaminant levels and the efficacy of water treatment operations. High turbidity levels can restrict light penetration, impairing photosynthesis in aquatic plants and altering food chains.
- c. Aquatic species rely heavily on dissolved oxygen (DO) to survive. DO sensors, which are commonly based on electrochemical (Clark-type) or optical (luminescent) technologies, detect the quantity of oxygen dissolved in water [43]. Electrochemical sensors detect oxygen by measuring the current produced by oxygen reduction at a cathode, whereas optical sensors measure DO levels by suppressing luminescence with oxygen [44]. Continuous DO monitoring aids in the detection of hypoxia (low oxygen) or anoxia (no oxygen), which can indicate organic contamination and eutrophication [45]. Eutrophication, which is frequently caused by agricultural fertiliser runoff, causes excessive algae growth and subsequent oxygen depletion, having a significant influence on aquatic life.
- d. Conductivity sensors evaluate water's ability to conduct electrical current, which is directly proportional to the concentration of dissolved salts (ions) in the water [46]. These sensors work by passing an alternating current between two electrodes and measuring the resulting voltage. Higher conductivity indicates increased ion concentration, which can be caused by natural processes or pollution from agricultural runoff, industrial effluents and sewage discharge. Monitoring conductivity aids in determining salinity, overall water mineral content and the influence of pollution [47]. High conductivity can indicate the presence of dangerous chemicals and compromise water quality for drinking and irrigation.

Physical sensors are frequently integrated into multisensor systems used in a variety of habitats, including rivers, lakes and coastal waters. These sensors can be mounted in fixed monitoring stations or on mobility platforms such as buoys and autonomous underwater vehicles. For example, multisensor systems have been created to detect pH, temperature, dissolved oxygen, conductivity, redox potential and turbidity. These technologies are critical for delivering complete water quality tests,

responding quickly to pollution incidents and monitoring the environment over time. They can identify pollutants such as heavy metals, pesticides and organic substances, which helps safeguard water resources and aquatic habitats.

Chemical sensors: Chemical sensors play an important role in modern water quality monitoring because they can detect and quantify a wide range of pollutants and parameters with high sensitivity and specificity [48]. The first big breakthrough in water monitoring occurred in 1930, when the glass pH electrode was developed, establishing pH as the primary criterion for assessing water quality. However, complete water quality monitoring necessitates the evaluation of numerous parameters, resulting in the creation of multisensor systems.

Multisensor systems have been used for a variety of water quality management applications [38]. For example, a voltammetric sensor array with electrodes consisting of gold, platinum, iridium and rhodium was used for multisite water quality monitoring in a treatment facility, effectively distinguishing between phases of water purification by principal component analysis (PCA) [48]. Another continuous water monitoring system comprised sensors for pH, temperature, dissolved oxygen, conductivity, redox potential and turbidity, all installed on a single platform with remote data transmission capability.

More advanced multisensor systems have been created to detect specific pollutants. A significant example is a Chinese system that uses a multiple light-addressable potentiometric sensor (MLAPS) to detect Fe(III) and Cr(VI) simultaneously, along with electrodes for other elements such as zinc, cadmium, lead and copper [49]. This technology obtained low detection limits that are appropriate for both saltwater and wastewater analysis.

Portable and remote systems are also being used. For example, a device with 14 buoys fitted with ion-selective electrodes monitored ammonium, nitrate and chloride concentrations in a lake and transmitted data via GSM and GPRS [50]. Despite some limitations, such as sensor drift, these systems provide real-time data that are critical for water quality management.

Additionally, sensor arrays have been utilised to detect rapid changes in effluent quality over extended periods [51]. An example is a sensor array made up of eight conducting polymer sensors that analysed gas phases emitted by bubbling liquids [52], providing great sensitivity and versatility whilst minimising the impact of long-term drift and environmental conditions.

Overall, chemical sensors, particularly those in multisensor systems, are critical for effective water quality monitoring, allowing for real-time, complete analysis whilst also ensuring water safety and environmental protection. Continuous developments in sensor technology and data integration are required to improve their effectiveness and dependability.

Biosensors: Biosensors are a promising alternative to traditional chromatography-based approaches, with electrochemical biosensors standing out for their benefits in real-time monitoring, miniaturisation, sensitivity and selectivity enhancement [53]. They make it easier to convert biological signals into readable output signals without the use of sophisticated signalling components, allowing for the creation of small clinical testing systems and environmental monitoring tools. Electrochemical biosensors use electrodes to translate biological signals, with sensitivity and selectivity gained by modifying specific biological elements such as DNA, cells or enzymes [54]. These biosensors are classified as biocatalytic or affinity sensors, depending on whether they can catalyse reactions or recognise specific targets [55]. Biosensors are used to detect dangerous heavy metals in the environment, such as lead, cadmium,

mercury and copper [56]. Electrochemistry, a field of science that studies the interplay between electrical and chemical processes, is critical in biosensor technology [57]. Potentiometric approaches in electrochemical sensors measure cell potential, whereas voltammetric methods investigate charge transport at the electrode-solution interface [58]. Voltammetric techniques, in particular, are designed to analyse electron transfer, making them appropriate for species susceptible to oxidation or reduction [59]. Overall, biosensors, particularly electrochemical ones, are useful instruments for a variety of applications, providing insights into chemical processes whilst also enabling precise detection and monitoring of target analytes. An overview on the classification of biosensors is shown in **Figure 2**.

Role of remote sensing in water quality detection: Remote sensing techniques play an important role in monitoring water quality by detecting changes in spectral fingerprints backscattered from surface water caused by suspended sediments, algae, dissolved organic matter (DOM), aquatic vascular plants and heat discharges [60].

Use of remote sensing in determination of suspended solids: Suspended sediments, the most abundant pollutant in freshwater systems in terms of weight and volume, have a substantial impact on the radiance emitted by surface waters, particularly in the visible and near-infrared spectrum [61]. Surface water radiance is influenced by a variety of elements, including sediment type, texture, colour, sun angles, sensor view and water depth. Studies have shown that spectral wavelengths between 700 and 800 nm are the most effective for determining suspended sediment, with empirical connections established between sediment concentration and brightness or reflectance [62]. Whilst many algorithms have been designed for specific locations and times, few have been used in many temporal or spatial settings. Nonetheless, curvilinear correlations have been found between suspended sediments and brightness, prompting more advanced modelling approaches such as Schiebe et al.'s [63] physically based reflectance model. Whilst mapping suspended sediments in vast bodies of water is possible with present satellite sensors, higher resolution data from newer satellites will improve monitoring capabilities, allowing for more informed water quality management decisions.

Monitoring of chlorophyll content: Remote sensing is critical for monitoring chlorophyll concentrations, which are required to manage eutrophication in lakes. Studies frequently rely on empirical connections between radiance/reflectance and chlorophyll, which are calibrated using field data [64]. Whilst excellent techniques exist, detecting chlorophyll in sediment-laden waters using current satellite data is difficult. Research on the 'red edge' of the spectrum has promise for enhanced estimate, particularly with the introduction of hyperspectral sensors [65]. Recent

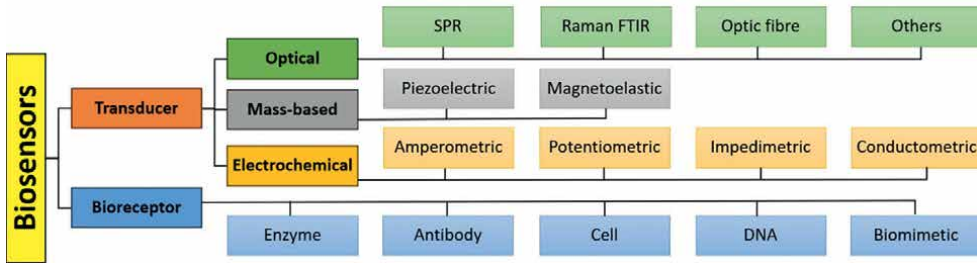


Figure 2.
Classification of biosensors.

satellite advances have the potential for improved differentiation amongst algae groupings. Fluorescence is a technique that helps identify phytoplankton species [66]. As hyperspectral and spatial data increase, monitoring chlorophyll will become more precise and complete. Recent satellite sensors, like SeaWiFS, Modular Optical Scanner (MOS), Ocean Colour and Temperature Scanner (OCTS) and Ikonos, show tremendous promise for assessing biological productivity in aquatic systems and distinguishing between algae groups [67].

Role of remote sensing in aquatic vascular plants: Giant *Salvinia* outbreaks in Texas waterways have been detected and monitored using advanced remote sensing techniques combined with geographic information systems (GIS) and Global Positioning System (GPS) technology [68]. Aerial videography and GIS mapping have helped assess the size and severity of gigantic *Salvinia* infestations.

Aerial videography uses airplanes at specified heights to take high-resolution colour-infrared (CIR) digital photos of the affected areas. These photographs provide precise visual data that analysts can use to distinguish enormous *Salvinia* mats from surrounding vegetation and bodies of water [69]. By including GPS data in the images, exact georeferencing is accomplished, allowing for the accurate identification and mapping of gigantic *Salvinia* populations across large and frequently inaccessible landscapes [68].

Role of remote sensing in temperature detection: Thermal pollution from human activity damages aquatic ecosystems by changing water temperatures. Remote sensing has proven beneficial in mapping thermal discharge from power plants into rivers, lakes, and coastal waterways, allowing for more accurate estimation of thermal plumes [70]. Remote sensing of absolute temperatures reveals spatial and temporal patterns of thermal emissions, which aids in their management [71]. Because of the fine control over data collection schedule, aircraft-mounted thermal sensors are very helpful in analysing thermal plumes [72]. Satellite platforms like AVHRR monitor seasonal fluctuations in surface water temperatures, shedding light on the ocean's role in climate control, including El Niño [73]. Several studies have used remote sensing data to track thermal energy emissions and algal densities in bodies of water such as Lake Baikal and the Great Salt Lake [74], uncovering relationships that help with ecological assessments. Thermal remote sensing, such as Landsat TM, makes it easier to monitor freshwater systems, detect thermal changes that affect biological productivity and guide management techniques [68]. SPOT imagery improves remote sensing capabilities by outlining lake margins, which is critical for ecosystem research and precise mapping of submerged vegetation, especially in variable water levels [75]. However, in some settings, excessive suspended solid concentrations can impair remote sensing's ability to assess submerged plant populations.

Nanomaterial-based sensors: Various nanomaterial-based sensors are used in water quality monitoring according to their sensing strategy, nanomaterial types and the analytes they detect [76]. These sensors are categorised as:

4.1 Optical sensing strategy

Colorimetric Method: Utilises gold nanoparticles and silver nanoparticles to detect analytes such as nitrite (NO_2^-), nitrate (NO_3^-), cocaine, lead (Pb^{2+}), copper (Cu^{2+}) and mercury (Hg^{2+}) [77].

Fluorescence: Employs quantum dots for detecting heavy metals like cadmium (Cd^{2+}), lead (Pb^{2+}), mercury (Hg^{2+}) and copper (Cu^{2+}) [78].

Surface-enhanced Raman spectroscopy (SERS): Uses gold nanoparticles to detect pesticides, bacteria, viruses and protozoa [79].

4.2 Electrical sensing strategy

Chemiresistors: Gold nanowires are used to detect halides, whilst metal oxide semiconductor nanowires and polymer nanowires are used for volatile organic compounds (VOCs), ammonia and nitrogen dioxide (NO₂) [80].

Field-effect transistors: Silicon nanowires (SiNWs) and two-dimensional transition metal dichalcogenides are used for detecting nucleic acids, influenza, glucose, hydrogen peroxide (H₂O₂), proteins, mercury (Hg²⁺) and pH levels. Gold nanoparticle functionalized polymeric FETs specifically target mercury (Hg²⁺) [81].

Phosphorene (black phosphorus): Targets IgG protein [82].

Graphene and carbon nanotubes: Used for detecting bacteria and ammonium, cobalt (Co²⁺) and organo-phosphate pesticides [83].

Copper nanowire electrodes and polymeric nanocomposite membranes: Detect nitrates, silver (Ag⁺), mercury (Hg²⁺) and copper (Cu²⁺) [84].

Reduced graphene oxide/gold nanoparticle nanocomposite: Targets organo-phosphate pesticides [85].

4.3 Electrochemical sensing strategy

Graphene, carbon nanotubes, copper nanowire electrodes and polymeric nanocomposite membranes: These materials are used for detecting a variety of analytes including bacteria, ammonium, cobalt, organo-phosphate pesticides, nitrate, silver, mercury and copper.

4.4 Magnetic sensing strategy

Magnetoresistance: Magnetite (Fe₃O₄) and maghemite (γ-Fe₂O₃) are used for detecting *Mycobacterium bovis* and Influenza A [86].

Hydrodynamic property changes and T₂ relaxation magnetic resonance: Magnetite (Fe₃O₄) and magnetic beads are used for spore detection and identifying *Salmonella enterica* and Newcastle disease virus (as a representative of *Escherichia coli* O157:H7) [87].

5. Conclusion

Real-time monitoring (RTM) systems, which are powered by modern sensor technologies, the Internet of Things (IoT) and remote sensing techniques, play an important role in combating water pollution and promoting sustainable water management. RTM systems provide real-time data on water quality parameters such as pH, temperature, dissolved oxygen, turbidity and conductivity, allowing for early detection of contamination events and timely measures to limit risk. Furthermore, IoT-enabled devices provide continuous monitoring capabilities, allowing for more effective management of water resources and maintaining environmental compliance. Furthermore, remote sensing techniques like spectral analysis and thermal imaging improve monitoring capabilities by identifying changes in water quality indicators and assessing environmental repercussions. Together, these technologies provide a holistic approach to addressing water pollution, protecting water resources and achieving the Sustainable Development Goals for clean water and sanitation. As sensor technology and data analytics progress, the integration of RTM, IoT and

remote sensing shows significant promise for improving water quality monitoring, increasing environmental sustainability and protecting public health.

Statements and declarations

Author contributions

Conceptualization and manuscript writing, Preeti Verma; Supervision, review and editing, Pankaj Mehta. All authors have read and agreed to the final version of the manuscript.

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Data availability

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Section 3

Long-Term Management and Sustainability Strategies

Protection of Water Resources from Nitrate Pollution of Agricultural Origin: Administrative and Methodological Aspects of Significant Interest of the Nitrates Directive 91/676/EEC

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Abstract

This chapter provides an overview of Directive 91/676/EEC, which aims to protect water resources from pollution by nitrates from agricultural source. An important aspect of this Directive is the identification and delimitation of Nitrate Vulnerable Zones (NVZs), areas identified as being at high risk of nitrate pollution and subject to specific regulatory measures. Furthermore, the chapter reports a methodology for slope calculation, which is crucial for assessing runoff potential and subsequent nitrate leaching and comprehensive case studies on livestock manure management technologies, highlighting innovative practices for reducing environmental impact.

Keywords: nitrate vulnerable zones (NVZs), directive 91/676/EEC, water pollution, slope calculation, livestock manure management

1. Introduction

The Directive concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC) so-called Nitrates Directive [1] is a European Union (EU) measure adopted in 1991 to reduce and prevent pollution of surface and groundwater and soil by nitrates from agricultural sources (mainly fertilizers and manure) [2, 3].

EU Member States, in order to protect waters from pollution caused by nitrates of agricultural origin, are required to implement water monitoring programs, with precise deadlines and timetables, on their respective national territories.

These monitoring programs shall include the analysis of parameters such as nitrate concentrations of surface and groundwater. Impairment of the water resource and,

where appropriate, its level of pollution shall be assessed based on nitrate concentrations greater than 50 mg/l, evaluated both as point data and an annual average and as a significant trend that identifies the short-term overshoot [4].

In these EU areas, the Directive provides for:

1. Identifying the Vulnerable Zones from Nitrates of agricultural origin (NVZs), where the spreading of wastewater over 170 kg of nitrogen per hectare per year is prohibited. The designation shall be reviewed and, where appropriate, reviewed at least every 4 years to take account of any changes that may have occurred.
2. Regulating and monitoring the agronomic use of livestock waste through action programs, a series of measures that farmers are obliged to take in farm management in order to improve the quality of water, such as periods when the application of certain types of fertilizer to soil or the limitation of the application of fertilizers to soil following good agricultural practices and which according to the characteristics of the vulnerable zone concerned is prohibited.
3. Developing a Code of Good Agricultural Practice (COGAP), which farmers apply voluntarily and which establishes a set of good practices, for example by indicating when fertilizer use is not appropriate. Examples of GAP are slurry storage and management to reduce the impact of nutrient losses in the riskiest time of the year and low emission slurry spreading, chemical fertilizer controls and others [5].

2. What are NVZs?

Nitrate Vulnerable Zones (NVZs), regulated by the Nitrate Directive, are designed to protect groundwater and surface water from pollution caused by agricultural nitrates. The Directive requires States and Regions to limit the use of nitrates in predetermined areas. These areas show compromises in water quality or have a higher sensitivity to contamination from chemical substances mainly derived from agricultural fertilizers and other sources of pollution. Vulnerable zones are periodically reevaluated and updated based on changes in environmental conditions, agricultural practices, regulations, and other relevant factors. The zones are established by institutions responsible for managing water resources at the regional level. Decisions are made involving environmental authorities responsible for monitoring water quality in various supply sources, such as rivers, lakes, and wells, to determine nitrate levels. Monitoring data are analyzed by a pool of experts identifying areas where nitrate levels exceed safety limits set by current legislation. The data provide the basis for assessing the potential risk of nitrate impacts on human health and the environment. Based on the results of the analysis and risk assessment, authorities define zones that are considered vulnerable to nitrate pollution. The identified NVZs are included in Plans and Programs aimed at reducing pollution through regulations, sustainable agricultural practices, continuous monitoring, and integrated management strategies involving farmers, local authorities, and other interested parties.

Effectively addressing this issue requires a coordinated effort at the local, national, and international levels to promote sustainable practices and reduce the impact of human activities on the environment. The current trend is exploring new methods to monitor and manage NVZs using advanced technologies such as drones or satellites for aerial monitoring. These technologies can help identify risk areas more accurately

and promptly. In addition, artificial intelligence (AI) and machine learning (ML) can be powerful tools in identifying zones and managing nitrate pollution [6–9]. They can be used to analyze large amounts of heterogeneous data concerning water quality, agricultural practices, weather data, and other factors that influence the presence of nitrates in the environment. It is possible to develop predictive models that estimate future nitrate levels based on historical and current data, helping to make proactive decisions. AI and ML can be used to optimize management strategies, making them more efficient and less subject to human error, and with continuous learning, they can exploit the ability to learn and adapt to new data.

A further trend envisages an integrated approach based on chemical and biomolecular methodologies for the identification and quantification of potential sources of nitrate pollution and site-specific pressures, implementation of the control register, implementation of precision livestock farming practices, enhancement of the use of biochar as an amendment in agriculture, and improvement of environmental communication [10–14].

3. Description of the action programme with principles and objectives

The Action Program is drafted at the regional level under the Nitrate Directive. The Program regulates the agronomic use of livestock effluents, wastewater, reclaimed wastewater for irrigation uses, digestates, other nitrogen fertilizers, vegetation waters from olive mills, and sewage sludge within Nitrate Vulnerable Zones (NVZs) of agricultural origin [15].

The program aims to ensure the protection of the soil and subsoil from potential nitrate pollution. It also seeks to protect water bodies and achieve surface and groundwater quality objectives [16]. Furthermore, the program aims to maximize the efficiency of fertilizing action for crops and soil amendment. Additionally, it aims to ensure the balance between the potential needs of crops and the inputs of exogenous and/or natural nitrogen and phosphorus. Moreover, the program aims to protect the Natura 2000 network, consisting of Sites of Community Importance (SCI) and Special Conservation Zones (SCZ) under the Habitat Directive [17], as well as sites designated as Special Protection Zones (SPZ). It also prioritizes the protection of air quality and the reduction of greenhouse gas emissions in line with the specific regional strategy contained in the current regional air quality plan [18, 19].

The purposes of the program are to ensure that distribution techniques limit as much as possible the diffusion of nutrients in surface and groundwater, ammonia losses due to volatilization, the dispersion of aerosols towards areas not affected by agricultural activities, and the emission of unpleasant odors. These must guarantee a uniform and rational distribution of fertilizers on a company scale, the adoption of good practices that favor the optimal absorption of nutrients by crops, such as the administration of nitrogen fertilizers as close as possible to the time of their use by plants, the fractionation of applications to cover the entire useful period, the use of distribution techniques and tools aimed at minimizing dispersions in the atmosphere. It is also necessary to provide recourse, whenever possible, to crop rotation practices, integrated management strategies of livestock effluents for the rebalancing of the agriculture-environment relationship, including the adoption of animal rearing and feeding methods aimed at containing, already in the production phase, nitrogen excretions [13, 20–22].

Manure, sewage and similar materials may contain high concentrations of nitrogen and other nutrients, which could contribute to water pollution. Digestate, produced by anaerobic digestion of organic waste, may contain high amounts of

nitrogen and other nutrients. Reducing the use of nitrogen fertilizers and/or phosphatic fertilizers is essential to limit nitrogen and phosphorus pollution. In the various action programmes, in addition to the constraints on quantities, there are spatial and temporal prohibitions according to the type of manure or fertilizer used. In Italy, as a general rule, agronomic use is prohibited in the vicinity of watercourses, sea and lake waters, in sloping land, in forests and on frozen land, snowy, with landslides in place or saturated with water and in all situations where the competent authority provides for specific prohibition measures for the protection of man and the environment. The temporal prohibition indicates no use of manure or fertilizers during the period from November to February, except in specific cases that must be specified in the action plan itself. For example, in Austria, it is forbidden to spread fertilizers on arable land in autumn after the harvest of the main crop, except for winter oilseed rape, winter barley and catch crops. The temporal prohibition prevents the use of manure and fertilizers in the period between November and February of the subsequent year [23].

In addition, in the Italian regulations [24, 25] there are prohibitions on space use related to slopes. The use of manure and similar materials, as well as nitrogen, is prohibited in case of significant risks of nutrient losses due to surface flow or depth percolation. In NVZs the use of sewage and similar materials is prohibited, as a rule, on soils with an average slope, referring to a homogeneous business area, of more than 10%. This slope can be increased by not more than 20% in the presence of hydraulic-agrarian arrangements if the best available spreading techniques are adopted (e.g. direct injection into soil or low-pressure surface distribution by plowing within 12 hours for arable land; direct injection, if technically possible, or low-pressure surface distribution on grassland and pasture; low pressure spreading in bands, or low-pressure surface spreading on cereals or second harvest).

4. Methodology for slope calculation

The methodology used for the calculation of the slope of the Territory at Resolution 100 meters is reported in order to comply with the provisions of current legislation.

The calculation of the slope of the land at 100 m resolution represents an important step of topographic analysis that provides valuable information for a wide range of applications, from urban planning to land management, from civil engineering to the prediction of natural events. In this context, the use of precise methodologies and accurate methods is essential to obtain reliable and meaningful results.

The procedure is divided into several processing phases, each aimed at ensuring the accuracy and reliability of the results obtained.

Step 1: Calculate the slope of each cell in the elevation raster file.

Initially, the slope of each cell of the territory under examination is calculated. This calculation is based on the method proposed by [26]. It is recognized for its effectiveness in topographic analysis. Through this preliminary phase, a detailed assessment of the local slope is obtained, providing a solid basis for subsequent processing. The elaborations are carried out on the raster of the digital elevation model (DEM).

Step 2: Calculation of the accumulation based on the length of the slope at the downstream point.

Subsequently, the downstream calculated slope length values are evaluated using a deterministic flow direction algorithm. This algorithm makes it possible to determine the preferential direction of water flow in each cell of the territory, which is essential for soil erosion assessment and hydrological modeling.

- Step 3: Apply a threshold value.
- A key element of this phase is the identification of a criterion for the application of a threshold value aimed at optimizing the accumulation values along the slope. In particular, accumulation occurs only if the slope of the receiving cell is steeper than half of the slope of the contributing cell. This criterion makes it possible to avoid insignificant accumulations in the presence of slope profiles that are not very pronounced, ensuring an accurate assessment of areas with significant slopes.
- Step 4: Manage multiple contributions.

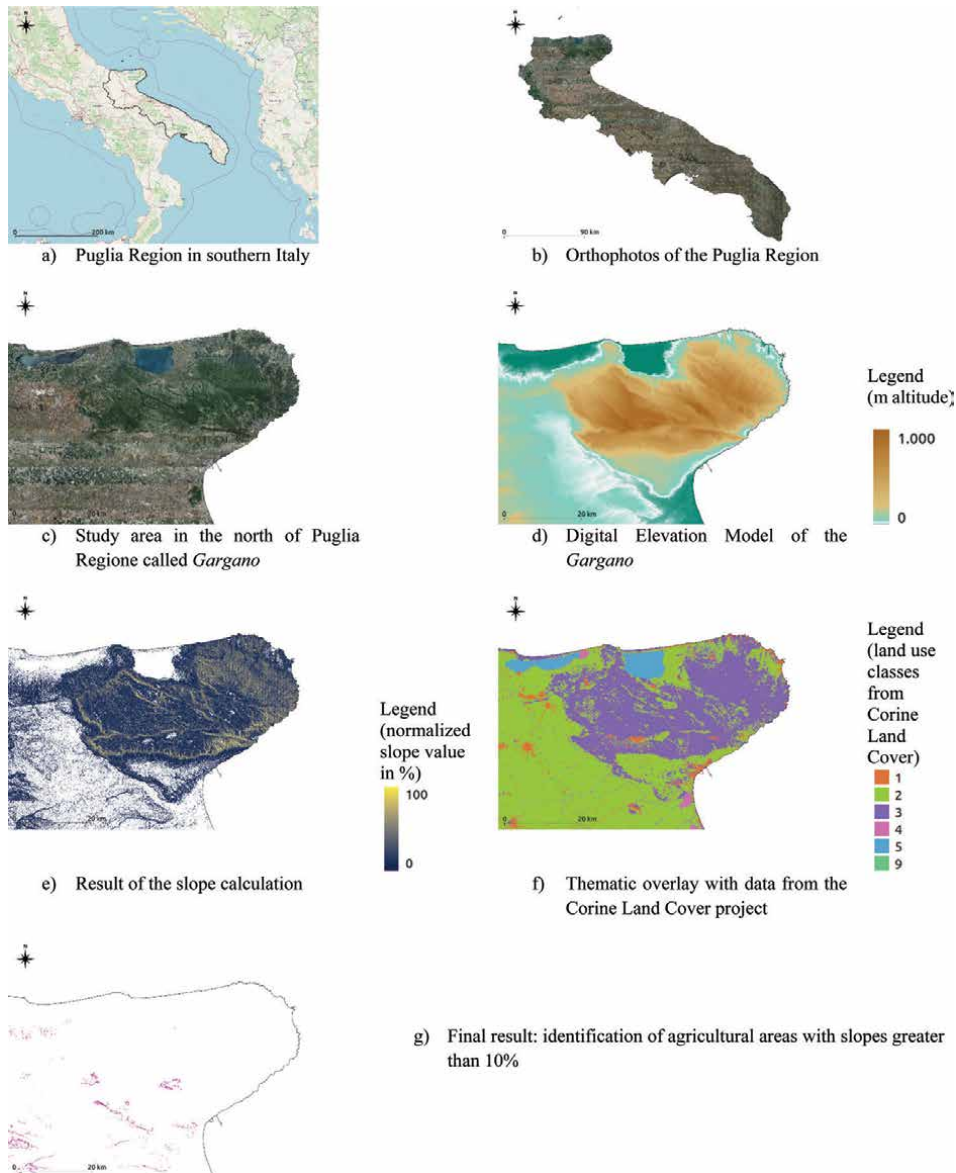


Figure 1.
Sequence of the calculations carried out to obtain the slope values to identify areas suitable and not for the spreading of agricultural slurry. Base map from: OpenStreetMap®, Orthophotos from: www.sit.puglia.it, Corine Land Cover map from: <https://land.copernicus.eu/>.

If multiple cells contribute to the value of a receiving cell, a multiple contribution management approach is adopted that consists of assigning the maximum length values of the different slopes calculated in the contributing cells to the receiving cell.

Final result: identification of agricultural areas with a slope greater than 10% (**Figure 1**).

5. Case studies on livestock manure management technologies: a comprehensive analysis

Livestock manure management poses a significant challenge for the livestock industry, with direct implications for the environment and public health. These effluents, primarily consisting of animal excreta and liquid waste, contain a wide range of nutrients and contaminants that require proper treatment to reduce environmental impact and valorize them as a sustainable resource. In this analysis, we will explore livestock manure management technologies, dividing them into conservative and reductive treatments and evaluating their applications, benefits, and limitations.

5.1 Conservative treatments: Preserving and distributing nutrients

Conservative treatments focus on preserving the total nutrient content in livestock effluents while altering the distribution between solid and liquid fractions. These treatments include:

- **Storage:** this phase does not constitute a treatment but rather a series of precautions to prevent environmental contamination. The use of controlled storage systems and appropriate coverings helps prevent nutrient leaching during precipitation.
- **Separation:** liquid/solid separation is a fundamental pretreatment aimed at dividing the liquid fraction from the solid fraction of livestock effluents. This process facilitates solid storage, reducing the risk of groundwater and soil contamination and optimizing overall treatment efficiency.
- **Aerobic digestion:** through the action of aerobic bacteria, nutrients and pathogens present in effluents are degraded. Aerobic digestion prepares the material for future use as fertilizer, reducing the environmental impact of livestock effluents.
- **Nitrification-Denitrification:** this process involves the conversion of ammonia ultimately into gaseous nitrogen, thus reducing the potential pollutant impact of effluents. Using different bacterial strains, nitrification-denitrification contributes to reducing nutrient concentrations in effluents.

5.2 Reductive treatments: Reducing and transforming nutrients

Reductive treatments act to reduce the total nutrient concentration in livestock effluents by transforming elements into inactive or less impactful forms. These treatments include:

- **Anaerobic digestion:** in this process, pathogens present in effluents are reduced, and the material becomes more stable for subsequent treatments. Anaerobic digestion occurs in an oxygen-free environment, also producing biogas as a byproduct.
- **Biological treatment:** through the action of microorganisms, nutrients present in effluents are metabolized and reduced. This process reduces the overall nutrient concentration in effluents, contributing to mitigating environmental impact.
- **Vermicomposting:** using worms to decompose organic matter in effluents, this process eliminates pathogens and enriches the material with nutrients. The vermicompost produced can be used as a natural fertilizer, reducing dependency on chemical fertilizers.

5.3 Applications and limitations of livestock manure management technologies

Each livestock manure management technology presents advantages and limitations that depend on the specific context in which it is applied. For example, anaerobic digestion is effective in reducing pathogens but requires adequate biogas treatment systems. Similarly, nitrification-denitrification can effectively reduce nutrient concentrations but requires precise control of operational conditions to ensure optimal results.

Livestock manure management technologies play a crucial role in reducing the environmental impact of livestock activities. However, to maximize environmental benefits and minimize negative repercussions, an integrated approach considering specific needs and local conditions is necessary.

6. Discussion

Water pollution by nitrates of agricultural origin is an increasingly critical environmental challenge, with direct consequences on public health and the aquatic ecosystem. The European Union's Nitrates Directive aims to reduce and prevent such pollution through concrete measures and water monitoring programmes, with particular emphasis on vulnerable territories and risk areas. The water monitoring programs required by the Nitrates Directive are a fundamental tool for assessing the quality of water resources and identifying any critical situations related to nitrate levels. Exceeding nitrate concentration limits of 50 mg/l is a warning sign of potential contamination of surface and groundwater. It is therefore necessary to implement timely and targeted actions to counter this phenomenon and protect water resources. One of these actions is the delimitation of Nitrate Vulnerable Zones (NVZs), identified according to the provisions of the Nitrates Directive, which play a key role in protecting water from agricultural pollution. Such areas, characterized by compromises in water quality or increased sensitivity to chemical contamination, are subject to restrictions on the use of nitrates to reduce the risk of pollution. NVZs must be regularly monitored and updated according to evolving environmental conditions and agricultural practices.

The elaboration of Action Programmes at the regional level, as required by the Nitrates Directive, is also a crucial step in the fight against nitrate pollution of agricultural origin. Such programmes must include restrictions on the use of manure, wastewater and other nitrogen fertilizers in NVZs while ensuring sustainable agricultural

practices and adequate nutrient management. It is important to provide for temporal and spatial bans on the use of materials with a high nitrogen content, to minimize the risk of water pollution.

Another very important aspect is the promotion and adoption of innovative technologies and practices for the management of livestock waste, to reduce the environmental impact of breeding activities. The use of conservative and reductive treatments, such as liquid/solid separation and anaerobic digestion, can contribute significantly to the reduction of nitrate pollution. However, a joint effort by farmers, local authorities and control bodies is needed to ensure the effectiveness and sustainability of these interventions.

To overcome these challenges and improve the protection of waters from nitrate pollution, the following strategies can be considered:

- Integrated monitoring: implement an integrated monitoring system that includes the evaluation of chemical, microbiological and isotope parameters of the water. This would allow for a more comprehensive understanding of the sources of pollution and the health risks.
- Vulnerability models: to develop hydrogeological models that consider the intrinsic vulnerability of aquifers and the presence of nitrate precursor compounds. This would allow for a more precise delimitation of NVZs and a more targeted allocation of resources.
- Specific Action Plans: draw up national and regional Action Plans taking into account the cultural and territorial specificities. Promote the adoption of sustainable agricultural practices such as precision fertilization, the use of cover crops, and crop rotation.
- Economic instruments: evaluate the use of economic instruments such as incentives for the application of sustainable practices and penalties for excessive use of fertilizers.
- Research and development: invest in the research and development of new technologies for the sustainable management of livestock manure, such as anaerobic digestion and nutrient separation.
- Training and technical assistance: provide farmers with training and technical assistance to facilitate the adoption of sustainable farming practices and to optimize nutrient management.
- Communication and involvement: promoting effective communication between authorities, researchers, farmers and citizens to raise awareness of the importance of water resources protection and encourage the active participation of all stakeholders.

7. Conclusions

What is reported in this chapter aims to contribute to the promotion of greater sustainability in companies through specific actions to reduce pollution caused by nitrates of agricultural origin.

Technologies to reduce impacts and data processing methodologies are proposed to obtain a more rigorous knowledge framework in the context of the application of community legislation on pollution from nitrates of agricultural origin.

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Perspective Chapter: Boiling Point, Melting Point, Freezing Point – Water Is the Essence of Life, and What we Need to Do to Avert Calamity

Oluwafikemi Iji and Oluwatisheyitoju Iji

Abstract

It is becoming increasingly clear that human activities lead to rapid changes in the environment which bring about ecosystem impairments that have direct health impacts involving water such as floods, water shortage, drought, and increased exposure to pollution. Although water constitutes 70% of the earth and we cannot add to the world's water, many natural water sources have become sinks for contaminants. In many developing nations, these waterbodies are a vital source of water for drinking, household, and other purposes but have become a thriving habitat for waterborne pathogens causing diseases in animals and humans. Proper water quality monitoring strategies are required to protect ecosystem services, preserve biodiversity, and improve the sustainability of water resources.

Keywords: ecosystem health, pollution of water resources, monitoring and surveillance, environmental impacts, sustainable water use

1. Introduction

Water is the essence of life. It exists as the only common substance that is naturally found as either a solid, liquid, or gas. The presence of water is regarded as the ultimate proof of existence, making it evidentially essential for survival and its dependence crucial for all life forms. Although it is considered a simple molecule composed of two small positively charged hydrogen atoms and one large negatively charged oxygen atom, its many roles in supporting life can be attributed to its molecular structure and other special properties.

Water is the most studied chemical compound [1]. It is a polar inorganic compound, liquid at room temperature; tasteless, colorless, and odorless. Water is the Earth's most abundant substance and the universe's third most abundant molecule

(behind molecular hydrogen and carbon monoxide) [2]. At freezing point, water is 0 and 100°C at boiling point. Water is amphoteric; exhibiting both properties of an acid or a base, depending on the pH of the solution it is in; by readily producing both H^+ and OH^- ions. It also undergoes self-ionization [3].

1.1 The biological uses of water

Water is a universal solvent [4]. This ability makes water such an invaluable life-sustaining force. Substances that mix and dissolve well in water are hydrophilic (“water-loving”), while those that do not mix well with water are known as hydrophobic (“water-fearing”) [5]. Water makes up 60–75% of the human body weight, this is critical for cellular homeostasis and life [6]. It helps the body regulate internal temperature by distributing heat throughout the body and cooling it through perspiration (sweat), keeping its temperature within a normal range [7]. It gives protection to joints, the spinal cord, and other tissues. It moistens the mouth as saliva, and the eyes as tears, cushions and lubricates the joints as synovial fluid, and prevents injuries by boosting tissue flexibility and elasticity [8]. More importantly, the blood is a water-based mixture without which the transport of nutrients, oxygen, and waste cannot reach their targets in the body.

Humans rely on plants as food sources. Plants are also inextricably dependent on water for their survival. About 95% of plant tissue comprises water, an essential nutrient for plant growth. Water is critical for a seed to sprout, plants to grow, and transporting nutrients and other important functions within the plant tissues. Water is necessary for photosynthesis, which is how plants use sun, carbon dioxide, and water energy to create food that we and other animals can eat for energy [9], and other important functions within the plant tissues such as cell structural support and turgor.

1.2 The role of water in health

This role is generally defined relative to the ideal hydrated state i.e., correlated with dehydration. There is a need for the water provision in the body to be sufficient to overcome water loss, which is achieved via withholding of fluids over time and during periods of heat stress or high activity. We get water not only directly as a beverage but also from food and water proportion from these sources varies with our diet [10] (fruits and vegetables have high water content). The different types of water are soft or hard, spring or well, carbonated or distilled water.

Dehydration is a deficiency of water in the body [11]. The body constantly loses water throughout the day through urinating, sweating, and breathing [12] which may become more pronounced on hot days with profuse sweating or when sick with fever, diarrhea, or vomiting or taking medications such as diuretics which can increase the frequency of urination, or in people who flat out do not take enough water. Dehydration may be fatal when not treated immediately. It can impact cognition resulting in loss of concentration, alertness, and short-term memory in children and adults [13, 14] or even delirium presenting dementia in elderly people [15].

Gastrointestinal functions are affected by dehydration. The amount of water influences the gastric emptying rate and constipation, characterized by slow gastrointestinal transit, and difficulty in passing stool [16, 17]. The kidneys, heart, and hemodynamic functions are all affected by dehydration and may serve as precursors for chronic diseases [18].

2. The world's water

Water is a finite resource essential for life, it has no adequate alternative. One of the major challenges of our society is the supply and allocation of water in sufficient quality and quantity. Although we cannot add to the world's water, water is always moving, thanks to the water cycle, the assurance of water availability for all living organisms remains a possibility. About 71% of the earth's surface is covered by water, this covers 1386 million cubic kilometers [19] and mostly occurs as oceans and large water bodies, groundwater, water vapor, and ice [20]. The statistics show that 97% of the world's water is saltwater and not drinkable, only 3% of this water is fresh and drinkable, and 77% of which is frozen. Of the 23% that's not frozen, just about 0.5% is available to supply every living organism with all the water they need to survive [21].

The Guide to the World Freshwater Resources [22] estimates that oceans, seas, and bays account for 96.54% of the world's total water which spans a water volume of 1,338,000,000 cubic km. Ice caps, glaciers, and permanent snow are about 1.74% with a water volume of over 24 million cubic km, and 68.7% being freshwater. Rivers are 0.0002% of the total water and the water volume is 2120 cubic km, while freshwater is 0.76% with 10,530,000 cubic km of water in volume.

2.1 Water classification

(See Table 1)

2.2 The water cycle

The water cycle shows the journey that water takes in different forms, moving around the earth. It is important to note that no new water is created in this process,

i. Precipitation according to moves	a. Classified according to phase • Solid-ice • Liquid-water • Gaseous-water vapor
i. Vertical (falling) precipitation: • Rain • Snow • Hail • Ice crystals	a. Classified according to meteorology • Hydrometeor • Precipitation:
i. Horizontal (seated) precipitation • Dew • Hoarfrost • Glaze ice	a. Classified according to occurrence • Groundwater • Brackish water • Freshwater • Mineral water
i. Levitating particles • Clouds • Fog	a. Classified according to uses • Distilled water • Portable water • Tap water • Bottled water

i. Ascending particles (drifted by wind) • Spindrift • Stirred snow	a. Classified according to other features • Soft water • Hard water • Distilled water • Tritiated water
i. Precipitation according to phase • Liquid precipitation • Rain • Dew	a. Classified according to microbiology • Drinking water • Wastewater • Surface water
i. Solid precipitation • Snow • Ice pellets • Frozen rain • Hail • Mixed precipitation	a. Classified according to religion • Holy water

(Source of classification originated from <https://www.wikidoc.org/index.php/Water>. Accessed 12 May 2024).

Table 1.
Water classification according to properties, uses and forms.

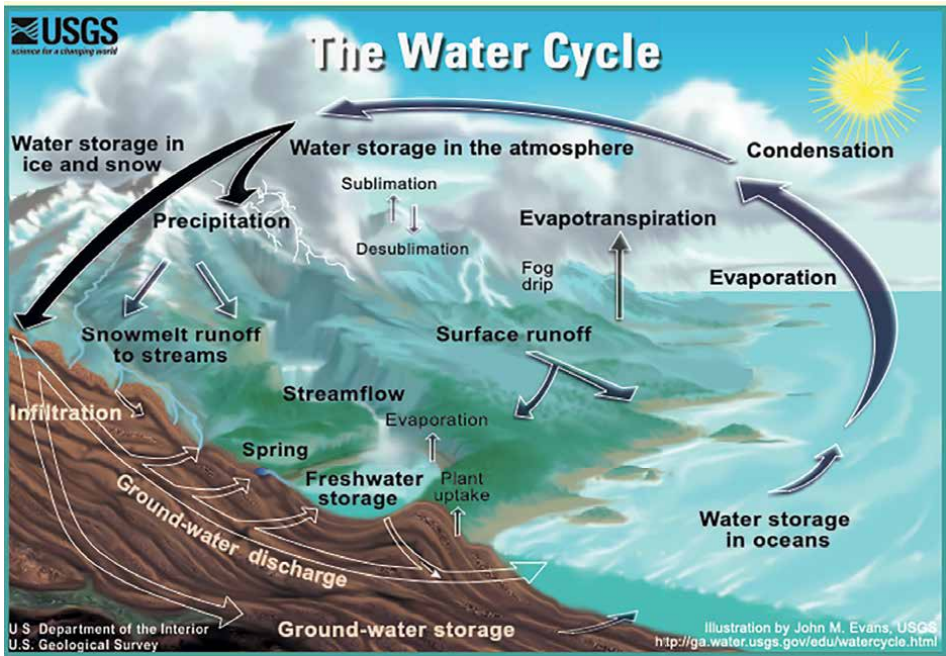


Figure 1.
The hydrologic cycle. Source: US Department of the Interior US Geological Survey. Usage Public Domain. <https://www.usgs.gov/media/images/natural-water-cycle-jpg>

and all of the Earth’s water is recycled, with limited amounts occurring as freshwater. With most of the Earth’s water in the ocean, the sun’s heat causes it to evaporate, forming water vapor. As the water vapor elevates, it becomes cooler and condenses

to form liquid suspended in dust particles called clouds. When this mass of water molecules is full, it dispenses them as precipitation in the form of rain, snow, or ice, which then flows as run-off, combining to form creeks or streams that form rivers that feed the ocean, hence the basic water cycle.

A deeper understanding of the hydrologic cycle and the pressure points where anthropogenic activities are causing changes that can affect the sustainability of water resources should be the focus for possible mitigation (**Figure 1**).

3. Ecosystem services: the role of water

Humans and animals benefit from ecosystem services provided and sustained by water which serves as a livewire of support for biodiversity, ecosystem functioning, and human well-being [23]. There are benefits derived from this ecosystem, with some linked to the water cycle and the provision of portable water, others to infrastructure that helps manage floods, hydroelectric power, transportation cruises, and those that create opportunities for water-associated recreation and cultural practices [24]. Several factors such as population growth and global climate change drive the continued abuse of ecosystem services [25]. Placing priorities on providing services and maximizing profits in most instances rather than on the costs of the impacts of anthropogenic activities on ecosystem services places some strain on its functions.

There is a need for ecosystem services-based approaches in natural resources management practice to include climate change water-based adaptation strategies [25], river basin and catchment management [26], and Integrated Water Resources management [27] in the proper governance of natural resources management crucial to protecting water. With resulting mounting pressures from polluted waterways, depleting aquifers, and degrading wetlands unabating in the nearest future, and as the human population grows with increased economic activities thrown in the mix, society must begin to place optimal value on the management of the water-based ecosystem to nurture its guaranteed support for human life for current and future generations.

Ecosystem services are largely interdependent due to the interconnectedness that occurs through water use and impacts. The probability that a trade-off drives decisions is not uncommon, however, an in-depth understanding of how an entire range of ecosystem services (values, cost) can better improve the decision-making process in a way that's meaningful, purposeful, critical, and balanced, resulting in enhanced overall ecosystem services improvement and optimal productivity remains a possibility [28].

3.1 Water: peace or conflict

It is imperative to note that a well-concerted and coordinated effort is needed to foster water management cooperation to avoid conflict and promote peace. With over 3 billion people worldwide depending on transboundary water, and fewer than 25 countries developing some form of cooperation agreement on their shared waters [29], clashes on water uses seem inevitable. This cooperation in water management can help with its distribution to accommodate everyone's needs.

An estimated 40% of the world's population lives in water-scarce areas, and up to 0.25% of the world's GDP is threatened by water scarcity-related incidences [30]. The various aspects of human prosperity and public health, food and energy systems,

and environmental integrity are anchored to functional and equitably managed water systems [29]. Many Farmer-herder conflicts in African countries like Nigeria and Senegal have been linked to water resources-associated issues either from access to water or water-shed land that grows pasture all year round. The frequency of incidences between these two groups is becoming more rampant and intense in severity [31] taking more lives than terrorism [32]. Half of more than the 15,000 deaths that occurred since 2018, happened in Nigeria [33].

The Nile waters for example are used for irrigation, hydroelectric power, fishing, tourism, etc. [34] Treats by Egypt to escalate tensions over its access by other Nile riparian states have necessitated the development of a framework for equitable distribution. Egypt maintains that a 2% drop in Nile water could result in 200,000 acres of irrigated land and any deprivation would be interpreted as provocation to war [35]. The competition between countries and among varying water-dependent sectors is such that it calls for proper water governance, especially as nations experience the effects of climate change, urbanization, industrialization, and political unrest. The United Nations World Water Day in 2024 calls for local actions to unite around the fair and sustainable use of water.

Some countries are classified as water-scarce countries and up to 1.2 billion people lack access to safe drinking water [36], with half the world’s population experiencing water scarcity during certain seasons in the year [37]. The World Wildlife Federation predicts that by 2025, two-thirds of humans may face water shortages with a population forecast of 9 billion, contributing to a 40% increase in water demand by 2030 [38]. With about 326 million trillion gallons of water on earth trapped in the air, as ice in the poles, in the oceans, or as underground aquifers, the quantity of access may depend on where you live. Kuwait is one of the poorest countries in terms of water per capita and Canada has over 10,000 times more (Figure 2) [39].

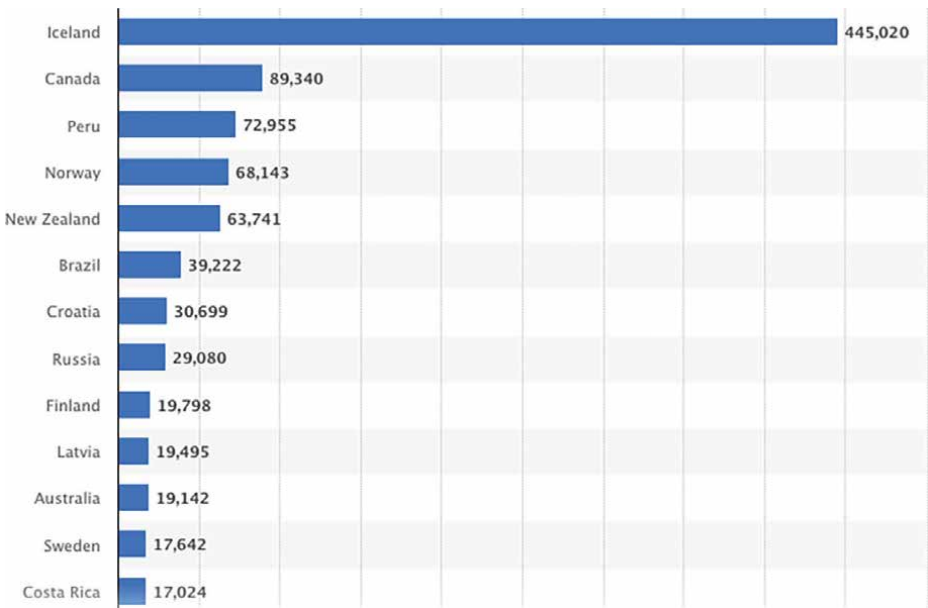


Figure 2.
Renewable water resources per capita worldwide as of 2022, by country (in cubic meters). Usage Public Domain.
<https://www.statista.com/statistics/269361/worldwide-renewable-water-resources/>

4. What's in the water? Pollutants and contaminants

Water contamination is the presence of a substance that should not naturally or originally be present in water regardless of whether the substance is harmful or not. However, an increase in the presence of these contaminants, especially beyond their permissible limits, such that they can cause harm or negatively impact biological systems is called water pollution [40]. All pollutants are contaminants but not all contaminants are pollutants [41]. Water pollution contributes significantly to water scarcity, and since the dawn of industrialization, there has been an uptick in the rate of water pollution. Although water pollution may occur in nature through volcanic eruptions or evaporation, most problems stem from human actions on land.

Historically, ancient cultures combated water pollution from human waste by building aqueducts [42]. After the Second World War, the preponderance of industries and factories produced wastes indiscriminately dumped into rivers with little to no care about the environment or downstream end users, many of these were later labeled as dangerous to humans [43].

4.1 Sources of water pollutants

The sources of water pollution could either be direct or indirect. Direct water pollution arises when pollutants are directly released into water bodies such as rivers, lakes, groundwater, and streams. These effluents directly impact the water quality, such as from a factory or sewage treatment plant, this is the so-called “point source pollution”. The indirect source is also known as diffuse pollution. Its main sources are run-offs from farming, fossil fuel power plants, and the atmosphere via rainwater, affecting water supply from soils/groundwater systems [44]. These contaminants can be classified into organic, inorganic, radioactive, and acid/base.

Organic waste comes from sewage, urban wastewater, industrial wastewater, and agricultural waste and they are made up of carbon, hydrogen, oxygen, nitrogen, and sulfur [45]. The natural breakdown of crop residues and soil organic matter, fertilizers, urine, and manure into nutrients which become the principal cause of eutrophication, an enrichment that leads to increased plant growth and the occurrence of algae. Inorganic pollutants are usually persistent and could stem from industrial, agricultural, and residential sources. The substances range from heavy metals such as lead, arsenic, and mercury to salts like phosphates, sulfates, and nitrates. Others are trace elements and mineral acids which affect aquatic flora and fauna.

Radioactive elements may cause water pollution when they leach from the earth's crust, less common is the pollution of artificial radionuclides from nuclear power plants. Uranium, thorium, and actinium are three naturally occurring radioactive materials contaminating water resources [46]. Acids and alkalis in freshwater are harmful, with both extremes causing toxicity and killing fish. The chronic effect of increased acidity in surface waters appears to be interference with the fish' reproductive cycle and the main pollutants responsible for acid deposition (or acid rain) are sulfur dioxide (SO₂) and nitrogen oxides (NO_x) [47].

4.2 Effects of water pollution on aquatic life and health

When untreated or inadequately treated water is released into natural water bodies, the degradation of the aquatic ecosystem occurs [48]. The aquatic flora and fauna

are not spared from the effects of water pollution which causes a decline and serious economic loss.

The direct impacts are (a) Habitat destruction because the immediate aquatic ecosystem becomes affected. Some contaminants may promote the growth of fungi, bacteria, and algae, and the preponderance of algae or moss may impede the penetration of sunlight and other life-giving nutrients [49]. (b) Oxygen depletion which is a more insidious threat as all aquatic organisms depend on oxygen for survival and the absence of it due to water pollution, may create a dead zone that becomes a threat to fish and other biota [49].

The cascading effect of water pollution in the food chain is significant because other animals that rely on fish as their primary food source may become threatened or sick when they consume food contaminated with chemicals and plastics. (c) Physical harm to fish and other aquatic organisms may arise from contact with oil spills, acids, pesticides, etc. They may also ingest toxic substances which are harmful or cause death. The World Wildlife Fund reported that plastic pollution in oceans is responsible for the death of 100,000 marine animals each year [50]. Reports of fish die-offs resulting from cancer in animals living in polluted aquatic environments are a stark warning that we need to pay more attention to the negative impact of anthropogenic pollution and what gets dumped in our waters [51].

4.3 Effects of water pollution on human health

Human health has been under renewed threats arising from the pollution of water bodies from countless anthropogenic activities [52]. This scenario is exacerbated in developing countries where the environmental laws are obsolete or non-existent and the treatment facilities are ill-equipped, making them sink where different types of waste marinate [53], becoming a human health problem.

4.3.1 Sewage

One of the leading worldwide causes of disease and death is attributed to water-borne diseases. Infectious diseases caused by pathogenic microorganisms account for 25% of human mortality [54] many of these are found in sewage. Sewage effluent entering surface and groundwater is usually laden with pathogenic organisms that transmit waterborne diseases [55]. Some common pathogens found in sewage are presented in **Table 2**.

Enteric pathogens causing diarrhea account for 2 million deaths worldwide per year in children under 5 years [57]. About 250 million people globally become infected with waterborne pathogens and the mortality rate is between 10 and 20 million [58] thus, the primary goal of water management should be that people are not exposed to doses of pathogens that cause disease and other potential toxins in sewage. It is thus crucial to protect water sources and standardize water treatment programs through routine water quality monitoring.

4.3.2 Oil spills

Oil spills happen when liquid petroleum hydrocarbons are discharged into the environment, mainly water bodies due to human activity. This results from transportation accidents and industrial and mining activities, and it is the most frequent and arguably most voluminous single organic pollutant of the aquatic ecosystems [59].

Agent	Species	Disease
Bacteria	<i>Escherichia coli</i>	Gastroenteritis
	<i>Salmonella</i> sp.	Salmonellosis, gastroenteritis, diarrhea
	<i>Salmonella typhi</i>	Typhoid fever
	<i>Shigella</i> sp	Dysentery
	<i>Vibrio cholera</i>	Cholera
Helminths	<i>Ascaris lumbricoides</i>	Ascariasis
	<i>Fasciola hepatica</i>	Fascioliasis
	<i>Schistosoma</i> (blood fluke)	Schistosomiasis (bilharzia)
	<i>Trichuris</i> (whim worm)	Trichuriasis
Protozoa	<i>Taenia</i> (tape worm)	Taeniasis
	<i>Balantidium coli</i>	Balantidiasis (dysentery)
	<i>Cryptosporidium parvum</i>	Cryptosporidiosis
	<i>Entamoeba histolytica</i>	Amoebiasis (amoebic dysentery)
Viruses	<i>Giardia lamblia</i>	Giardiasis
	Adenovirus	Respiratory disease and eye infections
	Enteroviruses	Gastroenteritis
	Poliovirus	Fever, rash, respiratory and heart disease
	Hepatitis A and E	Paralysis, aseptic meningitis
	Parvovirus,	Infectious hepatitis
	Coxsackieviruses	Gastroenteritis
		Herpangina, aseptic meningitis, respiratory illness, fever, paralysis, respiratory, heart and kidney disease.

Source: World Health Organization 2006; Christou, L. [56].

Table 2.
Microbial diseases associated with polluted aquatic environs.

These spills destroy habitats, such as mangroves or coral reefs, and cause marine animals to succumb to hypothermia, drowning, and smothering from the stickiness of the oil [60].

Humans who come in contact either directly or indirectly by inhalation or ingestion of contaminated seafood or drinking water show symptoms of dizziness and nausea, central nervous system involvement, and certain types of cancers [61]. Respiratory distress is also common due to the fire incidences associated with oil spills [62]. Due to the persistent nature of these hydrocarbons, they are difficult to clean up, and their impact lingers. A study of the human health implications of crude oil spills in the Niger Delta, Nigeria revealed that beyond the public health concerns, food security was also impacted and it likely contributed to a 24% increase in the prevalence of childhood malnutrition [63]. More must be done to deter oil spills (training, equipment, contingency plans, double-hulled tankers, and liability laws), and more importantly, monitoring because it is better and cheaper to prevent than fix.

4.3.3 Pesticides

Pesticides are usually applied to kill organisms such as weeds and insects. While they are useful in gardens, farmlands, and other public places they may end up in our water, adversely affecting the ecosystems and humans. Insecticides, fungicides, herbicides, garden chemicals, household disinfectants, and rodenticides that destroy and protect from pests are all considered pesticides [64]. There are different types of pesticides with varying uses listed in **Table 3**.

Type of pest	Pesticide sample	Function
Avicides	Avitrol (aminopyridine)	Kill birds
Acaricides	Bifenazate	Kill mites that feed on plants / animals
Biopesticide	Bacillus thuringiensis	Wide range of organisms
Bait	Anticoagulants	Wide range of organisms
Fungicides	Azoxystrobin,	Kill fungi (blights, mildews, molds)
Herbicides	Atrazine, glyphosate,	Kill weeds and other plants
Insecticides	Aldicarb, carbaryl,	Kill insects and other arthropods
Larvicides	Methoprene	Inhibits growth of larvae
Molluscicides	Metaldehyde	Inhibit or kill Mollusca
Nematicides	Aldicarb, Ethoprop	Kill nematodes
Ovicides	Benzoxazine	Inhibits the growth of eggs of insects
Piscicides	Rotenone	Act against fishes
Repellents	Methiocarb	Repel pests by its taste or smell,
Rodenticides	Warfarin	Control mice and other rodents
Virucides	Scytovirin	Act against viruses

Source: Fishel et al. [65].

Table 3.
Pesticide name, type, and target pests.

Exposure to pesticides could be both acute and chronic and both could be toxic to biological systems. The World Health Organization reported that annually [66], a million people are affected by acute pesticide poisoning with recorded fatalities being about 0.4–1.9%, most of which are work-related exposures [67]. Sub-chronic to chronic exposures to lower doses of pesticides have been implicated in tumor formation and central nervous system disorders [68]. There are over 2 million metric tons of pesticides in use (47.5% herbicides, 29.5% insecticides, 17.5% fungicides, and 5.5% other pesticides) the impact on water quality and associated environmental concern is mounting [69], and water contamination by pesticides aggravated by inadequate storing of agrochemicals which leach into ground and surface water [70].

Pesticide transfer is harmful to both terrestrial and aquatic ecosystems, not only directly affecting fishes and other organisms but likewise impacting behavior; changing food habits, and deteriorating the quality of the habitat [71]. They also tend to bioaccumulate and bio-magnify [67] and the reaction to toxicity could vary from mild (contact dermatitis) to moderate and severe (hematological morbidity and pulmonary dysfunction, in addition to immune system deficiencies, inborn deformities, and cancers) [72].

5. Climate change and the threat to water resources

Climate change is mostly about water. When addressed in context it is about food security (agricultural output) or rising sea levels, melting arctic ice, wildfires, and extreme weather conditions (floods, drought), and that essentially is a story involving water.

It is expedient that we pay more attention to the changes in water supply, demand, and quality which is exacerbated by the climate change problem because climate change makes water shortages more likely for everyone and the impact on water resources affects the quantity, variability, timing, form, and intensity of rainfall [73].

5.1 Climate change and water cycle

Climate change exerts its impact on the water cycle shaping when, where, and how much rain falls. When global temperatures rise, water evaporates in larger quantities, which will lead to higher levels of atmospheric water vapor and subsequently more frequent, heavy, and intense precipitations. The water cycle controls and maintains the balance between precipitation, evaporation, and all of the steps in between. Higher the temperature, the higher the atmospheric capacity to hold water [74]. The increased evaporation may dry an area and cause excess rains in another. Likewise, a warmer winter temperature would bring about more precipitation as rain rather than snow, and the snow consequently melts earlier in the year affecting the timing of streamflow into the rivers.

Climate change-induced excessive rainfall usually affects water quality, especially by impacting the water infrastructure such as sewer systems and the water treatment plants which overflow due to the volume of water [74]. The rippling effects of increased precipitation present as increased runoffs and rising sea levels, washed sediments, stripped soil nutrients, and organic/inorganic waste dumps into natural and stored water aquifers [75]. Conversely, a decreased water supply may also impair water quality by causing nutrients and contaminants to concentrate thereby, worsening water quality standards. Another impact on nature with rising temperatures and altered precipitation is the susceptibility to wildfires, which pollute the atmosphere with CO₂.

Similarly, increased evaporation rates worsen water supplies, especially during the dry seasons in tropical countries or summer in temperate regions. This leads to reduced soil moisture levels and agricultural drought. Climate change-linked drought continues to influence the management of water resources for users with corresponding economic consequences. In the USA, prolonged droughts have caused over \$6 billion in damages to the agricultural and municipal sectors [76].

5.1.1 Statistics of some climate change-induced flooding

Climate change is responsible for the extreme weather events making water scarcer, more polluted, and unpredictable. The UN forecast that by 2050, 1.6 billion. People would be at risk of flood and up to 3.2 billion would live in potentially severely water-scarce areas [77].

Floods are the most common type of natural disaster in Europe. Extreme weather events like flash floods are expected to increase in frequency in Belgium, Germany, Luxembourg, and the Netherlands [78]. In EU countries between 1980 and 2021, floods caused more than €250 billion in losses, about 5600 deaths, and nearly 75% of those affected ended up with mental health issues [79]. In 2022, West and Central African regions experienced one of the worst flooding disasters spanning 20 countries, with over 8.5 million people affected; 1567 fatalities, 4401 injured, 3.2 million people displaced, and 517,000 houses destroyed across 18 countries. The flooding devastated 1.6 million hectares of farmland, putting the livelihoods of communities at risk [80].

The monsoon flooding in the South Asian countries of Afghanistan, Bangladesh, India, Nepal, Pakistan, and Sri Lanka since 2020 has become the region's deadliest flood with over 3700 people dead [81]. South American floods have been extensive, this year alone, 15,000 families were affected in Bolivia and 40 people were killed. Ecuador has experienced 821 weather-related events; flooding (62.97 percent), landslides (18.88 percent), and structural collapses (7.55 percent). About 11,300 people evacuated due to flooding in Brazil, and 100 districts in Peru were placed on emergency flooding alert [80].

The USA and Canada have experienced an increase in flash flood events and flood fatalities, many of which Flash flood-producing rains can also trigger catastrophic mudslides and a 10% increase by 2030 of people facing annual flood risk [82]. The aftermath of a "derecho" in May of this year, resulted in fatalities and over a million customers being without power for weeks [83].

5.1.2 Statistics of some climate change-induced drought

The United Nations Convention to Combat Desertification (UNCCD) estimated that out of 1.84 billion people worldwide, living under drought in 2023, huge numbers resided in low- and middle-income countries [84]. Although drought does not get as much media coverage as it should, it remains a silent destructor arising from climate change events. Drought has been reported to affect both developed and developing countries, with consequences extending beyond the immediate lack of water, to communities and ecosystems, more disproportionately, vulnerable communities in the developing world.

Many continents have been experiencing excessive, abnormal heat. The year 2023 was the warmest year on record for North and South America, Africa, and globally, the second warmest year for Asia and Europe, and the eighth warmest year for Australia [85]. Women and children are said to be 14 times more likely to be killed by climate-fueled disasters than men, and drought is responsible for food insecurity in 23 million people across the Horn of Africa and forced migration [86, 87].

Statistics show that moderate-to-severe droughts are increasing in China by 15–20% [88], and 5% of the area of the contiguous United States suffer severe to extreme drought [89]. In 2022, Europe experienced its worst drought in 500 years, and should the average global temperatures rise 3°C above pre-industrial levels, 170 million people are expected to experience extreme drought [90]. The extreme heat and dry conditions come with its ecological toll especially on the world's largest forests, as massive wildfires ravaged the trees that serve as kinder due to the dryness.

6. Monitoring water quality

Freshwater is a finite resource, so monitoring water quality is very important. Monitoring allows us to evaluate how seas, rivers, surface, and groundwater change. This information would allow us to analyze the change trends that then inform plans and strategies for improving water quality so that water in use meets its designated standards. Water quality monitoring is a fundamental tool in the management of freshwater resources.

USEPA [91] described the rationale behind monitoring water quality as to allow for the identification of changes or trends in water quality over time; identify specific existing or emerging water quality problems; use the information gathered to design

pollution prevention or remediation programs and other pollution compliance regulations and also to be able to respond to emergencies, such as spills and floods.

The International Organization for Standardization (ISO) [92] defines monitoring as: “the programmed process of sampling, measurement and subsequent recording or signaling, or both, of various water characteristics, often to assess conformity to specified objectives” which could be long-term, short-term, and continuous monitoring. It is almost impossible to determine every possible contaminant in water at every particular time per time, therefore a combination of analyses that involve physicochemical analysis and biological assays are conducted to give information on the condition of the water.

Several parameters can be determined in water samples. Water temperature, turbidity, pH, conductivity, and dissolved oxygen are determined on-site. The physicochemical constituents: alkalinity, aluminum, biochemical oxygen demand, chemical oxygen demand, boron, calcium, chloride, chlorophyll, fluoride, iron, magnesium, manganese, nitrogen, ammonia, nitrogen, nitrate, nitrite, phosphorus, potassium, selenium, reactive silica, sodium, sulfate, total dissolved solids, and total suspended solids are usually analyzed in the Laboratory [93].

Using differing standard techniques and instrumental methods; nutrients, major ions, and trace elements can also be determined. Atomic absorption spectrophotometry (AAS) is commonly used to determine trace elements in water samples, sediment, or biological tissues. Gas chromatography detects molecules containing halogens, peroxides, quinones, and nitro groups, and a mass spectrophotometer is used to identify any unknown compound. Trace amounts of lithium, potassium, sodium, and strontium are analyzed using Flame photometry [94].

Microbiological analysis detects fecal contamination of water using the Multiple fermentation tube technique or the membrane filter technique [95]. The changes in the physical and chemical nature of water may be negligible or significant, this tells a story about the state of the water and its resident organisms for which possible implications for the intended use of the water and risks to human health may be inferred.

Biological monitoring is conducted to determine if the habitat has been adversely altered by testing the responses of biological communities, or individual organisms. These changes could be behavioral, physiological, or morphological and can also be considered responses to stress or the presence of contaminants, which are called toxicity tests and bioassays [96]. The bio-monitors serve as early warning signals expressed as bio-signals in test organisms due to fluctuations in water quality for which further actions could take a more detailed investigation [97]. The most commonly used organisms are fish, the crustacean *Daphnia* sp., algae, and bacteria. Organisms may also accumulate certain contaminants in their tissues over time known as bioaccumulation, which may activate a physiological outcome and bio-magnify in higher organisms that consume them. Suppose a correlation can be established between the concentration of a contaminant in a water body and its concentration in the tissues of an aquatic organism. In that case, the organism may be suitable for chemical monitoring of the contaminant in the water body [98].

Due to the interconnectedness of all waterbodies both surface and underground, and the land-based involvement in waters, water quality monitoring can be conducted at regular sites or stations continuously or at selected sites as the need arises or on a seasonal basis or at random sites and on an emergency basis when accidents or spill occur. Depending on their environmental laws, the national, state, or local government should conduct water quality monitoring within their boundaries, and provide technical guidance on monitoring and reporting results. Private entities

such as universities, watershed associations, environmental groups, and permitted dischargers also conduct water quality monitoring for their purposes, or to share with government decision-makers.

6.1 The future of water quality monitoring

The water issue is nothing new in the developing world, but it is becoming increasingly important in the developing world. The UN Sustainable Development Goal 6 is to ensure access to clean water and sanitation because this is the most basic human need for health and well-being. The UN views water as the string with ties to health, poverty reduction, food security, peace and human rights, ecosystems, and education [99].

With better infrastructure and management, most water-related diseases such as cholera and diarrhea, will become preventable. There would be a reduction in the loss of biodiversity and ecosystem resilience will be further strengthened. Promoting accountability is also crucial, civil society organizations should coordinate to keep governments accountable, and the government and private organizations must drive investment in water research and development, and promote the inclusion of women, youth, and Indigenous communities in water resources governance.

There is a lot of complexity associated with monitoring water quality thus requiring constant improvement on how monitoring should be conducted, how information is shared, and how decisions based on monitoring are made. The future should also include providing electronic reports of monitoring data to make it increasingly accessible to the public and to decision-makers at all levels of government [91].

6.2 Water refining processes

6.2.1 Water purification

This process renders water fit for consumption as undesired chemical compounds, organic and inorganic materials, and biological contaminants are removed from the water. This involves a lot of processes such as coagulation, flocculation, sedimentation, filtration, and disinfection [100]. Water purification may be small-scale (e.g., for individual households) or large-scale (e.g., for an entire city). Coagulation is often the first step in water treatment. In coagulation, positively charged chemicals are added to the water to neutralize the negative charge of dirt and other dissolved particles present in the water. As the particles bind with the chemicals, they form slightly larger particles. Common coagulation chemicals are aluminum or iron.

Flocculation follows the coagulation. This is achieved by the gentle mixing of the water to produce larger, heavier particles called flocs. Water treatment plants often add additional chemicals during this step to help the flocs form [101]. The sedimentation process separates solids from the water and flocs settle to the bottom of the water because they are heavier than water. The water is then filtered by allowing the clear water to pass through filters of different pore sizes and materials (such as sand, gravel, and charcoal).

An ultrafiltration process may be used in addition to or instead of traditional filtration. Using reverse osmosis filtration method removes additional particles from the water making it very efficient when treating recycled water or salt water for drinking. The last stage is disinfection which involves adding one or more chemical disinfectants such as chlorine, chloramine, or chlorine dioxide to kill any remaining parasites, bacteria, or viruses.

6.2.2 Reclaimed water

This is known as wastewater reuse, water reuse, or water recycling. It involves converting municipal wastewater or sewage and industrial wastewater into water that can be reused for some purposes such as irrigation for agricultural purposes, household or industrial use, or even possibly to reach drinking standards [102]. The principal objective of wastewater treatment is reducing nutrient and contaminant loads to the environment, thus maintaining aquatic ecosystem health [103].

In many countries including the USA, federal regulations and coordination among states are lacking, as water recycling regulations and standards are left to the states. This absence of federal involvement allows for diverse standards to exist across the country, despite the differing standards, it is expected that a multi-barrier approach is implemented in water recycling processes.

The World Health Organization recognizes increasing water scarcity and stress, increasing environmental pollution, and the increasing recognition of the resource value of wastewater, excreta, and greywater are the driving forces for municipal wastewater reuse [104] and that reclaiming water for reuse applications instead of using freshwater supplies can be a water-saving measure. Likewise, discharging treated water into natural water sources, benefits the ecosystems by improving streamflow, nourishing plant life, and recharging aquifers, as part of the natural water cycle.

6.2.3 Desalinization

Oceans cover 70% of the planet and there is no shortage of seawater. Desalination is the process of removing salts from water. This purification process achieves drinkable freshwater from vastly available saline sources such as brackish or seawater water [105]. Countries, such as the Maldives, Malta, and the Bahamas, meet all their water needs through the desalination process, while Saudi Arabia gets 50% of its drinking water from desalination and up to 16,000 desalination plants are operating in 177 countries [106].

Thermal and membrane methods are the two main desalinization technologies. Thermal technologies use heat for their operation and it involves heating hyper-saline water and gathering condensed vapor for the production of freshwater examples include multi-stage flash (MSF), multi-effect distillation (MED), vapor compression distillation (VCD), adsorption desalination (AD), humidification-dehumidification (HDH), and freezing technologies [107].

The membrane-based desalination uses the principle of osmosis to transport water from a low concentration to a high concentration aqueous environment through a semi-permeable membrane until stability in concentration is achieved. This process utilizes membrane and electrical energy to power its process and is classified into forward osmosis (FO), electrodialysis (ED), electrodialysis reversal (EDR), reverse osmosis (RO), and nano-filtration (NF) [108].

Desalination is responsible for just about 1% of the world's drinking water, we have a lot to do with harnessing this seeming "drought-proof" and "limitless" power of the ocean [109]. The downside, however, is its environmental footprint as it is considered energy-intensive and expensive.

6.3 Water conservation: way forward

While creating water out of thin air may be in the foreseeable future, water conservation practice employs using water efficiently to reduce unnecessary water usage.

By sustainably managing fresh water's natural resources, and protecting the hydrosphere, both current and future human water demands may be met. Water conservation efforts should include policies, strategies, and activities to manage freshwater resources and water consumption sustainably.

In 2018, when Cape Town became the focus of South Africa's water crisis, a statewide awareness to reduce water consumption and wastage ensued. The dystopian scenario was averted as many feared for their livelihoods; analysts estimated that the water crisis would cost some 300,000 jobs in agriculture and tens of thousands more in the service, hospitality, and food sectors [110]. Residents' efforts began to have an impact, as water consumption fell and impending doomsday was pushed further.

Every little contribution goes a long way, in our daily activities, we often overlook the amount of water used in various processes. By becoming more aware and making informed choices, individuals can contribute to water conservation. Turning the tap off while brushing, choosing shorter shower times, and using washing machines and dishwashers only when fully loaded all help to conserve water [111]. Installing water-efficient appliances and fixtures, and fixing leaks on time can make a significant impact in the long run. Strategies to promote water conservation attitudinal change would be beneficial within affected communities.

Policy shifts should put water at the heart of action plans. Encouraging collaboration and partnership among countries promotes better-coordinated trans-border support geared toward balancing the water needs of communities, industry, agriculture, and ecosystems. A sustainable water management plan that helps society adapt to climate change by building resilience, protecting health, and saving lives. When natural buffers such as wetlands are protected, flooding, extreme weather events, erosion, and pollution reduction follow in surface and underground water. Regulators who enforce compliance must ensure acquiescence with established standards and guidelines, especially with industries to implement water-efficient practices and court them as pioneers of renewable energy sources, and mitigators of the impacts of climate change.

In addition, climate mitigation strategies: reducing greenhouse gas emissions and improving energy efficiency, would limit climate change's impact on water resources. Since agriculture also consumes a lot of water, adopting climate-smart agriculture, which uses modern-day conservation techniques that improve soil moisture retention thus, requiring less water for plant growth [112].

Governments and corporate entities can increase funding for research and development initiatives that target innovative water-saving technologies and practices. Financing water resource management research will foster sustainable, affordable, and scalable water solutions. Reusing wastewater can help reduce the pressure on freshwater as regulated treated wastewater, can be used for irrigation and industrial and municipal purposes. It is also important to facilitate means to capture rainwater for small-scale use (rooftop capture) or large-scale (surface dams) to reduce run-off and increase aquifer reload.

7. Conclusion

One of the biggest threats to global ecosystems is water scarcity. Without concerted water conservation efforts, the threat to humanity is inevitable. The ability to anticipate and prepare adequately for future water resource management challenges is contingent on how seriously we address the issues of climate change, water

pollution, and ecosystem health. Understanding the rate and scale of change and the consequences for our well-being is crucial to implementing a sustainable water-based management system.

Our effectiveness in predicting the threat of global warming and looming water scarcity, responding to associated changes in water resource availability and quality, identifying the pressure points attributable to water resource changes, preventing uncertainties about future climate and water-related conditions that make adaptation more difficult, and preparing for improvements that detect water shortages in advance, forecast their duration and intensity, would help form the management strategies to curb future water resource challenges.

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