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REVIEW **Open Access**

A review of the current status of the water quality in the Nile water basin

Nathan K. Kipsang[1], Joshua K. Kibet[1*] and John O. Adongo[1]

Abstract

Background Water contamination has become one of the most challenging problems to clean water supply and infrastructure in the twenty-first century. Accordingly, access to clean water is limited by negative impacts of climate change and pollutants of varying health risks. Overtime, global population has experienced an exponential growth, which has put pressure on the limited water resources. At least 3 billion people globally rely on water whose quality is largely unknown.

Main body of the abstract The Nile water basin, found in East and Central Africa, covers 11 countries including DRC, Tanzania, South Sudan, Kenya, Uganda, Burundi, Egypt, Ethiopia, Eritrea, Sudan, and Rwanda. The Nile River flows through it before draining its water into the Mediterranean Sea in Egypt. Nile River water was pivotal for the ancient civilization in the Sudan and Egypt through provision of fertile soil and water for irrigation, drinking, fishing, animal husbandry, and channel of transport and in modern times, on top of the historical utilization, for generation of hydroelectric power leading to conflict and cooperation over the shared water resources. Literature on water quality in the Nile water basin is summarized, using the traditional review method to point out gaps, compare the water quality with other areas and suggest recommendations based on the findings of this study. The Nile water basin has been contaminated by numerous pollutants such as toxic heavy metals and organic contaminants, therefore pushing the resident water quality above the World health organization (WHO) acceptable guidelines for drinking water, agricultural irrigation, and aquatic life support. Cases of contamination outside the recommended limits of cadmium in little Akaki River in Ethiopia, aldrin and dieldrin in the Tanzanian side of L. Victoria and other areas clearly show contamination above the WHO limits in the Nile water basin.

Short conclusion The effect of fish cages, micro-plastics, heavy metals, organic contaminants and suspended sediment load primarily from human activities like agriculture, industries and municipal wastes is continuously contaminating the Nile basin water toward poor quality water status. Consequently, interventions like transboundary laws and regulations to mitigate the risks must be enforced.

Keywords Water, Transboundary laws, Acceptable guidelines, Nile basin water, Micro-plastics

Background

Water is a critical resource with regard to life and human socioeconomic development, but access to it is limited by freshwater scarcity, climate change, and population growth. Remarkably, over 70% of the earth's surface is covered by water; however, only 2.5% of earth's water is fresh, with majority of the freshwater frozen or submerged. For the purpose of hydration, food digesting, and nutritional provision, the majority of plants and animals require fresh water to survive. For the various uses of water such as irrigation and household consumption, periodic water quality monitoring is necessary. Due to lack of monitoring and evaluation strategies, the quality of water that at least 3 billion peo-

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*Correspondence:
Joshua K. Kibet
jkibet@egerton.ac.ke
[1] Department of Chemistry, Egerton University, P.O Box 536, Egerton 20115, Kenya

ple depend on is largely unknown or unregulated. Climate change has limited access to fresh water already affected by pollution through high temperatures, frequent floods, and droughts (Dixit et al. 2022; Yildiz et al. 2022). The Nile water basin—a water basin found in East and Central Africa, comprise 11 countries—DRC, Tanzania, South Sudan, Kenya, Uganda, Burundi, Egypt, Ethiopia, Eritrea, Sudan, and Rwanda with the Nile River flowing through it before it empties its water into the Mediterranean Sea (Abtew et al. 2019; Pemunta et al. 2021). The main tributaries of the Nile River are the Blue Nile whose source is L. Tana in Ethiopia, White Nile from L. Victoria, and the Atbara from northwest Ethiopia. The Nile water basin is divided into two major sub-systems, the Eastern Nile sub-system and the equatorial Nile sub-system. The Eastern subsystem comprise the main Nile sub-basin, Blue Nile sub-basin, Baro-Akobo-Sobat sub-basin, and Tekeze-Atbara Sub-basin (Yihdego et al. 2016). The equatorial Nile sub-system comprise of the White Nile sub-basin, Bahr El Jebel sub-basin, Bahr El Ghazal sub-basin, Victoria Nile sub-basin, L. Victoria sub-basin, and L. Albert sub-basin (Degefu 2003).

The significance of the Nile water basin in the 11 countries dates back to the pre-colonial times where the water of the Nile River was critical in the rise of one of the earliest civilization in the Sudan and early Egypt. The waters of the Nile River provided the ancient Egyptians with fertile soil and water for irrigation, drinking water, fishing, raising livestock and a channel of transport (Halawa 2023). The significance of the Nile River has continued over the years with the construction of hydroelectric power generation in the modern times which has sometimes led to conflict and cooperation over shared water resources including the recent conflict over the construction of the Grand Ethiopian Renaissance dam (GERD) by Ethiopia where Egypt did not consent to its construction, and the on and off conflict between Kenya and Uganda over L. Victoria maritime resources (Allam and Eltahir 2019; Mwinyi et al. 2022).

The motivation behind this study is based on the current trends in industrialization, agriculture, and human settlement which have posed serious challenges to water quality, health concerns, environmental, and the general economic and social development in the Nile basin. The study aims at coalescing previous water quality studies in the Nile basin with a view to defining the current water quality standing of the basin. This perspective will help identify the pollutants affecting the water status in the Nile basin. Because the general water quality status is associated with human activities such as fishing, agricultural practices, and information on the choice of water infrastructure development, clean water supply and transboundary policy formulation to protect the Nile basin water quality has become necessary.

Main text

Methodology

The review methodology adopted in this study is the traditional review which summarizes literature on water quality in the Nile water basin, identifying gaps, comparing the area of study with other areas and provides recommendations based on the findings. The impact of inherent pollutants assessed, permissible levels based on various international standards, and remediation strategies in decontamination of polluted water is presented.

Gaps in previous studies

Previous studies to ascertain the status of the water quality in the Nile basin has been extensively examined based on individual categories of contaminants such as toxic heavy metals or organic contaminants in specific parts of the Nile basin. With this approach, the general water health of the water basin cannot be predicted clearly. Therefore, this review examines in detail the water quality studies conducted in the Nile basin with the aim of providing a clear picture of the current water quality standing of the Nile basin.

The study area

The Nile basin is defined by the Nile River—which is the longest river in Africa, flowing through the basin from its source in the equator of Eastern Africa in the L. Victoria and Lake Tana in Ethiopia through a length of 6,695 km and emptying its waters into the Mediterranean Sea in Egypt. The major tributaries of the Nile River are Kagera in Rwanda, Victoria Nile, Baro-Akobo-Sobat, Bahr el Jebel, Bahrel Ghazal, Tekeze-Atbara, Blue Nile, White Nile, and the main Nile River which originates from L. Victoria in the East Africa (McCartney and Rebelo 2018). The basin comprises natural Lakes including Victoria, Albert, Kyoga, Edward, and the Tana as shown in Fig. 1.

The Nile River is a special source of fresh water in Egypt, primarily for drinking and irrigation. The River has its origin in the East Africa and the Ethiopian highlands, and drains its water in the Mediterranean Sea in Northern Egypt (Abdel-Satar et al. 2017). Ascertaining the pollution nature of the Nile River is essential because it influences the quality of life in the basin (Abdel-Satar et al. 2017; El-Sheekh 2017). The Nile River in Egypt is considered the primary artery of life in Egypt. Nonetheless, the basin is under serious pollution risk stemming from significant levels of fertilizer based nutrients, silicates, organic contaminants, heavy metals and micro-plastics largely associated with anthropogenic activities such as farming, fishing, oil spillage, recreation

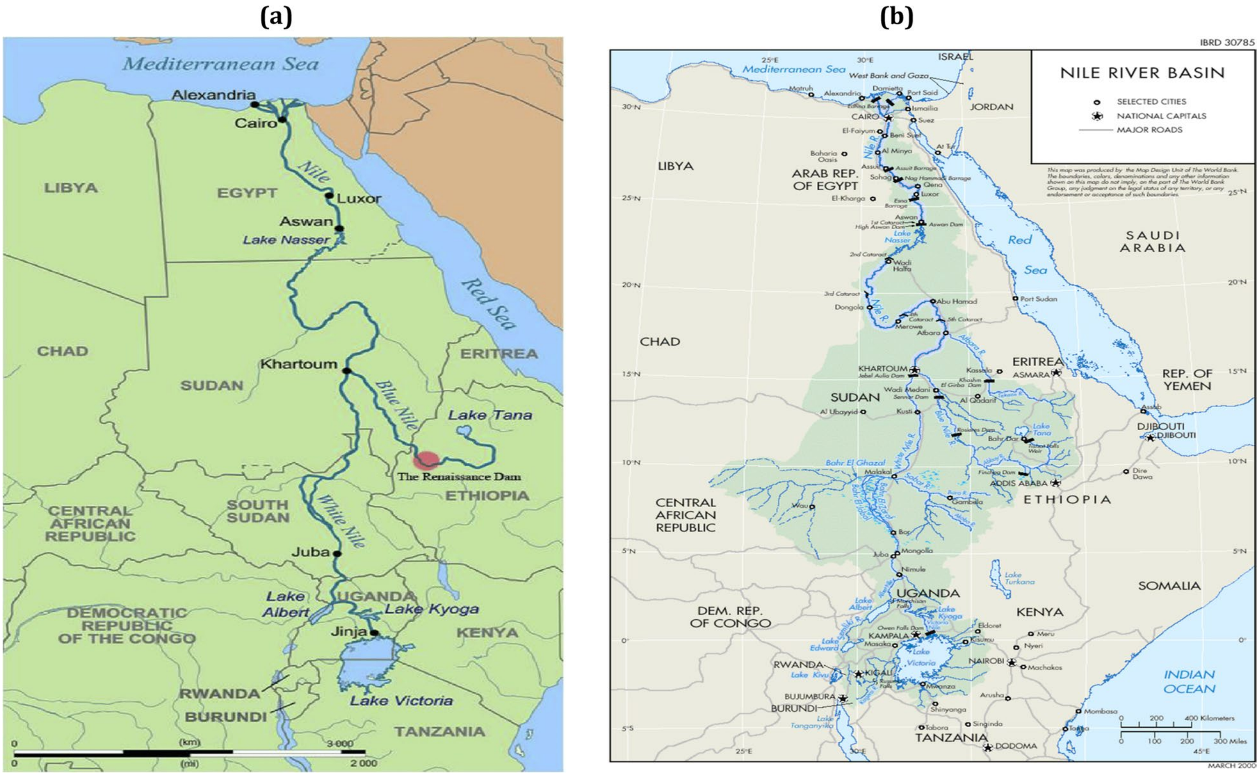

Fig. 1 A map showing the countries covered by the Nile River basin **a** Abd Ellah (2020) and **b** the Nile water basin map—adopted from Madani et al. (2011)

and industrial waste discharge (El-Sheekh 2017). These activities have been known to significantly compromise water quality not only in the basin, but also in various parts of the world.

Water quality status

Life on earth requires optimal quantity and quality of water to thrive; however, population growth and its associated factors such as industrialization, mechanized agriculture, and climate change are putting significant pressure on water quantity and quality (Cosgrove and Loucks 2015; Mishra 2023). Water quality expresses how appropriate the water is to sustain the various uses and applications—this quality varies seasonally from place to place (Ram et al. 2021). Physical, chemical, and biological properties define the quality status of water which further indicates the suitability for a specific use. The physical properties of water include turbidity, temperature, total dissolved solids (TDS), color, odor, conductivity, salinity, and dissolved oxygen (DO), while chemical characteristics include pH, chlorides, fluorides, organic contaminants and heavy metals among other pollutants whereas biological parameters include bacteria, algae, virus load and fecal matter (Jasim 2020). Ambitious strategies for hydroelectric power generation, agricultural irrigation, rapid population growth and climate change have exacerbated challenges in sustainable management of water resources and climate adaptation in the Nile basin (McCartney and Rebelo 2018).

Chemical compounds applied to deter pests and weeds in order to improve crop and animal production are defined by various negative environmental and health impacts. Pesticides, for instance, are deposited in the soil compartment because of their high soil affinity; however, through surface runoff, these pesticides may drain into the water bodies where they are reported in low concentrations. Because of bio-accumulation and bio-magnification, their concentration increases to the apex of the food chain mimicking important hormones once in the human body which ultimately compromise body immunity, damaging hormone balance, impacting reproductive health, impairing growth, and are precursors for carcinogenicity among other etiological risks (Syafrudin et al. 2021). There is a significantly low awareness about risk and safe handling of agrochemicals among farmers, an observation supported by Abong'o et al. (2014), with many farmers missing critical information on safety and the recommended dose, further exacerbating the risk of agrochemicals which usually find their way to water bodies and ultimately affecting human health, and the general environment.

Chemical, microbial, photo-oxidative, thermal, and mechanical forces lead to slow degradation of large plastic materials resulting in minute plastic particles of sizes below 5 mm (Yang et al. 2021). The surface of these minute micro-plastics adsorb organic pollutants such as pesticides and polycyclic aromatic hydrocarbons (PAHs) which expose organisms to combined toxicity (Yu et al. 2021). The exponential growth in human population around the Nile water basin exposes the water bodies to pollution by micro-plastics and other contaminants of serious concern. There are also numerous threats to the wetlands in the basin resulting from inappropriate agricultural practices like overfishing, invasive plant species such as hyacinth, mining activities and oil exploration events (McCartney and Rebelo 2018).

Various water uses and applications have quality requirements for physical, chemical and/or biological characteristics which are dictated by a range of natural and anthropogenic activities such as mining, agriculture, water transport, fishing and climatic dynamics. Cumulatively, the levels of dissolved oxygen (DO), bacterial load, salinity, suspended mater denoted as turbidity, algae, organic contaminants and toxic trace metals present in the water systems characterize the status of water (Ewaid et al. 2020; Simeon et al. 2019). Regular quality monitoring of water resources is essential for a healthy ecosystem, industrial and domestic use, and agricultural activities, which are critical towards a healthy nation (Grafton et al. 2013).

Factors affecting water quality

Effect of fish cages on water quality

The fishing industry has enormous significance ranging from beneficial health effects on the human body through the nutritional impact, balance in aquatic ecosystem, and the economic contribution from the fish supply chain (Mauli et al. 2023). The practice of the cage culture which targets to reduce predation, improved efficiency in feeding, fish husbandry, health management, and in fish harvesting is a common practice in the Nile water basin (Mwamburi et al. 2021; Njiru et al. 2019; Obiero et al. 2022). Consequently, on top of cage culture benefits, there has been concern on its potential pollution impact from feed residues and fish fecal matter, fish metabolic by-products, and residual biocides (Nyakeya et al. 2022). The pollution potential can be exacerbated by cage aquaculture enterprises established with total disregard to the cage culture best management practices as demonstrated by Musinguzi et al. (2019). Mawundu et al. (2023), explored the effects of net cages on water quality and nutrient levels of L. Victoria at Kadimu Bay which lies on the Kenyan side of L. Victoria, and reported physicochemical factors and eutrophic state for aquatic life processes which were within the standard of the WHO limits. These findings showed that the fish cage culture did not pose any significant threat to water quality. The findings were in agreement with studies conducted by Mwebaza-Ndawula et al. (2013), Ngodhe (2019) in Winam Gulf of L. Victoria, Kenya, and Egessa et al. (2017) who monitored the environment surrounding the cage area for possible pollution impacts. Nonetheless, the findings of Khaled et al. (2010) in their study on the effects of fish cages on the Nile water status at Damietta branch indicated a significant water quality improvement after the removal of fish cages which can be considered a minimal negative impact on water quality by cage fish farming. This assertion is supported by El-Kholy (2012), although their sampling did not target the cage locations only. Musa et al. (2022), reported significant impacts on nutrients, planktons and macro-invertebrates restricted within the neighborhood of cage culture for rearing Nile Tilapia on the quality of the water and bottom sediment in Anyanga beach in Kadimu Bay, L. Victoria, Kenya. These findings is an indication of the possibility of minimal effects of the cage culture which if not managed well can result in detrimental effects on water quality. In the short run, the water system may be able to create a balance from the cage culture; however, there is a high risk if it is not practiced in total compliance to cage fish farming best practices (Ragasa et al. 2022).

Effect of human activities

Anthropogenic activities such as farming and disposal of waste contribute immensely to a given status in a given water body. Njiru et al. (2018) noted that eutrophication in L. Victoria resulting from increased nutrient load dominated shallow bays near large human settlements practicing agriculture and other potentially polluting activities. Investigations by Ongom et al. (2017) concluded that the pollution of L. Kyoga by anthropogenic activities was evidenced by the high concentration of nitrites and phosphates. The influence of human activities was further confirmed by the impact of wastewater discharge and agriculture on water quality and nutrient retention of Namatala wetland, Eastern Uganda, where they reported sediment and nutrient loads were strongly correlated with seasonal variations in rainfall and river discharge, and to the corresponding enhanced activities in agricultural practice; however, it was noted that the wetland was able to performs its sediment and nutrient regulating ecosystems, although the wetland could be compromised by intense agricultural practices which further puts this function into the risk of heavy pollution and possible extinction. However, a study by

Saturday et al. (2021) showing spatial and temporal variations in physicochemical qualities of water of L. Bunyonyi showed significant variation with seasons in the physicochemical parameters.

Omran and Elawah (2023) investigated the L. Nasser water for physical and chemical properties and found that the water was suitable for aquatic life; however, some areas had high turbidity values in excess of five nephelometric turbidity units (NTU) which is unacceptable for drinking, and also lowers the effectiveness of disinfection. This study agrees with Goher et al. (2021) in their in-depth study of the L. Nasser regarding water quality and biotic life before the operationalization of the GERD, which showed high variations in spatial and temporal distribution on the physicochemical parameters to be within the acceptable standards for drinking water as reported by the Egyptian drinking water quality standards (EWQS), the USEPA and the WHO. The findings further reported compliance with the criteria for irrigation, according to the Food and Agriculture Organization (FAO), and for the thriving of aquatic communities against the allowable limits of the Canadian council of ministers of environment (CCME), reflecting the ability of the L. water to sustain the different purposes without negative effects. A study done by Korium (2021) to ascertain the effects of nutrients and water quality in some Khors of L. Nasser, Egypt, found L. water suitable for different purposes based on the physicochemical parameters reported to be within the recommended levels by USEPA, FAO and the WHO, for irrigation and for the life of aquatic communities.

Rice farming, which is widespread in the Nile River basin from Ahero region (Yamane 2023) and Nyando Wetlands (Adunde et al. 2023) in Kenya, in Uganda (Hong et al. 2021), in Sudan (Abdalla et al. 2022), and Egypt (Bakr and Afifi 2019), indicated that a semi-aquatic farming is a possible anthropogenic source for water contamination. Research conducted on rice fields such as by Gosetti et al. (2019) in Italy at the Padana plain for rice cultivation and Bouman et al. (2007) reported that rice fields contaminate through methane and minimal nitrous oxide, nitrate and use relatively little to no herbicides with all the other water quality indicator parameters such as total suspended solids, biological oxygen demand (BOD) after 5 days, total hardness, total amount of phosphorus, nitrogen, and heavy metal concentrations were under the limits set by European regulation commission. At the time of this review, there was no documented information on the possible negative effects of rice farming on the suitability of the Nile basin water.

Heavy metals

Because of the expansion and increased industrialization, pollution by substances known to be carcinogens and toxic such as heavy metals, which are capable of affecting the entire food chain and the environment have increased significantly (Mao et al. 2019). In the water column, heavy metals settle down along with sediments. Selected concentrations of toxic trace metals in sediments in parts of the Nile water are reported in Table 1. Following exposure of toxic heavy metals in water, air, and food organisms can develop either acute or chronic toxicities, where further bio-accumulation and bio-magnification may cause a range of tissue aberrations in various organisms (Balali-Mood et al. 2021b). Heavy metal toxicity can have serious impacts on normal cell processes such as growth, proliferation, differentiation, cell repair, and apoptosis (Balali-Mood et al. 2021b; Oyugi et al. 2021).

Mekuria et al. (2020) conducted a study on the little Akaki River in Ethiopia to evaluate heavy metal enrichment in the river sediment and found out that the river sediments were highly loaded with Cd and Pb which exceeded US EPA and the Interim marine sediment quality guidelines (ISQGs), which could occasionally cause potential hazards on exposure to the sediments and the water system which is the major habitat for aquatic life. The researchers associated the origin of the heavy metals to industries and agrochemicals which can be mitigated by domestic and industrial effluent treatment to meet the national discharge standards before release into the river system. The data in Table 2 clearly show a high heavy metal load way above the limit set by WHO, an indication that the Nile basin has been extremely contaminated by potentially toxic heavy metals.

With regard to living organisms, metal elements are either essential or non-essential depending on their role to living organisms (Mao et al. 2019). Essential metal elements which include iron, copper, zinc, cobalt and

Table 1 Heavy metal load summary in sediments of the Nile River water basin

Site	Cu	Cd	Pb	Cr	Zn	Reference
1. Port Bell, L. Victoria(g/kg)	6.467	3.283	42.184	0.456		Baguma et al. (2022)
2. L. Nasser (mg.kg^{-1})	17.32	0.2546	1.99	–	31.4	Rizk et al. (2022)
3. Little Akaki River sediment, Ethiopia (mg/kg	–	3.14	129.68	109.51	148.28	Mekuria et al. (2020)

Table 2 A summary of selected heavy metals in water compartment of a section of the Nile water

Site	**Cu**	**Cd**	**Pb**	**Cr**	**Zn**	**Fe**	**Ni**	**Mn**	**Co**	**Ref**
WHO Limits(mg/L)	2.0	0.003	0.01	0.05	–	–	0.07	0.08	–	WHO (2011)
L. Nasser (mg element L^{-1})	3.26	0.039	0.028	–	8.70	–	–	–	–	Rizk et al. (2022)
Rosetta Branch	14–72	0.81–2.3	9.3–67.9	3.9–27.4	21.1–133	396–1640	3.9–25.1	40–220	5.0–28.1	Al-Afify and Abdel-Satar (2022)
Holeta River	0.1053 ± 0.068	0.003 ± 0.003	0.05 ± .019	0.1805 ± 0.13	0.6050 ± 0.29	204.3200 ± 129.73	0.19 ± 0.15	3.8535 ± 3.31	0.0445 ± 0.04	Temesgen and Shewamolto (2022a)
Golli River	2.4175 ± 2.36	0.01 ± 0.0021	0.02 ± 0.02	0.1670 ± 0.15	0.9725 ± 0.89	60.1525 ± 37.68	0.16 ± 0.12	2.748 ± 2.63	0.03 ± 0.02	Temesgen and Shewamolto (2022a)

chromium among others are important for living organisms at low concentrations for physiological and biological functions; however, in excessive levels, they are toxic to the body and can cause adverse health effects. On the other hand, non-essential metals are those metal elements with no known physiological or biological function in living organisms (Rilwanu 2021). Elements known to be toxic include cadmium, beryllium, lead, mercury, aluminum, barium, bismuth, and thallium, which on exposure to organisms may result in the occurrence of toxicities which are dependent on dose and duration of exposure (Skalnaya and Skalny 2018).

Organic contaminants

Organic contaminants have the ability to bio-accumulate, bio-magnify and are not only recalcitrant in the environment, but also resist degradation. With the application of pesticides and other human activities around the catchment area of L. Victoria, there have been significant identification of these pollutants in the L. water and sediments (Kandie et al. 2020; Twesigye et al. 2011). A number of studies point to low concentrations of organic contaminants in the water phase as compared to the sediment, demonstrating that sediments are a sink to various organic pollutants. The Tanzanian side of L. Victoria was investigated by Wenaty et al. (2019b) and reported higher levels of the organic contaminants in sediments as compared to in the water phase, with organochlorine in the lake water and sediments reported being the sub-threshold residue limits set by European Union and FAO. However, based on the threshold effect level for fresh water ecosystems, aldrin and dieldrin levels constituted harm to aquatic communities and humans. Aldrin and dieldrin as a threat to aquatic life was further reported by Wasswa et al. (2011) where they identified and quantified endosulfan sulfate aldrin, dieldrin, dichlorodiphenyltrichloroethane (DDT) and its metabolites, which were a threat to the lake water quality on the basis of threshold effect concentration (TEC) normally applied to ecosystems of fresh water. Aura et al. (2023) reported higher mean for hexachlorocyclohexane (HCH) isomer residues in Winam Gulf compared to open waters, therefore raising concern over the possibility of organic contaminants in the lake water. Nonetheless, organochlorine residues in the water were reported to be below the WHO allowable limits, but sediment samples exceeded these limits, indicating the need for regular monitoring of water quality to assure safe and health human and environmental, and implementation of appropriate mitigation measures for clean water supply and infrastructure.

Dalahmeh et al. (2020) reported a number of pharmaceutically active substances in Kampala, Nakivubo, and demonstrating contamination of water resources by wastewater. The findings agree with Kimosop et al. (2016) who reported significant levels of the selected antibiotics in effluent treatment plants, hospital lagoons, and rivers within the L. Victoria basin in Kenya. Sludge contained the highest levels indicating that antibiotics are preferentially partitioned onto the solid phase. These findings suggest the need for proper waste handling and treatment before discharge to avoid possible contamination of water resources. The substantial margin of exposure and margin of safety with respect to concentrations that can occur in pharmacological effect and the concentrations in water bodies of pharmaceutical compounds lowers the possibility of public health risks (Bruce et al. 2010; Kumari and Kumar 2020).

Agriculture including sugarcane farming which practices sugarcane burning every other harvesting season, rice farming, chemical industrial effluent, municipal solid waste incineration, and shipping industry are major contributors of polychlorinated biphenyls (PCBs) to the environment (Sadañoski et al. 2023). A study by Wenaty et al. (2019b) reported the presence of PCBs and organochlorine pesticides (OCPs) at higher sediment concentrations compared to the water compartment in the Tanzanian side of L. Victoria. The mean residue concentrations of most of these pollutants were below European Union and FAO threshold effect concentration and maximum residue limits for fresh water ecosystems; however, aldrin and dieldrin concentrations constituted a threat to aquatic life and humans depending on the water. Lower levels of PCBs were also reported in Napoleon Gulf of L. Victoria in Uganda, by Ssebugere et al. (2014); however, the levels in the two studies were much higher than levels reported by Afful et al. (2013). The detection of pollutants in water and sediments, although at allowable limits indicates a risk of bio-accumulation and bio-magnification, which may put humans who feed on products from such water bodies at risk. PCBs were detected below the maximum recommended limits known to be of low risks with respect to cancer, and insignificant in regard to non-cancer associated risks for fish and fishery products by Wenaty et al. (2019a), Wenaty and Chove (2022), when they evaluated fish products from L. Victoria with sampling in Tanzania, alluded to the safety of fish products with respect to human health risks.

Concentrations of organic pollutants in most water bodies outside the Nile water basin has been reported to be within the allowable limits. Montuori et al. (2020) reported levels of PCBs and OCPs in the Volturno River and its estuary in Italy to be within the acceptable WHO limits in sediments, and therefore not a threat to immediate aquatic communities on the sedimentary environment. However, a study by Nthunya et al. (2019) in in the Nandoni dam found in Limpopo province of South Africa detected a range of phenolic compounds higher than the limits allowed by the South African standard, WHO and US EPA in drinking water, with concentrations of PAHs falling within the threshold limits.

Micro-plastics

Micro-plastics comprise minute particles of sizes less than 5 mm from disintegration of larger materials in the environment which may be precursors for adverse health effects such as malnutrition from blockages of the gut, inflammation, infertility, and mortality, on human and organisms living in aquatic environments (Guzzetti et al. 2018; Lee et al. 2023). Various compartments of the environment have shown levels of micro-plastics including air, soil and water bodies (Hale et al. 2020). Khan et al. (2020) reported a high level of micro-plastics which included micro-plastics made of polyethylene, polypropylene, and polyethylene terephthalate ingestion in fish sampled from the Nile River in Cairo. Polyethylene/polypropylene co-polymer, polyethylene, polyurethane, polyester, and silicone rubber polymers were recovered by Biginagwa et al. (2016) from the gastrointestinal tracts of sampled fish from L. Victoria Nile perch and Nile Tilapia. Similarly, Egessa et al. (2020) reported a similar composition of polyethylene and polypropylene in micro-plastics found on the surface water of L. Victoria indicating that most of the micro-plastics originated from secondary sources, from degradation of larger plastics, and are less than 1 mm in size, which is in agreement with a review conducted by Dusaucy et al. (2021) in which they reported that the common micro-plastic size class studied was 300–1 mm. Aragaw (2021a) identified polyethylene terephthalate, polyethylene, and high density polyethylene in the shorelines of L. Tana, a similar composition of what was reported in L. Victoria with the addition of high density polyethylene. Hydrophobic pollutants are usually sorbed onto the surfaces of these small sized plastic particles thus influencing mobility and bio-availability of these hydrophobic pollutants, which are precursors for serious health problems (Gateuille and Naffrechoux 2022; Prajapati et al. 2022).

Sorption of organic contaminants onto the surface of micro-plastics results to synergistic effects of pollution from the sorbed organic contaminants on aquatic biota including on important aquatic microbes (Chang et al. 2022). Remarkably, even with the known potentially negative effects of micro-plastics in the environment, there is no standard method for sampling, analyzing, and reporting on micro-plastics to ease information sharing and comparison from different sources and various regions (Enfrin et al. 2021). The micro-plastic threat calls for regulations on prevention of micro-plastic wastes which some African countries have rarely adopted, despite challenges in implementation. Most of the African countries have not yet established these regulations, further advancing the threat from micro-plastics in the environment (Aragaw 2021b). Fishing nets also serve as a source of micro-plastics since their material is made of plastic. Jeevanandam et al. (2022) reported polyester (82%), polyethylene (15%) and polystyrene (3%) in Hawassa Lake in Ethiopia, which the researchers attributed to fishing nets, fishing lines and plastics bags. Polyethylene, polypropylene, polyethylene terephthalate, polyethylene vinyl acetate, and polytetrafluoroethylene were further reported by Shabaka et al. (2022) in the Nile delta estuaries. These findings underscore the extent of micro-plastic pollution which is solely from anthropogenic activities of the Nile water basin and the need to institute regulations to mitigate the micro-plastic environmental threat.

Suspended sediment load

Suspended sediments load (SSL) comprise of fine inorganic particles of clay and silt below 0.063 mm in size, fine sand of 0.63–0.250 mm size, and particulate organic matter (AlDahoul et al. 2021). Gravity assists in settling suspended particles through sedimentation; however, suspended sediments are fine to the extent that turbulent eddies outweigh sedimentation, causing them to be suspended in the water phase (Doychev and Uhlmann 2014). The suspended matter reduces light penetration in the water column consequently affecting aquatic plant life and the entire food chain (AlDahoul et al. 2021; Doychev and Uhlmann 2014). The reduction in penetration of light into the water column causes a drop in water temperature and a shift in ion concentration. Suspended solids damage fish gills leading to respiratory distress; nonetheless, suspended matter acts as habitats for microbes (Walch et al. 2022). As rivers flow, they carry suspended sediments along and deposits them at different places; however, the deposition of these matter erodes the health of the environment, lowers agricultural production, and reduces the suitability of portable water resources (AlDahoul et al. 2021).

Suspended sediment load has been used as one of the measures and benchmarks of soil erosion and sometimes sediment transport rates (Bannatyne et al. 2022). Transported sediment is largely from agricultural areas through erosion as reported by James et al. (2023) in the Simiyu River. The Nile sediment load is dictated by the constructed dams upstream before the basin drains its water into the Mediterranean Sea with additions from wind-blown particles mixed with fluvial and deltaic deposits in Egypt—a process that has been extensively modifying the river course in the last century (Garzanti et al. 2015).

The biological implications of contaminated water

The health impacts of the different heavy metals vary from one element to another, and also from organ to organ with lead, cadmium, chromium, arsenic and mercury posing significant human etiological risks (Balali-Mood et al. 2021a; Rahman and Singh 2019). Heavy metal toxicity occurs through various mechanisms such as generation of free radicals leading to metal-induced oxidative stress destabilizing oxidant-antioxidant balance and consequently causing damage to biological molecules such as proteins and lipids through radical oxidation (Fu and Xi 2020; Manoj and Padhy 2013). In oxidative stress conditions, transcription factors which are sensitive to redox conditions like STAT3, NFκB, AP1, and Nrf2 are activated giving out signals that results in cell proliferation or cell fatality (Valko et al. 2006). Also, most heavy metals have a strong affinity for sulfur atoms in biological molecules thus weakening sulfur bonds in enzymes and proteins, and consequently affecting cellular regulatory proteins and or signaling proteins that regulate cell sequence, apoptosis, cell repair and methylation of DNA, growth and cell division which is a precursor for carcinogenesis (Briffa et al. 2020; Permyakov 2021). Other mechanisms of heavy metal toxicity can include heavy metal inhibition of protein folding and protein aggregation (Jacobson et al. 2017). The details of oxidative processes are presented in Fig. 2.

A study conducted by Ssanyu et al. (2023) which investigated the factor that shapes community risk perception with regard to pollution by heavy metal in the L. Victoria wetlands reported findings showing age category, level of education and the type of occupation being the major factors that determine community risk perception. The same study indicated that less than a quarter of those interviewed attributed the effect of heavy metal pollution with respect to human health to shallow awareness among the wetland dwellers. The researchers recommended synchronizing education curriculum with pollution concepts that are essential to communication risk challenges in the exploitation of wetlands resources. Therefore, involving the communities on wetland adaptation strategies is very important to sustainable use of wetland resources especially in the Nile water basin.

In surface water, undissolved pollutants are sorbed to suspended matter and in cases where the sorption is strong enough, the suspended particles with the sorbed pollutants settle as sediments therefore removing the pollutants out of the water phase and concentrating the pollutants in the sediments (Zhu et al. 2017). Being a pollutant sink, sediments equally act as a source of pollutants when the right conditions of pollutant desorption are provided, ultimately impeding or allowing free movement of the pollutants between the water phase and sediment phase (Chiaia-Hernandez et al. 2022; Rizk et al. 2022). Baguma et al. (2022) evaluated the spatial

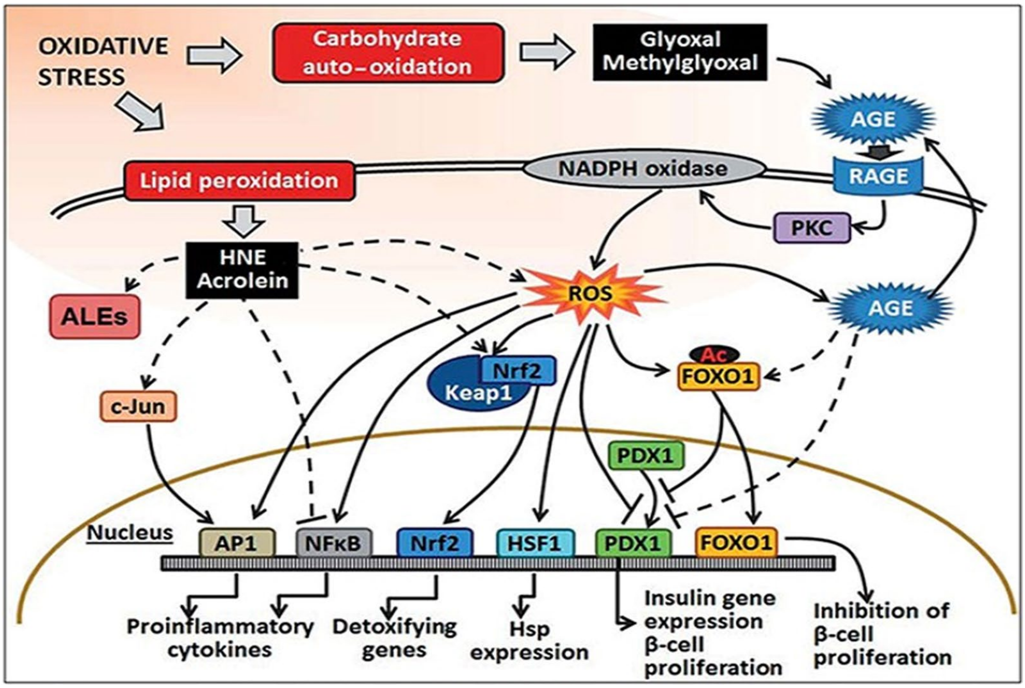

Fig. 2 Representation of the pathways activated by the oxidative stress on biological macromolecules (Chaitanya et al. 2016)

distribution and metabolic functions of bacteria in sediment of Kisat and Auji rivers that pass through Kisumu City in Kenya, reported sediment of the highly urbanized stream catchment zones that had noticeably elevated levels of organic matter and nutrients and very high Pb, Cd, and Cu content. Baguma et al. (2022) reported that contamination levels raised no serious concerns, in Port Bell L. Victoria in Uganda however the potentially ecological risk indices showed considerable pollution with Cd which can be associated with human activities like industrial effluent disposal, oil exploration activities and water transport. The anthropogenic association of heavy metals was further reported by Al-Afify and Abdel-Satar (2022) where they established that the sediments downstream at the Rosetta branch of the Nile was polluted by Cd, Ni, and Pb, with no seasonal variation thus posing low to moderate overall etiological risks.

A study on heavy metal behavior in sediments sampled from the Ugandan side of L. Victoria by Ribbe et al. (2021) reported no significant heavy metal pollution in the sediments. However, the investigation showed that heavy metal concentration variation like high levels of copper, titanium and vanadium near shore sediments in urban surroundings could be associated with industrial waste waters. Wilbera et al. (2020) reported high Pb, levels which were above WHO permissible guideline of 0.01 mg/L, high pH and turbidity in Ugandan Kasese district. Further studies by Abdalla et al. (2019) showed a higher than US EPA limits for Zn and Cd concentrations for the Nile River sediments from the banks approximately a kilometer away from both localities of Dongola and Morowe in the Northern state of Sudan. Compared with the main lake site, the inlets contained higher concentrations of pollutants. A study by Outa et al. (2020) in Winam Gulf reported significantly elevated levels for conductivity, organic matter, bound nitrogen, and trace elements such as Cr, Zn, As, Ag, Cd and Pb in shore water and surface sediments, indicating increased pollution potentially from anthropogenic activities in the gulf. The surroundings of Winam Gulf are home to industrial activities which discharge effluents into L. Victoria potentially polluting the lake with toxic trace metals and other pollutants of grave concern. The influence of these events to the lake water and fish pollution has not been fully determined. Evaluation on the impact of the activities around the lake and seasonal variation on the metal levels in water and fish from Winam Gulf is described by Kiema et al. (2017) who conducted water and fish sample analysis in areas with high anthropogenic activities from the shoreline into the lake, and the lake near Kisumu city, and reported heavy metal concentrations above the WHO limits in lake water and fish. Also, of significance as a source of toxic trace metal contaminants in the water basin is the natural occurrences as evidenced by the high heavy metal concentrations in Coco yam which was above the optimal allowable limits recommended by FAO, WHO, and EU in a study conducted by Mongi and Chove (2020) in Kenya, Uganda, and Tanzania. In this study, the soils recorded higher heavy metal content than in Coco yam samples in all the three countries. Through erosion and surface runoff, these heavy metals find their way to the surface water bodies including the L. Victoria basin and ultimately serving as a source of trace heavy metal contamination in the entire Nile water basin.

Temesgen and Shewamolto (2022a) reported heavy metal—Cd, Ni, Cr, Fe, Pb and Mn concentration in Holeta and Golli Rivers which were above the WHO limits for drinking and irrigation water. Flower farms discharging wastewater into rivers without treatment exposes the water users to grave health and socioeconomic risks emanating from direct and repetitive exposure to river pollution by the flower farming activities (Temesgen and Shewamolto 2022b). The discharge of untreated water into water systems is supported a study by Dessie et al. (2022) which reported that all of the factories investigated violated the regulatory recommendations of one or more pollutants set by the environmental protection agency of Ethiopia, US EPA and the United Nations FAO, with respect to release of wastewater considered high in pollutants.

It has been noted that there is a regular built up in heavy metals in Nile River as reported by Hassan and Elhassan (2016) in White Nile and Blue Nile with respect to Cd and Cr, although the concentrations were within the WHO permissible limits but higher than for drinking water, except for lead which was in the marginal level. Bio-accumulation and bio-magnification further worsens the pollution effects through their contributions to pollutants up the food chain. This perspective points out to the need for regular monitoring and evaluation of sea food products including fish for possible presents of pollutants as reported by Rizk et al. (2022) whose study, indicated excellent quality of water and safe fish for human consumption, where the sediment was believed to have played a critical role as a sink for heavy metals. These finding share similar observations with findings in a study conducted by Haile et al. (2015) in L. Hawassa, Ethiopia whose water was excellent for drinking, had good quality edible fish, and pristine bottom sediment.

Tools used to monitor and assess water quality

Traditionally, water suitability for a given purpose is evaluated through comparison of experimentally obtained values of a given parameter against the existing guidelines (Poonam et al. 2013). In most cases, many parameters are tested per sample, and in a given study, one samples more than one sample thus making the data generated big and hard to evaluate in order to present a conclusive position of the water usability status. Water quality index, originally developed by Horton (1965), is the most appropriate method for determining water quality based on the selected water parameters; however, it has undergone modifications by different experts over time (Tyagi et al. 2013) so that any slight change in the value of a given parameter affects the overall water quality index (Chidiac et al. 2023). Water quality indices are broadly classified into four categories based on area of application and the mode of determination. The first classification is the public indices which includes the National sanitation foundation water quality index (NSFWQI) used for general water quality evaluation which disregards the intended use of the water in the evaluation process (Poonam et al. 2013). NSFWQI is based on the analysis of nine variables, such as biological oxygen demand (BOD), dissolved oxygen (DO), nitrate (NO_3^-), total phosphate (PO_4^{3-}), temperature, turbidity, total solids (TS), pH, and fecal coliforms (FC) (Gradilla-Hernandez et al. 2020). The second category of indices, specific consumption indices, comprises the British Colombia, Canadian Council of Ministers of Environment Water Quality Index (CCMEWQI) and Oregon Water Quality Index (OWQI) indices which assess the water quality by taking into consideration the intended use of the water such as for drinking or industrial use. CCMEWQI delivers a water quality evaluation for the suitability of water bodies, to support aquatic communities, and has been used in all states in Canada and many other parts of the world (Aljanabi et al. 2021). Moreover, this measure provides data about the water quality for both those in authority and the public. Accordingly, this index can be used by various water agencies in many countries with minor modifications (Alexakis 2022). OWQI, a variant of the NSFWQI, evaluates swimming and fishing water quality for managing major streams with the determination of sub-indices by investigative procedures (Chidiac et al. 2023). The third classification, planning indices, includes indices that are used for planning and decision making in quality management projects. The fourth classification of water quality indices is the weighted arithmetic water quality index (WAWQI) which uses statistical methods to monitor water quality (Ahmed et al. 2021; Akhtar et al. 2021; García-Ávila et al. 2022). Public indices, specific consumption indices, and planning indices use expert judgment in allocating weight to the various variables resulting in same variable allocated different weights by various panels of experts therefore making them subjective (Tripathi and Singal 2019). For the statistical category, personal opinions are not considered thus removing the subjectivity affecting the first three and hence making it more objective.

The water quality indices simplify complex water quality data sets into a single dimensionless quantity which represents overall water quality at a certain location and time, and allowing for comparisons between different sources or same source from different seasons or sampling points (Lkr et al. 2020; Teshome 2020). This quantity gives the combined effect of the different parameters that analyze water quality and predicts if a water body poses a potential harm to the various uses of the water from a given source (Akter et al. 2016). Because water quality index is a measure that expresses water quality state as a single dimensionless number, classification of the water quality status is summarized as shown in Table 3.

A study by Abdel-Satar et al. (2017) investigated 24 sampling sites on the water quality in the Egyptian segment of the Nile River reported remarkable results based on seasonal patterns and the influence by the GERD on the Nile River water quality. The sampling points are presented in Fig. 3.

Pollutants are either directly or indirectly discharged into the basin through surface runoff, and these pollutants remain low during the rainy season when river flow is high (Abdel-Satar et al. 2017). Anthropogenic activities contribute in magnifying the risk of pollution, with total metal concentrations and the environmental indices showing that the Nile water samples are significantly contaminated with potentially toxic metals (Abdel-Satar et al. 2017; El-Sheekh 2017). From the findings of Abdel-Satar et al. (2017), it was concluded that the water quality situation in the Nile basin could get worse by the operationalization of GERD which could lead to a decrease in water volumes in the Nile basin to Egypt. From this study, the pattern of WQI was not clear because of fluctuating nature of water quality caused mainly by seasonal patterns variations and the commissioning of GERD.

Moreover, the discharge of used irrigation water, effluents from industries and municipal waste into the Nile river, containing high levels of pollutants may deteriorate the water quality of the Nile, and subsequently causing

Table 3 Water quality index classification (Poonam et al. 2013)

Water quality index range	Water quality status
> 80–100	Excellent
> 60–80	Good
> 40–60	Moderate
> 20–60	Bad
> 0–20	Very bad

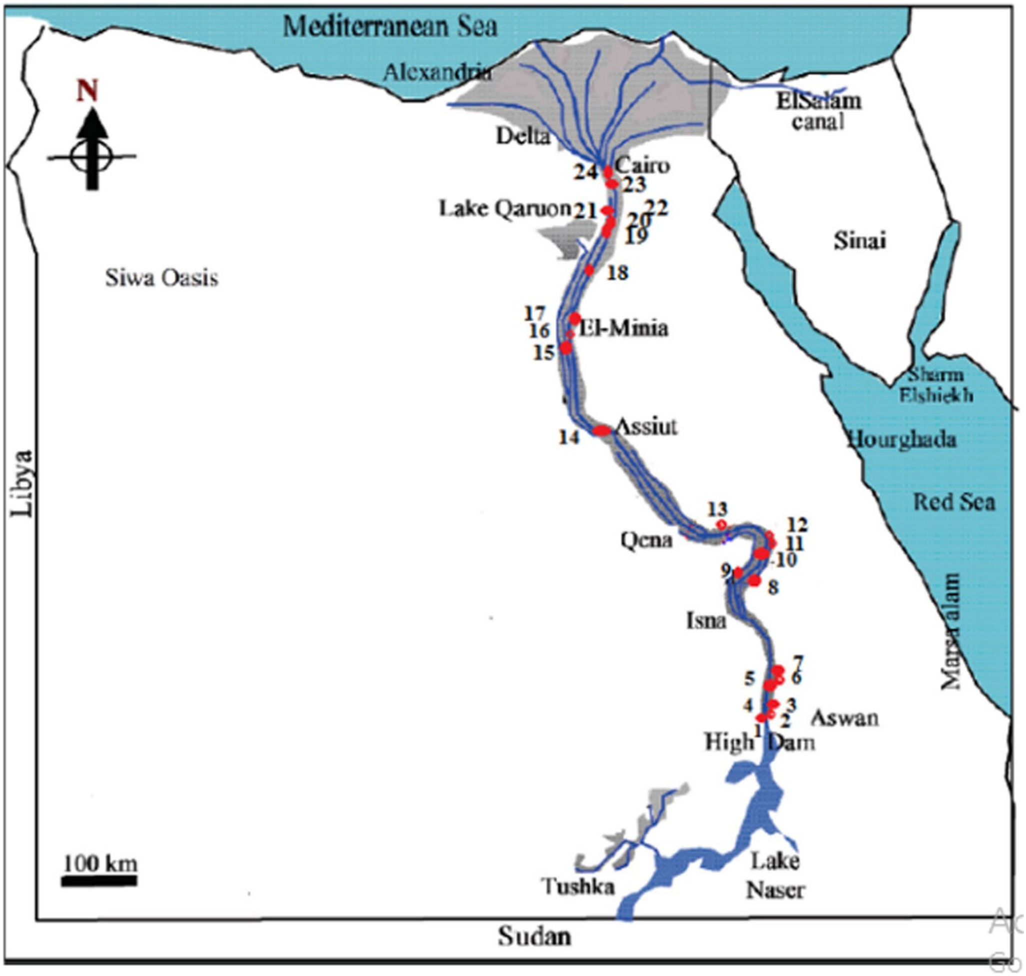

Fig. 3 A map of sampled points in the Egyptian section of the Nile River (Abdel-Satar et al. 2017)

the river water to become unsuitable for the intended various purposes (Abdel-Satar et al. 2017; El-Sheekh 2017).

Hazard quotient

Non-carcinogen associated risk factor is expressed as the hazard quotient (HQ) relating the dose delivered (ADD) in form of average daily dose at the point of exposure to a toxicological result on a given organ represented by the reference dose (Rfd) as shown in Eq. 1 (Rahman et al. 2021).

$$\mathrm{HQ} = \frac{\mathrm{ADD}}{\mathrm{RfD}} \tag{1}$$

Nonetheless, pollutants in the environment do not exist in isolation but as a mixture. The cumulative risk of simultaneous exposure of an organ to several non-carcinogens in the environment is found by adding the HQ values of the individual pollutants in existence in the specific environment to obtain an Hazard Index (HI) with HI and HQ < 1 being the acceptable values where adverse effects are not likely to occur (Billionnet et al. 2012; Genthe et al. 2013).

AquaChem

AquaChem is a numerical software for data management, data analysis and reporting with the ability of converting units, calculating charge balance errors, plotting, modeling, and statistical data manipulations (Kumar 2012). The software has also been used to evaluate trends for tens or hundreds of samples and parameters within a short period of time and assesses aqueous geochemical interactions during acid mine drainage (Said et al. 2022). AquaChem was used by El Kashouty (2013) in modeling the limestone aquifer in the western Nile River between Beni Suef and El Minia in Egypt.

Artificial neural network

Artificial neural network (ANN) is an intelligent system constructed through biological neural network motivation for solving numerous problems through a set of stages such as recognition of pattern, prediction, optimization, associative memory, and control developed with an intention of mimicking intelligent behavior (Lin et al. 2020; Thakur and Konde 2021). Six environmental parameters that included pH, TDS, DO, COD, BOD, and ammonia were used by Sulaiman et al. (2019) in Malaysia to classify water quality using ANN, which gave a water quality classification of 80% accuracy. The numerical tool helps reduce the water quality sampling site parameters, and ultimately cutting down on costs and reveals the patterns of water quality for decision making by governments and stakeholders (Isiyaka et al. 2019).

Adaptive neuro-fuzzy inference system

Adaptive neuro-fuzzy inference system (ANFIS) is a an artificial intelligence program which combines fuzzy inference system (FIS) and ANN to approximate highly complex and nonlinear systems by taking advantage of its accuracy and interpretability (Santoni et al. 2019). ANN numerical code has been adopted recently for statistical models because is able to capture complex nonlinearities in a system against linear regression methods to mimicking how the human brain operates by processing information available to the input layers in order to achieve a desirable output (Ahmed et al. 2019). It takes advantage of neural network merits and theories of fuzzy logic systems in its operation to learn the features of a given data and alter the system parameters to suit the required error criterion of the system in order to generate an output by translating the information to experts in a set of rules, where ANN automates the process thus reducing the searching time. Ahmed and Shah (2017) developed ANFIS model which accurately predicted BOD. Mohadesi and Aghel (2020) used ANFIS/genetic algorithm and neural network to predict inorganic indicators of water quality, while Yan et al. (2010) employed ANFIS model that used a number of water quality parameters to classify the water quality of major river basins in China, including Songhua River, Liaohe River, Haihe River,Huaihe River, Yellow River, Yangtze River, Pearl River,Taihu Lake, Chaohu Lake, Dianchi Lake, Qiantang River, and Minjiang River, with the model predicting approximately 90% of the river quality status.

The benefits of water monitoring and assessment

Water covers 71% of the earth surface; however, a small percentage of water is fresh and accessible for use as drinking water and other activities including irrigation. The quality of water for drinking, and use by aquatic communities, irrigation, and industry are under constant threat from pollutants which are constantly becoming a risk to both human and the natural environment (Qadri and Faiq 2020). Monitoring and evaluation of water status is essential in determining specific contaminants and their source in order to identify existing and emerging problems, analysis of trends to identify short and long-term water quality patterns, managing and preventing water contamination, design appropriate water pollution mitigation measures, for compliance with water quality standards, determining whether pollution control programs are working, inform plans and policy frameworks that improve water quality to meet designated use of water and for managing emergencies (Dansharif et al. 2023; Keiser et al. 2019).

WHO and European commission limits and their implication on the Nile water basin

Exposure to pollutants in the environment over extended period of time stretching to many decades precipitate health concerns that lead to adverse health effects on the exposed organisms. The WHO, EC, and the US EPA established internationally accepted guideline values for chemical substances based on possible health problems (Garnick et al. 2021; Tsaridou and Karabelas 2021; WHO 2011). Physical parameters like taste, odor and appearance, even at very low concentration of the contaminants of health concern may sometimes make the water unpalatable leading to rejection of water, although no guideline value has been set (Brusseau and Artiola 2019; Omer 2019). A guideline value represents the concentration of a particular contaminant below which the contaminant does not cause any significant risk to health over a lifetime of consumption. Pesticide metabolites are regarded as relevant to drinking water guidelines if it has inherent characteristics similar to those of the parent pollutant in terms of its pesticide target action or that either it or its transformation products cause a health problem to the general public (Villaverde et al. 2016). From the limits presented in Table 4, it is evident that the WHO has provided guideline values for most of the selected pollutants. Some guideline values have also been provided by the US EPA and the European Commission.

Remediation strategies in water supply and infrastructure

The presence of a pollutant substance in significant concentrations that can cause adverse effect on public health and or the environment necessitates remediation to be taken by the respective authorities in order to return the water quality from being polluted to the desired quality level (Zamora-Ledezma et al. 2021). Remediation removes contaminants, treats the affected site to convert

Table 4 Selected water quality guidelines (Baran et al. 2022; Brusseau and Artiola 2019; Dettori et al. 2022; WHO 2021)

Element	WHO limits (mg/L)	EC limits (mg/L)	US EPA limits(mg/L)
Arsenic	0.01	0.01	0.01
Fluoride	1.5	1.5	4.0
Chromium	0.05	0.025	0.1
Copper	2.0	2.0	1.3
Lead	0.01	0.005	0.015
Nickel	0.07	0.02	–
Manganese	0.08	0.05	–
Cadmium	0.003	0.005	0.005
Mercury	0.006	0.001	0.002
Nitrate (as NO_3)	50	50	10
Nitrite (as NO_2)	3	0.5	1
Aldrin and dieldrin	0.00003	–	unregulated
2,4-D	0.03	–	0.07
Eldrin	–	–	0.002
Chlorpyrifos	0.03	–	–
Lindane	0.002	–	0.0002
Methoxychlor	0.02	–	0.04
Metolachlor	0.01	–	unregulated
Benzo[a]pyrene	0.0007	0.00001	0.0002
DDT and metabolites	0.001	–	–
pH	6.5–8.5	–	–
Dioxin	–	–	0.00000003
Glyphosate	–	–	0.7

pollutants into less toxic substances and or contain the pollutants in the state they are in order to prevent them from spreading into other compartments of the environment. Water remediation strategies are either incident-specific or site-specific, taking hours to months or years and are divided into three phases that include characterization, decontamination, and clearance phases which may overlap or occur simultaneously (Kumar et al. 2019). The remediation methods include filtration, evaporation, reverse osmosis, ion exchange, redox reactions, precipitation, and electrochemical removal strategies.

Characterization phase determines the extent of contamination through the identification of contaminants, their concentration, their interaction, and mobility in the water system. Location of contaminants and the extent of contamination is determined through chemical analysis with an objective of determining the extent of remediation to be applied (Debnath et al. 2021). Once the extent of contamination and the risks are defined, appropriate water treatment methods are selected, appropriate infrastructure chosen and implementation of preferred water treatment decontamination method. Sometimes the whole infrastructure decontamination can be necessitated by contaminant properties and in situations where a large portion of the system is contaminated (Khan et al. 2021). Decontamination process extents to management and disposal of any contaminated wastes including contaminated water, infrastructure unable to be decontaminated, and or by-products generated during decontamination.

Decontamination strategies can be biological, chemical or physical. Biological approaches, commonly referred to as bio-remediation, involve the use of organisms such as plants, bacteria, and fungi to remove or neutralize pollutants from a contaminated site (Pant et al. 2021; Sharma 2020). The organisms break down hazardous substances, usually organic substances and in some cases in reducing or oxidizing inorganic substances such as nitrate into less toxic or non-toxic substances. Bacteria species such as *Pseudomonas aeruginosa* can convert mercury (Hg^{2+}) by bio-transforming it to the neutral non-toxic form (Hg) (Ma et al. 2019). Prokaryote bio-remediation of oil spills by adding inorganic nutrients to help bacteria already present in the environment to grow and multiply, consequently feeding on the hydrocarbons in the oil droplet by breaking them into inorganic compounds such as water and carbon dioxide (Baniasadi and Mousavi 2018). Some species, such as *Alcanivorax borkumensis*, are known to produce surfactants that break oil into droplets accessed by bacteria that degrade the oil (Panchal et al. 2018). Oil-consuming bacteria present naturally in water bodies before oil spills naturally bio-remediate with reports of up to 80% non-volatile components of oil degraded within the first year of spill (Bacosa et al. 2022). This form of remediation strategy has attracted significant interest with researchers genetically engineering other bacteria to consume petroleum products. Engineering of catabolic enzymes to enhance degradation rate or broaden the substrate specificity constructs organisms that accomplish numerous related or unrelated metabolic events by enhancing the likelihood and optimal performance of the process (Das et al. 2023). Similarly, genetic engineering provides genes at disposal that encode the biosynthetic pathways of biosurfactants, thus improving efficiency of the biological degradation process through enhanced contaminant bio-availability in the natural environment or through incorporation of genes on the used organism that give them resistance to critical stress factors thereby increasing survival under extreme conditions and operational efficiency of the catalyst (Imam et al. 2022; Sokal et al. 2022). Phytoremediation is a cost-effective variant of bio-remediation using plants that absorb the contaminants over time over a very large volume of contaminated environment, which therefore provides in-situ remediation without excavation (Garbisu and Alkorta 2001; Mani and Kumar 2014).

Chemical remediation such as reactive barriers introduces chemicals to remove the pollutant or make it less detrimental, which can be achieved through chemical precipitation, oxidation, ion exchange, and carbon absorption (Saravanan et al. 2021). Reactive barriers contain a permeable wall in the ground or at a discharge point with the ability of chemically reacting with contaminants in the water, some such as those made of limestone can increase the pH of acid mine drainage which is capable of removing dissolved contaminants by precipitation into a solid form (Budania and Dangayach 2023). On the other hand, physical remediation involves removal of the contaminated water and either treating with filtration or disposing of it (Saravanan et al. 2021).

Nano-remediation applies a reactive materials of various sizes ranging from 1.0 to 100 nm size which have a huge potential to decontaminate affected sites (Fei et al. 2022). This process utilizes both catalysis and chemical reduction of the pollutants of concern, ultimately resulting in detoxification and transformation of pollutants into eco-friendly forms (Fei et al. 2022). The minute size and surface coatings in nanoparticles provides a large surface area for optimal degradation efficiency in comparison to larg-sized particles, therefore making them good candidates for in-situ applications (Saravanan et al. 2021).

Conclusions

The Nile water basin has greatly influenced human settlement since the prehistoric times of human civilization. The human activities from this settlement in the Nile basin have significantly contributed towards the deterioration of water quality over time. Discharge of municipal wastes has negatively impacted on water quality as determined by the presence of pharmaceutically active compounds, high conductivity, and biochemical oxygen demand. Agriculture such as sugarcane, rice and fish farming has also contributed to pesticides, OCPs, and PCBs, in the Nile water basin. Heavy metal, one of the major contaminants of the water basin has been largely attributed to industrial activities, mining and municipal waste, with little contribution from the soil. Most of the water quality parameters in the basin are still within the recommended levels; however, caution must be paid to the high levels of cadmium, aldrin and dieldrin as reported in literature. Sediments of the water basin have acted as sinks for pollutants from their relatively high concentration as compared to the pollutants in the water column. This is an important process that limits the transport of pollutants downstream thus reducing the transportation risks. Micro-plastics, an emerging pollutant component which in entirety comes from anthropogenic activities, have also been reported in the water basin. Aquatic animals from the basin have been severely exposed to pollutants to levels that pose risks to their survival or affecting those who feed on them. These findings point to the need of instituting policies, laws and regulations to govern the management of the transboundary water resources with an aim of mitigating the already out of limits pollutants and prevent the within limits pollutants from crossing the limits. There is need to embrace water remediation strategies, and also to conduct public sensitization on the consequences of human activities on water quality.

Abbreviations

ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
BOD	Biochemical oxygen demand
CCME	Canadian Council of Ministers of Environment
DDT	Dichlorodiphenyltrichloroethane
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
EWQS	Egyptian drinking water quality standards
EU	European Union
FAO	Food and Agriculture Organization
HI	Hazard index
HQ	Hazard quotient
HCH	Hexachlorocyclohexane
NSFWQI	National sanitation foundation water quality index

NTU	Nephelometric turbidity units
OWQI	Oregon water quality index
OCPs	Organochlorine pesticides
PCBs	Polychlorinated biphenyls
TDS	Total dissolved solids
TEC	Threshold effect concentration
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorous
US EPA	United States Environmental Protection Agency
USEPA ISQGs	Interim marine sediment quality guidelines
WHO	World Health Organization
WAWQI	Weighted arithmetic water quality index

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NKK involved in writing and editing, JKK involved in conceptualization, editing and supervision, and JOA involved in editing and supervision. All authors have read and approved the manuscript.

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Availability of data and materials
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Declarations

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Competing interests
The authors have no competing interests.

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