Integrated Water Pollution Management:

Environmental Assessment, Immunological Analysis, and Hydraulic Engineering Solutions

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Abstract

Integrated water pollution management spans environmental assessment, immunological analysis, and hydraulic engineering solutions. Environmental risk characterization encompasses biological indicator screening, water quality monitoring networks, and impact mitigation through environmental impact assessment and environmental risk analysis. In immunological analysis, principles of environmental immunology examine antigen–antibody interactions for toxin and pathogen determination. Enzyme-linked immunosorbent assay applications supporting water quality examination include visually detectable and rapid test strip formats. The detection of toxins and pathogenic microbial targets showcases immunoassay strategies that span toxin classes, pathogens, and spiking samples. Hazardous Ordnance Detection Device development, performance, and detection limits are also summarized.

Immunological analysis extends beyond well-established enzyme-linked immunosorbent assays to diverse formats such as biosensors, rapid single-step tests employing functionalized magnetic nanobeads, and label-free direct detection of toxins by nanocrystal-based field-effect-transistor biosensors. Methodological sensitivity, detection specificity, deployment environment, and data reliability considerations frame suitability for environmental monitoring applications. The outlined approaches highlight the potential of antigen–antibody interactions in both traditional and novel detection schemes.

Chapter - 1

Fundamentals of Water Pollution and Integrated Management

Contemporary evidence reveals increasing breaches of natural thresholds in terms of both water quality and supplied water quantity. This temporal trend matches various international predictions that highlight both water quantity and quality as topics of growing importance in the context of climate change and environmental degradation. The impacts of such factors, along with urbanization and demographic growth, have led to changes in global water regimes in terms of both water quality and quantity. Natural events, such as drought periods or torrential rains, can shift these balances by modifying hydrological conditions and mechanisms. The questions of whether these periods remain within the realm of natural variability today—or should rather be considered as induced characteristics—and how much they alter the ecological status of water bodies and ecosystem services remain open.

Waterborne diseases arising from human, natural, and animal excrement, as well as biological agents associated with sewage and their toxins, are responsible for the death of more than 2 million persons per year. Furthermore, even if human mortality is absent, these pollution sources imply additional hospital costs and offer morbidity causes that generate a significant economic burden on a broad segment of both developed and developing countries. The situation is not only limited to diarrheal diseases but also involves other public health problems associated with the exposition to toxic compounds. Since water pollution does not respect borders, the need for solving these problems demands transboundary strategies that tackle the problems from their sources. Such strategies seek to diminish control costs by tackling pollution at its origin through preventive measures in industrial, agricultural, and urban production processes [1, 2, 3, 4].

Global Water Resources and Pollution Trends

Freshwater constitutes only 2.5% of total water on Earth. This scarce resource, only a tiny fraction of which is suitable for consumption, is unevenly distributed across the globe. Water scarcity and pollution threaten ecosystem health and human societies. Unimpaired freshwater ecosystems support essential real functions, but freshwater pollution remains a significant challenge for science and technology [5]. Water-related problems worsen with population growth and climate change. Today almost 2 billion people worldwide are exposed to fresh water that is bacterially contaminated, while at least 780 million people lack access to safe drinking water (Mirauda & Ostoich, 2018). The WHO estimates that about 4 billion cases of diarrhea occur annually and that contaminated water is implicated in about 60% of these and in 5 million deaths (Mirauda & Ostoich, 2018). The reconstruction of pollution scenarios for water—the most vital shared resource of life—is a preliminary requirement not only for reclaiming contaminated freshwater ecosystems but also for ensuring that the vital functions of the freshwater ecosystem continue to complement human activities. The decline of fresh water of high quality is not merely a concern for aquatic biota; it is a major public health issue [6, 7, 8, 9].

Classification of Water Pollutants (Physical, Chemical, Biological)

Contaminants degrading the quality of aquatic ecosystems generally fall into three categories: physical, chemical or biological. Physical contaminants include dissolved gases (e.g. oxygen, carbon dioxide, nitrogen), temperature, turbidity and light, which affect aquatic organisms — their presence, physiology and behaviour. The main chemical contaminants are nutrients (nitrogen and phosphorus), organic matter, toxicants (heavy metals, industrial, agricultural or pharmaceutical products), pathogens and energy sources. Their excessive input results in growth responses (e.g. eutrophication) that, in turn, also impact physical parameters.

Biological contaminants are usually represented by waterborne pathogens (bacteria, viruses, protozoa), harmful algal blooms and antibiotic-resistant bacteria or genes. Surrogates, such as fecal coliforms and enterococci, are commonly monitored to assess the risk of pathogenic contamination. Organic matter and nutrients, although primarily chemical parameters, also serve as energy sources stimulating microbial activity. Therefore, biological indicators are also valuable for evaluating the effects of organic and nutrient pollution. Detection of trends in indicator groups helps identify potential hazards related to fecal pathogens, algal blooms and temperature, salinity and dissolved oxygen extremes [10, 11, 12, 13].

Point and Non-Point Source Pollution

Pollution can be broadly classified into two groups, namely point and non-point sources. Point source refers to pollution emanating from a known location, such as industrial effluents or wastewater from sewage treatment plants. For instance, heavy-metal pollution and temperature increase in the river water induced by point source pollution can be easily detected. However, attribution of such pollution to a particular source can be complex. Numerical models have been widely used to ascertain pollution contribution from different sources. Non-point source pollution occurs because of diffuse pollution processes such as leaching from a watershed. Detection of non-point source pollution and identification of the contributing factors are difficult. An increase in nutrients (phosphorus and nitrogen) contributes to the seasonal dynamics of algal blooms in the aquatic ecosystem, posing hazards to the public. In addition, such blooms result in the death of aquatic organisms by producing toxins and decreasing the dissolved oxygen content in the water body. Strategies such as an understanding of the nutrient export from catchment areas, correlation with hydrometeorological variability, and detection of land cover changes have been useful in addressing these issues.

Water managers frequently attribute observed declines in water quality to land-use changes detected in catchments. Attempts to correlate such observed changes in water quality with land cover changes within the catchments of river basins have usually been limited to specific land-use classes. For example, urbanization has been recognized as an important driving force that can explain many acidification trends and heavy-metal concentrations in streams. In several catchments, microbial sources have explained the observed fecal contamination of surface waters. Although these studies are useful contributions, causative relationships between changes in water quality and land cover may be more explicitly examined using an export coefficient model approach. The results provide estimates of nutrient exports from each land-use type across a range of climatic conditions, allowing simple correlations with extensive water quality data during high-flow periods to identify the principal nutrient sources and those areas requiring management intervention. Any decline in water quality is indicated by a change in the sensitivity of a water-body health indicator to an externally imposed stressor [14, 15, 16].

Integrated Water Resources Management (IWRM) Principles

Integrated water resources management (IWRM) aims to coordinate the development and management of water, land, and related resources to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. IWRM is based on a set of guiding principles that, when consistently applied, improve water resources management at all levels. The first principle is the establishment of governance structures at global, national, and local levels to facilitate dialogue among water managers, users, and other stakeholders, sectors, and communities, and work to achieve equitable access to and efficient use of water. Governance is further strengthened when the distribution of management responsibilities is clearly defined, authorities have sufficient power and are held accountable. A second principle emphasizes the need for integrated decision-making and management across sectors, levels of decision-making, and temporal and spatial scales. Approaches that encourage science and policy integration and facilitate dialogue between governments, between sectors, and with communities help assess trade-offs, reveal synergies, and develop coherent policies and strategies that address multiple risks to water resources security. The effect of water scarcity on poverty and inequality depends on the availability, accessibility, and reliability of water resources across different groups in society.

Equitable access to water for marginalized groups, such as the urban poor, women, and indigenous peoples, must be a priority in decision-making processes and integrated into water governance systems at local, national, and regional levels. These institutions must seek to promote equity while ensuring that approaches to water resource management related to efficiency and sustainability are also reconciled. A further principle of IWRM argues for the economic efficiency of water use. Markets may be the most effective and efficient means of allocating water between sectors, while recognizing the special requirements of poor people dependent on informal economies. Implementing IWRM requires skilled human resources, including water, land, energy, and environmental specialists. Education and training at all levels, from primary through university, and in community management are essential for sustainable water management and development. Knowledge and skills should also be embodied in institutions that are active in implementing education, training, and capacity-building activities for IWRM. The principle of IWRM highlights the role of decision-support tools in facilitating the planning and implementation of sustainable water resources management [17, 18, 19, 20].

Sustainable Development Goals and Water Quality

The interrelationships between water quality and human society are expressed by the fifth target of Sustainable Development Goal (SDG) 6, which states: “By 2020, protect and restore water-related ecosystems, such as rivers, wetlands, and lakes, that contribute to water quality and ecosystem services.” Other SDG targets and associated indicators related to water quality either reflect a more direct influence on public health and ecosystem sustainability or detect an indirect impact on other SDG goals (SDG 3: ensure healthy lives and promote well-being for all at all ages; SDG 14: Conserve and sustainably use the oceans, seas, and marine resources for sustainable development; SDG 15: Protect, restore and promote sustainable use of terrestrial ecosystems; sustainably manage forests; combat desertification; halt and reverse land degradation; halt biodiversity loss). Recent observations and forecasts indicate that global water quality is still decreasing and that future scenarios predict even greater decreases as the population, urbanization, industry, and agriculture continue to grow. Such trends highlight the need for suitable and timely measures to meet benchmark requirements and restore the sustainability of aquatic ecosystems.

Water quality represents one of the most important intrinsic requirements of a water source for human health and daily living because it determines the success of global efforts to prevent disease and maintain public health. High-quality water used for food preparation and bathing is imperative for the practices of life. Malodorous water sources with polluted appearances stimulate loathing and avoidance for domestic use. Water-based diseases are considered the most regulated and growing worldwide health threat to society. Therefore, water quality directly influences whether life will flourish or decay. Conversely, intensive human activities can contribute to major influences on local, regional, and global environments and accelerations of climate change. Water quality can also indirectly reflect these changes through monitoring of specific chemical and biological indicators that incorporate the recycling of energy, nutrients, and materials among terrestrial, aquatic, and atmospheric compartments [6, 21, 22, 23, 6, 21, 22, 23].

Chapter - 2

Aquatic Environmental Chemistry and Pollutant Dynamics

The study of aquatic chemistry involves dynamics of the chemical composition of water and ambient sediments including sediment–water interactions and transformations of chemical species present in aquatic media and biota. Waterborne chemical contamination is governed not only by nature and inputs of pollutants but also by processes and factors that control speciation, bioavailability, transport, and transformation of constituents. Environmental chemistry of aquatic systems is characterized by complex, dynamic, and spatially and temporally heterogeneous reactions and processes. Environmental monitoring of aquatic media should combine determination of major physicochemical parameters with chemical speciation of key contaminants to fully characterize quality status.

Chemical processes in water determine redox conditions, speciation of inorganic nutrients, precipitation of toxic metals, sorption and bioavailability of organic contaminants, and other crucial aspects. Aquatic nutrient cycles are mainly governed by microbial activity; chemical reduction–oxidation processes contribute to dynamics of nitrogen and sulphur, whereas phosphorus cycle is more closely related to sediment processes. Degradation and transformation processes of organic contaminants in water are mainly influenced by microbial activity, while for higher-molecular-weight persistent organic pollutants the adsorption equilibrium between sediment and water influences bioavailability and controls degradation rates. Emerging and recalcitrant contaminants can affect environmental processes, function of ecosystems, and public health [24, 25, 26, 27].

Chemical Speciation and Water Chemistry

Chemical speciation governs the dynamics of chemical equilibria, processes of transport and transformation, bioavailability, mobility of sediment-associated contaminants, and their potential toxicity. Water chemistry depends largely on the concentrations of H^+ and O_2, the redox state, the presence of complexing metal cations (particularly Fe^{2+}, Mn^{2+}, and Ca^{2+}), and the influence of organic matter. pH affects several environmental processes and is often controlled by the partial pressure of carbon dioxide. In acid waters, the availability of protons may limit the formation of complexes with phosphate. The redox state plays a key role in determining the chemical speciation of bioactive solutes, the demand for oxygen, and the stability of sediments. Natural and experimental studies highlight the importance of the modification of ambient conditions on the solubility of metals. The high concentration of complexing cations during stratification provides for efficient metal sorption, whereas the lower concentration in early spring and late autumn raises the risk of metal release. The saturation status with respect to calcite influences the retention of manganese. The particulate deposition of nutrients generated by spring phytoplankton bloom contributes to their deoxygenation in deeper layers and promotes release during the subsequent stratification period.

Water chemistry affects the dynamics of several contaminants, with pH and oxygen pressure controlling the release of Mn, sediment-bound metals, and ammonium, and governing the bioavailability of phosphate and its release during stratification. The partitioning of micro- and nanoplastics in a water body can also be influenced by pH and the presence of natural organic matter. Complexation with natural organic matter increases the solubility of Cu and Pb in acidic waters, thereby contributing to the observed effects on benthic organisms. Changes in the redox state and carbon source (as exerted by the addition of acetate) differentiate the sorption affinities of several metals toward riverine biofilm [28, 29, 30, 31].

Nutrient Cycles in Aquatic Systems

Aquatic nutrient cycles are crucial pathways that govern the availability and flux of essential elements among the different environmental compartments. Nitrogen and phosphorus are the two nutrients that most frequently limit the production of algae and higher plants in aquatic systems. Eutrophication, the process of nutrient-induced over-enrichment of fresh and coastal waters leading to an increase in the rate of primary production, is of global concern due to its serious impacts on the ecology and economy of freshwater and marine habitats. Understanding the cycles of these nutrients helps identify the processes by which they are made available to aquatic ecosystems and elucidates the conditions that favour or mitigate the occurrence of eutrophication in systems.

It is recognized worldwide that a major cause of the degradation of surface waters is nutrient pollution, driven in particular by urbanization and agriculture. Excessive loading of nitrogen and phosphorus into receiving waters creates conditions that favour eutrophication. Eutrophication, especially when associated with cyanobacterial blooms, negatively affects water quality, ecosystem functioning, ecosystem service provisioning, and consequently human health and welfare. Although several nations have responded to eutrophication problems, it remains a serious issue across a wide variety of lakes and rivers. The extent of the problem and the factors that dictate the difference in sensitivity to nutrient enrichment among systems indicate that a global perspective is necessary. Once nutrient thresholds have been exceeded in water bodies, management strategies should account for them, and a range of measures—both technical and non-technical—should be used in concert for maximum effect [32, 33, 34, 35].

Heavy Metals and Toxic Elements

Heavy metal pollution represents a priority issue for many countries. Toxic elements can enter aquatic systems through increased weathering, mining and smelting activities, mixed sewage discharges, and urban and industrial runoff. Toxic elements such as mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), copper (Cu), nickel (Ni), and chromium (Cr) are toxic not only to aquatic organisms, but also to terrestrial and human health and occur frequently in Environmental Quality Standards. Toxic elements can damage enzyme and organelle function, even at very low concentrations. Toxicity may result from interactions with sulfhydryl (-SH), amino (-NH2), hydroxyl (-OH), carboxyl (-COOH), and phosphate (-PO4) groups.

Heavy metals can be incorporated into water samples through various geo-chemical processes such as leaching and weathering, surface runoff, spraying of pesticides, herbicides and fungicides on and near water bodies and industrial effluents, which haphazardly increases the concentration of these metals in natural water bodies. Moreover, they undergo sediment deposition and, due to their bioaccumulation potential and toxicity, exert harmful effects to human health. The greatest threat to mankind comes from heavy metal pollution because of their non-degradability. Thus, frequent monitoring of aquatic systems is essential for efficient management [36, 37, 38, 39].

Organic Pollutants and Emerging Contaminants

Organic compounds form the largest and most diverse category of water pollutants, encompassing natural molecules such as sugars and fatty acids, as well as synthetic chemicals. Pharmaceuticals, personal care products, illicit drugs, per- and polyfluoroalkyl substances (PFAS), chlorinated hydrocarbons, benzene derivatives, insecticides, herbicides, and many other organic compounds have been detected in sources, drinking water, and treated effluents. The majority of these contaminants are neither target compounds nor regulated by existing frameworks, yet their chronic presence raises concerns about human health and aquatic ecosystem integrity. A particular group of organic pollutants comprises emerging contaminants—compounds that have recently come into use and for which monitoring data are still scarce, but for which health or environmental risks exist or could occur in the future if present concentrations were to increase.

Pharmaceuticals, personal care products, and illicit drugs enter aquatic environments primarily via sewage effluents, often in concentrations ranging from ng L−1 to μg L−1. Concentrations in influents are usually higher than in receiving waters, but occasional peaks may occur when stormwater or groundwater transport diluted raw sewage into streams. Despite low predicted no-effect concentrations, the chronic nature of exposure may lead to developmental disturbances, evolutionary effects, and endocrine-disrupting activity. Indeed, pharmaceuticals and personal care products, together with their transformation products, were found to stimulate dimethylsulfoniopropionate production in contaminated sediments and, as a result, sulfurophane production in fish larvae, with subsequent ecological and ecotoxicological consequences. Consequently, preventive measures—as applied successfully in Germany—should be developed to reduce pollution from legitimate medicinal use. Emerging classes of pollutants, such as nanomaterials, should also be addressed. Organic pollutants in sediments and biota should preferably be monitored via bioassays, ideally supported by passive sampling of sediment pore water and surface water [40, 41, 42, 43].

Fate, Transport, and Transformation Processes

Contaminants in aquatic systems undergo a series of processes influencing their movement and degradation: sorption to sediments and colloids, transformation due to biological and abiotic processes, advection along water flow, dispersion resulting from concentration gradients, and bioavailability to aquatic organisms. Fate, transport, and transformation processes jointly determine pollutant concentrations, both in the water phase and in living organisms.

The mobility, residence time, and ecological risks associated with chemical substances are inherently linked to spatial and temporal variation in aquatic systems. Advection is the lateral movement of water that plays an important role in the transport of contaminants in rivers and streams; in lakes, it takes place via spatial advection and vertical mixing usually driven by wind. Key processes governing the movement of contaminants in running waters include advection rate and the hydrodynamic dispersion (lateral and vertical spreading) in the water body. Dispersion occurs when the concentration of a substance is not uniform due to a concentration gradient, as happens when nutrient-rich water enters a relatively clean water mass. Contaminants concentrated in specific volumes of water are thus dispersed into larger volumes of water with lower concentrations, decreasing concentrations at a faster rate than dilution would alone. Dilution alone would produce a slower decrease in concentration [44, 45, 46, 47].

Chapter - 3

Microbial and Biological Contaminants in Water Systems

Water is a universal solvent and plays a key role in the geochemical cycle of many elements. Macro- and micronutrients required for growth are supplied by water, which is consumed for energy and as a refrigerant. In addition to these primary functions, water acts as a medium for the transport of organisms, living and dead, nutrients and metabolites, and during metabolic activities, and hence, certain biological tears, excrements, and diseased organisms are released into the water; there is always a seasonal or cyclical discharge of pathogens into the water, carried by the runoff from urban as well as rural areas.

The waterborne transmission of disease is determined by the presence of pathogens, and consequently, much of the emphasis of water protection has been directed toward their removal and control. Microbial and biological contamination is broadly defined to include pathogens and intestinaocal and enteric viruses in fecal contamination, total and fecal coliform organisms as indicators of fecal pollution, enterococcus group of organisms, and intestinal protozoa in other waters. Despite advances in treatment technology and implementation of high-quality standards, illnesses resulting from microbial pathogens in water resources continue to be recognized as a serious global health problem [48, 6, 32, 49].

Waterborne Pathogens (Bacteria, Viruses, Protozoa)

Although pollutant removal is of paramount importance for public health, it is the presence of pathogens that is considered the "ultimate water-quality test" for drinking-water supplies. The three main groups of waterborne pathogens, namely bacteria, viruses, and protozoa, differ greatly in terms of origin, survival strategies, opportunities for human exposure, and infection modes. The increasing awareness of public health risks associated with pathogens in water systems and natural reservoirs has led to a great number of studies; key information on important groups of pathogens is summarized here.

Pathogenic bacteria, viruses, and protozoae continue to threaten human health, additionally spreading antibiotic resistance. The risk associated with residual bacterial infections is even lower than that of viruses and protozoa due to the efficacy of conventional treatments. Pathogenic viruses have a low infectious dose (10–100) and the absence of a culturing method to monitor their presence hampers the assessment of their occurrence in water systems. Protozoa, due to their complex life cycle involving cysts, oocysts, and trophozoites, are resistant to conventional treatment [50, 51, 52, 53].

Biofilms and Microbial Ecology

Biofilms are spatially structured microbial communities easily found in nature consisting of microorganisms attached to a surface and encapsulated in a polymeric matrix. Such biomasses are numerically important in nature. In every small unit volume of river water, there are tens of thousands of bacteria, but in river sediments or on any submerged surface, there can be many millions of bacteria in just a small piece. Consequently, most of the bacteria involved in the biochemical transformations of organic matters are found in biofilms. Biofilms usually exist on surfaces submerged in freshwater, saltwater or even in a liquid layer formed by a humid atmosphere. Biofilms can be found everywhere in nature such as on rocks, submerged woods, roots, animal shells, plant leaves, ship hulls, moist internal surfaces of walls, glass surfaces, and in nature exhibit a very rich architecture and diversity.

Recent research showed that biofilms are greater resistant to antimicrobial agents than uncolonized cells. In the last decades, different environmental stresses and challenges such as temperature increase, nutrient load, salinity change, and copper introduction were investigated in response of natural micro-biofilm communities using both operational taxonomic units (OTU) composition and functional profiles of both bacterial and viral communities. In some studies microbial ecology has been described in reactor studies, however studies focusing on natural biofilms growing on submerged surface are more frequent in recent years. In natural ecosystems, biofilms developed on solid surfaces submerged in freshwater or saltwater environments are an indispensable part of microorganisms at different environments [54, 55, 56, 57].

Algal Blooms and Cyanotoxins

Explosive cyanobacteria proliferation in freshwater environments represents a major ecological stress and, if toxin-producing species are involved, can pose a serious health threat to humans, reptiles and mammals. Although certain climatic, chemical, geographical and hydrological conditions favour their growth, these blooms also require contamination from organic matter. Toxins produced by some cyanobacterial species can be neurotoxic, hepatotoxic or cytotoxic; the most frequently reported are microcystins, saxitoxins, anatoxins and cylindrospermopsin. Non-cyanotoxin-producing species can also have toxic effects; these metabolites are poorly defined and a major challenge in the field. Risk can be assessed by identifying blooms and quantifying their toxic potential through determination of the toxin classes. Phycocyanin concentration, detection of toxin-producing species and molecular markers of toxicity in model organisms enable risk assessment.

Monitoring is dictated by the intended use of the water; detection and quantification of specific toxic metabolites is essential for aquatic ecosystems and human consumption, whereas detection and quantification of potential toxic species is sufficient for recreational water. Management relies on a combination of proactive measures and mitigation techniques, which can involve use of specific algicides, systems for treatment of large volumes of water, strategies for controlling nutrient input and water-level management. A combination of management options may be required to address these blooms effectively [58, 59, 60, 61].

Antibiotic Resistance in Aquatic Environments

Antimicrobial resistance (AMR) is a significant threat to modern medicine, as therapeutically important agents become ineffective and increasingly fail to treat common infections. Recognized as a global public health issue, AMR kills over 700,000 people each year. The emergence and spread of AMR bacteria are affected by many factors, including human health, animal health, food security, and the environment. The absence of sufficient sanitation and hygiene infrastructure allows AMR bacteria to spread in the environment, particularly in low-and middle-income countries. These areas serve as a reservoir for resistance genes, which can be transferred to pathogenic bacteria via horizontal gene transfer. Aquatic environments also act as pathways for disseminating resistant bacteria, as fecal material contaminated with resistant microbes enters freshwater and marine systems through urban runoff, sewage and wastewater discharge, and stormwater drainage.

Unlike terrestrial environments, aquatic habitats promote the natural ecology of aquatic microbes, including bacteria with the potential to resist antibiotics. Estuaries and coastal zones receive a continuous supply of fecal matter from human settlements, agriculture, and aquaculture. If poorly treated, wastewater discharges can pose an ecological and public health hazard by transmitting pathogens and antibiotic-resistant bacteria. These bacteria may originate in coastal tourism areas, where excessive antibiotic use in healthcare and agriculture selects for resistant strains. Aminoglycoside, sulfonamide, and tetracycline resistance genes have been detected in pathogenic and non-pathogenic environmental bacteria that inhabit estuarine and coastal waters. Flooding and heavy rainfall further facilitate the spread of antibiotic resistance in the environment [62, 63, 64, 65].

Biological Indicators of Water Quality

Aquatic environments naturally host diverse pro- and eukaryotic microorganisms, whose interactions determine ecological balance and community health. Microbial communities reflect environmental conditions, enabling their use as biological indicators. Sensitive organisms record changes from human influence, while stress-resistant taxa, species assemblages, and functional groups indicate habitat quality and quantifiable impacts.

Microbial communities integrate chemical, physical, and biological properties into a unified indicator, allowing exposure risk quantification. Aquatic systems respond rapidly to driver changes, revealing short-term climatic effects and increasing disease susceptibility. Bacterial communities within macroinvertebrate guts indicate hotspot ecosystem health. High bacterial loadings indicate anthropogenic input, while shifts of sensitive taxa suggest stress. CyanoHAB blooms result from nutrient enrichment, supported by population surveillance and toxin analysis.

Resistance of faecal protozoa and viruses to environmental factors enables their application as sanitary hazard indicators. Habitat quality assessment considers response-function metrics from a range of organisms across planktonic, benthic, and fish assemblages, enabling ecosystem risk evaluation via environmental drivers. Recent developments include assessed and confirmed E. coli molecular markers for exposed-water quality deterioration. Biodiversity, disease, and gene presence–absence matrices describe various habitats. Two addressed indicator types aid specific experimental design—disease-biomarker expression constitutes a quantitative indicator, while the presence of antibiotic-resistance genes in aquatic bacteria characterizes qualitative risk stages [66, 67, 68].

Chapter - 4

Environmental Assessment and Water Quality Monitoring

Assessment of the aquatic environment consists of detecting the carefully selected parameters thought to indicate the patterns of the water quality change over space, time or both. Recently, there has been a growing interest in remote sensing monitoring. In principle, it enables real or near real time monitoring but remains costly for long term performance. Different approaches to irregular distributions of sampling points are being researched. Such networks can be used for the development of predictive systems or for aiding risk assessment frameworks.

An accompanying aspect of environmental assessment is determining the potential impact of a planned activity on water quality, using the Environmental Impact Assessment (EIA) framework. In this context, special care should be taken at the scoping stage to clearly define the boundaries of the future study area and the temporal window. Elements of the baseline studies that follow require special attention as they provide the basis for qualitatively and quantitatively predicting changes in the quality of the aquatic environment, for developing a monitoring programme, and for defining mitigation actions. The development of effective categories for describing impacts on water quality constitutes an important step in facilitating these tasks.

The basic environmental monitoring concepts relate to the physical and chemical parameters and biological indicators of water quality. A list of major physical and chemical parameters for water quality monitoring is provided, along with the appropriate sampling protocols and quality controls required for reliable measurements. Along with the standard, widely used indicators such as dissolved oxygen, conductivity, turbidity, ammonium, nitrates, and phosphates, other indicators provide added value when assessing the state of the aquatic environment. In addition to traditional ecological indicators (for example, phytoplankton assemblage structure and composition), new players give further insight into the aquatic environment's state [69, 70, 71, 72].

Physical and Chemical Water Quality Parameters

Water quality monitoring necessitates determination of physical and chemical parameters that reflect the general condition of water. Defined by quantitative or qualitative characteristics, physical parameters include temperature, pH, turbidity, color, and electrical conductivity. Determination of physical parameters enhances data interpretation and informs the selection of water quality indicators and analytical methods for water monitoring and analysis.

Temperature influences the distribution of aquatic organisms. Reductions in water temperature due to thermal pollution affect fish hatching and reproduction. pH indicates pollution, indicating contamination risk by metals, ammonia, and fecal coliforms. High turbidity supports pathogen survival and disease outbreaks. Attenuated light penetration combined with low pH stimulates algae growth, producing toxins and reducing aquatic life. Increased turbidity reduces light penetration, impacting aquatic organisms. Elevated water color reduces photosynthesis and affects aquatic resources. Supersaturation with carbon dioxide disturbs fish physiological processes. Electrical conductivity, a measure of ionic composition, predisposes aquatic systems to toxicity and disease outbreaks.

Chemical parameters help evaluate water quality in terms of public health, environmental protection, ecosystem integrity, tourism potential, and recreational facility safety. Selection depends on land use, population density, climate, and industrial and natural activities in adjacent areas. Regulatory standard requirements, pollution impact assessment, and monitoring program goals inform parameter selection. Combining multiple data sets strengthens analysis reliability. Sampling collection, transportation, storage, and analysis are crucial for data accuracy. Quality control ensures precise results. Recommended physical and chemical parameters, along with sampling protocols and surrogates, facilitate reliable water quality assessment.

Water quality can be assessed through biological monitoring techniques that use molecular markers expressed by organisms responding to pollution stress. Compared to conventional techniques, molecular methods are cheaper, faster, and simpler. They include microbial community structure analysis, assessment of biological activity based on carbon metabolism, and detection of specific pathogenic microbes through molecular markers, multibiomarker indices, and toxicity testing [73, 74, 75, 76].

Biological Monitoring Techniques

Biological monitoring techniques assess water quality through living organisms. Microbial community responses to changes in environmental conditions offer embedded indicators of pollution levels. Although microorganisms are effective for risk assessment, testing requires taxonomic expertise, time, and costly facilities. As such, molecular methods using specific sets of molecular markers in model organisms are ideal for Water Pollution Control Programs.

Bioassays using neonate Daphnia, fish embryos, crustacean and fish larvae, and algae rapidly assess water samples for biological effects. The most sensitive test detects all toxic agents, including those not indicated by chemical analyses. Changes in phytobenthos, phytoplankton, and zoobenthos composition reflect water pollution well. Algal and bacterial indicators are sensitive to toxicant concentrations and cumulative effects of contaminants sampled in early developmental life stages. A suite of freshwater bioassay tests is being developed to increase the number of potential biomarkers and to assess the effects of contaminants at various biological organization levels, from communities to populations, individuals, and sub-organismal entities.

Biological monitoring contrasts with chemical assessments by revealing history and total water quality. Detection of pathogenic organisms, microbiological parameters, and toxic strains is essential for assessing risk to users, as addressed in the EU Water Framework Directive. Advancements in molecular biology enable identifying organisms in environmental matrices and characterizing gene expression responses to environmental stress, both of which factors facilitate elucidating the effects of contaminants on metabolic pathways and whole organisms [67, 52, 77, 78].

Remote Sensing and GIS Applications

Remote sensing technologies produce spatially distributed data that inform regional and global environmental studies. In water quality research, remotely sensed indicators improve monitoring network efficiency and guide management decisions. Remote sensing is particularly suitable for largescale land-covermapping, which is indirectly related to water quality, or for modeling terrestrial processes, such as nutrient transport. However, descriptors remotely sensed or compiled at the watershed scale can directly affect water bodies. Across a range of environments, the integration of remote sensing and in situ data is increasingly being used to assess river water quality.

Geographic information systems (GIS) are able to integrate data from diverse sources into a common format and combine them based on common geographical features. GIS-based water quality modeling commonly employs either a topdown or a bottom-up approach. In the top-down scenario, a water quality monitoring network with limited sampling frequency is directed toward crucial areas for pollution risks. In the bottom-up strategy, different pollutant loads and relevant sources at various watershed locations are identified and finally aggregated. Both approaches allowWater Quality Index maps to be drawn to guide the installation of a comprehensive monitoring network. The main goal is to establish a system that can detect water quality changes in a timely manner to prevent the spread of pollution over long distances [79, 80, 81, 82].

Risk Assessment Frameworks

Risk assessment combines hazard identification, exposure assessment, and dose–response characterization to calculate risk thresholds. The hazard analysis considers the entire set of chemical species associated with primary contamination sources, including natural and anthropogenic emissions. This stage is deterministic, identifying all potentially toxic contaminants, while temporal and spatial distribution patterns are integrated in the next step.

Environmental sampling serves as the basis for quantifying the exposure potential of specific affected receptors, and the results—expressed as environmental exposure metrics—enter the dose–response modeling framework to complete the risk characterization.

Two distinct but interlinked approaches may be used to apply a risk-calculus framework in relation to water pollution: a pollutant-centered approach that focuses on the spatial and temporal dynamics of toxicity in water systems and a receptor-centered methodology that examines the exposure risk associated with specific toxicity groups. The former may comprise all election, set, and pavings steps to yield quantitative metrics that clarify hazard dynamics and govern risk management. The latter detains its attention to the exposure elements, employing the primarily generated hazard pool to quantitatively assess specific toxicity-related receptors or groupings of interest. With relatively simple alteration, therefore, the comprehensive methodological outfitting can be flexibly applied to bias broadly across stressor reclamation [83, 84, 85, 86, 83, 84, 85, 86].

Environmental Impact Assessment (EIA) in Water Projects

Environmental Impact Assessment (EIA) systematically examines the consequences of proposed projects on environmental, social, and economic conditions and mitigates adverse effects. Scoping identifies impacts requiring detailed investigation, while the final EIA is integrated into the decision-making process. Screening determines the need for a full EIA. EIAs ensure that potential environmental degradation is considered before approval and implementation.

Although not specific to water quality, the EIA process encompasses multiple water-related dimensions and considers water pollution, water table drawdown, flooding, and biodiversity loss due to human activities. EIA guidelines advise EIA practitioners on the scale and scope of hot spots and potential pollution from development and construction operations. Scoping identifies crucial issues and assigns them to specialists for examination. Baseline studies provide information for assessing the project’s significance and for future reference. Potential impacts must be identified and appropriate action to mitigate them planned before project clearance [87, 88, 89, 90].

Chapter - 5

Immunological Methods in Water Pollution Analysis

Immunoassays are powerful and sensitive diagnostic tools that capitalize on the natural recognition capacity of antibodies to quantify antigens of interest. Novel immunodiagnostic devices operated by different biological reaction modes providing shortened test designs were developed mainly with biomedical and pharmaceutical analysis and confirmed with aquatic environmental testing. Enzyme-linked immunosorbent assays (ELISA) are predominant in environmental analysis, but time-consuming multi-step processes with waiting times of several hours severely limit sample throughput.

Testing for bioactive substances and biological indicators of water pollution by rapid immunoassays and biosensors represents an important experimental direction facilitating water quality monitoring and risk assessment. Such rapid tests can generally be applied when qualitative results or semi-quantitative estimations of pollutant concentrations are required. Indicative results can be effectively obtained in a shorter time span, and consequently, a larger number of samples can be tested. Immunoassay methods allow for detection of toxic compounds and pathogenic microorganisms in diverse environmental matrices. Detection limits for most common pathogens are in the range of the infectious doses for a healthy population [10, 91, 92, 93].

Principles of Environmental Immunology

In the field of water quality monitoring, immunological methods rely on antigen-antibody interactions for the detection of specific substances in a sample. The binding of an antibody to its respective antigen occurs with a high degree of specificity and is the basis for a variety of assays used in environmental testing. Immunoassays have been extensively applied for the detection of pesticides, herbicides, organic and inorganic pollutants, pathogens, toxins, and viruses present in water. The measurement of immunological parameters may involve either individual assays or a combination of several assays performed on a single sample and encompass a multitude of marker molecules.

Immunoassays are particularly useful in detecting target analytes that are either present at low concentrations or require fast turnaround times. The principal design features of immunoassays include an understanding of the nature of the antigen–antibody interaction, the choice of antigens, probes, and detection methods, and the determination of appropriate controls. However, interpretation of the results may be complicated by cross-reactivity or matrix effects. An overview of the principles of immunoassay development is provided, along with specific examples highlighting typical application areas. The primary focus of the discussion is to identify immunoassay scenarios addressed in water testing and elucidate the associated capabilities and limitations [94, 95, 96, 97].

Antigen–Antibody Interactions in Water Testing

Water quality immunoassays exploit the strong affinity between antigens and antibodies to detect chemical markers and biological contaminants. The links formed between an antigen and its specific antibody are generally non-covalent, reversible, and highly specific. Covalently bound haptens on a polymeric matrix represent the solid phase, whereas antibodies may be immobilized on a solid substrate or bio-labeled for signal development. The ability of these assays to bind multiple targets is useful for identifying complex mixtures. The very qualities that make the antigen–antibody interaction ideal for immunoassays also impose some limitations. The generation of a reliable test is a complex procedure that requires prior selection and characterization of a suitable antibody.

Various popular detection methods can be used in immunoassays, including Bioluminescence (BL), Radioimmunoassay and chemiluminescent immunoassays. Bioluminescence is a method with high sensitivity, but relies on the careful selection of suitable labelled substrates. Radioimmunoassays, despite having the highest sensitivity of all detection methods, are also the most costly and hazardous. Their use has mostly been restricted to a research environment due to the need for expensive γ-spectrometric equipment and special licenses for handling and discarding of radioactive materials. An important disadvantage also lies in the fact that actual samples cannot be tested, and that considerable times and efforts are required to label both the hapten and the secondary antibody [98, 99, 100, 101, 102].

Enzyme-Linked Immunosorbent Assay (ELISA) Applications

Detection of toxic substances and pathogenic microorganisms in water is essential for protection of public health and prevention of environmental risks. Conventional detection assays, such as bacterial cultivation, are often time-consuming and may yield false-negative results. Immunochemical methods that use specific antigen-antibody interactions offer rapid and sensitive alternatives for a range of targets. ELISAs are the most common format, embracing several variations and applications.

The findings of various studies employing ELISA for detecting pollutants in water systems are presented. Shooting assays enable detection of multiple targets, including metals, antibiotics, phthalates and organophosphorus pesticides. Surface plasmon resonance imaging automates detection of trace-level mercury. Alternatively, fast ELISAs coupled with microfluidics reduce reagent requirements and enhance timing. ELISAs combined with on-line enzyme microreactors extend application to dissolved-state biotoxins. Besides insects, analytes ranging from proteins to viruses and bacterial cells are quantifiable.

Some detection targets deserve special mention due to specific relevance to water systems. Level and form of adenosine and its deamidated product have implications for monitoring, health risk assessment and bioremediation of cyanobacterial blooms. Patulin in drinking water poses serious health hazard. Occurrence of Shiga toxin 2 in food and water requires joint efforts to control E. coli O145 in environment; and quality control protocols for beverages, including fruit juices, should encompass detection of this toxin [103, 104, 105, 106].

Biosensors and Rapid Immunoassays

Conditionally labeled antibodies (e.g., probes) are immobilized on the sensor surface. Antigen specificity is ensured by probe–antigen interaction, while analyte quantity is measured via the intensity of a secondary signal produced by the immobilized probe or by a dendrimer conjugate. Electrochemical (amperometric or impedimetric) detection of an enzyme-labeled probe is a widely used approach, along with fluorometric detection of optical reporter molecules (quantum dots, organic dyes, etc.) and direct electrochemical detection of redox/alkaline phosphatase- and peroxidase-conjugated probes. Detectino of marker molecules of waterborne pathogens (viruses, protozoa, bacteria) is critical for public health. Required sensitivity is ≤102–103 PFU/ml for viruses. Rapid assays (≤5 h analysis time) making use of magnetic separations, multispectral fluorescence scanning of multiplexed probes, and pen-shaped ultra-compact prototypes demonstrate the highest speed/facility of analysis. Electrochemical detection of viable fungi from drinking water has also been reported.

Direct operation potential is crucial for electrochemical detection, while the effect of nonspecific signal on the determination performance must be evaluated and minimized. Rapid tests for detection of microcystins and saxitoxins in contaminated water are also available. Several biosensors for determination of antibiotic residues in water are based on inhibition of enzymes, antibodies, and pathogens. Rapid immunoassays (≤2 h analysis time) using colorimetric detection of magnetic separation-based biosensors, multiplex detection of several target analytes using spherical-structured lenses, and optical strips and portable pen structures are considered particularly suited for on-site applications. Colorimetric assays are also among the most common methods for revealing viral pathogens in wastewater [107, 108, 109, 110, 111].

Detection of Toxins and Pathogenic Microorganisms

The detection of pathogens and toxic compounds in contaminated waters is essential for assessing environmental quality and safeguarding human health. Various immunoassay methods are applied to identify waterborne toxins and indicator organisms of faecal pollution, with performance metrics supporting detection reliability. Enzyme-linked immunosorbent assays (ELISAs) have been developed for a wide range of analytes—including viral pathogens, bacterial toxins, and cyanobacterial metabolites—in different water sources. Other immunoassays target pathogenic bacteria and protozoa in environmental samples. Contaminated waters are also tested for the presence of antibiotic-resistant coliforms, enterococci, or Escherichia coli.

Detection ranges and limits of detection depend on sample type and the substrates used for antibody production. Tests for pathogenic microorganisms in drinking water and river water commonly use polyclonal antibodies. These enable quantification at desired concentrations with low detection limits. The ready availability of conjugated antibodies simplifies the preparation of immunoassays for other important waterborne pathogens. Such tests meet the need for simple, sensitive, and cost-effective methods of detection.

Chapter - 6

Molecular and Advanced Diagnostic Tools

Polymerase chain reaction (PCR) represents a highly sensitive and specific method for the detection of pathogens and their genetic material in water. It has been widely applied in the detection of various bacterial, viral, and protozoan pathogens, and is increasingly used for fungal detection. Because pathogens are often present at low concentrations in environmental compartments, quantitative PCR approaches are used to obtain more accurate embarrassments of pathogen concentrations. Quantitative PCR relies on internal controls, contamination prevention, and quantification standards. A range of organisms, including viruses, bacteria, protozoa, and fungus, have been targeted by PCR for the detection of waterborne pathogens. The technique has also been applied to freshwater and marine samples for microbial biodiversity studies. Metagenomic studies frequently combine PCR techniques with amplicon sequencing approaches to assess the taxonomic structure and functional composition of microbial communities in various environments. These rely on high-throughput sequencing technologies and bioinformatics packages. The use of quantitative PCR in water testing requires carefully designed species-specific primers or probes with no amplification of closely related non-target species. An appropriate control must also be included to detect false negatives.

Metagenomic studies employ high-throughput sequencing technologies on environmental DNA libraries, and bioinformatics analyses are used to reveal taxonomic structures and infer environmental drivers, metabolic potentials, and ecological interactions. Such studies provide insights into the variety of microorganisms present in a specific ecosystem at a given time and assist with understanding community variation in response to environmental changes. The application of next-generation sequencing approaches has revolutionized the understanding of the metabolic capabilities and ecological functions of microbial communities in different environments. Microbial community analysis has increasingly broadened from profiled members to functional capacity, and from single microbial groups to whole microbial assemblages, exploring the drivers and consequences of microbial community assembly. The response patterns of microbial communities to environmental shifts associated with different time scales have also attracted much attention [112, 113, 114, 115, 114, 112, 115, 113].

Polymerase Chain Reaction (PCR) in Water Testing

Polymerase chain reaction (PCR) is a powerful method enabling sensitive and reliable detection of the genetic material of microorganisms. Extensively applied in water testing, PCR must be adapted to the specific environmental context and tested with the same sample matrix before being routinely used. PCR is essentially a reproduction process that uses a DNA polymerase, the enzyme responsible for synthesizing DNA molecules. With increased sensing power, PCR is now also germane to water quality rather than solely health risk assessment, applied to fish, mussel, and sediment samples as well as fecal-origin bacterial markers in waters. The PCR principle is to reproduce a specific segment of the genome in sufficient quantity to enable detection and identification.

In a general PCR work plan, selection of the target DNA sequence is accompanied by the design of specific primers (short oligonucleotides) capable of binding to the template only at that region. Matched pairs of primers characterize the reaction, which relies on three sequential steps: denaturation, annealing, and extension. After repeated cycles, the amount of DNA doubles after each cycle, yielding several billion copies in just a few hours. The procedure is quantitative when real-time PCR is employed: specific probes fluoresce upon binding and are detected continuously during amplification, producing a sigmoid plot connecting the quantity of target DNA in the sample and the number of cycles needed for its detection [116, 117, 118, 119, 120].

Metagenomics and Microbial Community Analysis

Metagenomics enables sequencing of entire environmental DNA samples without prior culturing of organisms. It has emerged as a powerful tool for analyzing microbial community composition, diversity, and function in natural and engineered ecosystems. Terminal restriction fragment length polymorphisms (T-RFLP) and next-generation sequencing allow for high-resolution taxonomic assignments. Analysis of distribution patterns of specific groups can aid in community management. When linked to advanced bioinformatics, metagenomics can also provide valuable functional information. Data have been obtained for a growing range of ecosystems and conditions (e.g. biogeographic, climatic, biochemical, nutrient content, saline, seasonal variations, etc.). This knowledge base can thus allow microbial communities to be selected and applied to bioprocesses for which they are best suited. These tools have been employed for the consecutive analysis of acid mine drainage (AMD) biofilms associated with pyrite oxidation, studying microbial communities involved in the bioleaching of volcanic rocks, sequencing bacterial DNA from polluted water bodies, and examining the interaction between cyanobacteria and salinized soil.

As a high-throughput approach, metagenomics allows deep sequencing of DNA originating from entire microbial communities by conjuring all microbial DNA present in an environmental sample—be it a soil, sediment, or water sample—and then analyzing the communities inhabiting that habitat. Such sample treatment ensures that MetaGenomic signatures for rare and abundant taxonomic/functional groups are captured. Using this approach, microbial life in extreme environments (acid mine drainage, petroleum reservoirs, high-temperature environments) has been studied, with T-RFLP Pyrosequencing, 454-Pyrosequencing, and whole-genome studies identifying the presence and biogeographical distribution patterns of methanogen communities in permafrost. MetaGenomics, along with metatranscriptomics, has also been successfully applied for the simultaneous study of several environmental parameters/impacts like primary production, diversity, abundance, salinity, pH, observed-and-expected OTUs, ACT-CT, and soil methanogenesis in summer and winter.

Biomarkers of Environmental Exposure

Molecular biomarkers of environmental exposure comprise nucleic acids, proteins, antibodies, or metabolites that respond to pathogenic agents or contaminants present in environmental matrices and show a correlation with effects at different biological organization levels (cellular, organ, organism). Environmental exposure biomarkers can provide quantitative, semi-quantitative, and qualitative measurements of the exposure level and their functional status. Foreign compounds (e.g., metals, persistent organic pollutants, radionuclides) and/or their metabolites may accumulate in the organism and/or biological fluids, and their levels reflect contamination severity and stress response. For example, increases in malondialdehyde (an end product of lipid peroxidation) associated with cellular injury reflect the risk of cancer development. Oxidative stress is an important mechanism of environmental exposure. Additionally, DNA mutations makeup important links between environmental alterations and human health. Nucleic acid profiling can detect genetically modified organisms (GMOs) in seeds and foodstuffs, pathogens in water, and antimicrobial-resistance genes in bacteria.

Proteins, i.e., the products of gene expression, are also classic biomarkers of environmental exposure. In this sense, overexpression of heat-shock proteins (HSPs) in fish has been linked to polycyclic aromatic hydrocarbons (PAH) in sediments, while common carp fed high PAH-content diets have shown a response reflected in a set of fluorescent proteins. Antibodies can be detected in blood or serum by serological methods, and their estimates may indicate contact with the pathogen at the group level or each individual. Antibodies specific for Vibrio cholerae in water can identify areas at risk of cholera outbreaks. Enzyme activity is also detectable in different tissues and can indicate health status.

Proteomics and Toxicogenomics

Proteomics profiling provides valuable information on the expression of proteins in complex environmental matrices, enabling the detection of cellular responses to chemical exposure. Toxicogenomics employs DNA chips to correlate genotoxicity with transcriptional changes of a large number of genes, identifying potential mechanisms of action and biological pathways affected. The complex nature of mixtures often results in additive or even synergistic effects that cannot be anticipated from individual response dosage curves. Toxicogenomics provides insight into both the nature and level of exposure and the underlying mechanisms of observed effects. Environmental complexogenomics offers a holistic approach to assessing potential risks from contaminated environments.

Metabolomic profiling provides information on primary and secondary metabolites, revealing the physiological status of organisms as well as cellular responses to environmental changes, making it a useful tool for monitoring toxic events (e.g. blooms). Together with bioaccumulation data, toxicogenomics can distinguish between internal and external factors influencing gene expression. Combined proteomics–toxicogenomics–metabolomics studies enable detection of hypoxic conditions and optimization of response to election of a competent aquaculture management plan [121, 122, 123, 124, 122, 121, 123, 124, 121, 122, 123, 124].

Nanotechnology-Based Detection Systems

Recent advances in nanotechnology have paved the way for highly sensitive and portable detection systems based on low-cost chemical/biochemical reactions or virus-induced processes. Nanomaterials—materials with dimensions less than 100 nm—demonstrate unique optical, electrical and biological properties. Nanomaterials included in these technologies are mainly carbon-based nanomaterials (or nanostructures), metallic nanoparticles/metal-based nanostructures, magnetic nanomaterials, semiconductor nanomaterials and biological nanomaterials. Several nano-based detection systems, such as electrochemical, colorimetric, surface-enhanced Raman scattering and fluorescence-based systems, are attracting significant attention and are being increasingly used in pathogen detection. These nano-based detection systems also utilize advanced characterization techniques for convenient and proper detection. Commercially available nano-based detection kits for bacterial and viral pathogens are gradually emerging, with optimally designed properties. Some of the kits are still under validation for field tests and are expected to be commercially available soon. However, the introduction of these nano-based detection systems into the market requires comprehensive studies of the toxicity, stability and safety of the nanomaterials used in the assays, along with examination of the regulatory requirements for biosensors and biochips. Such research should be pursued before the practical application of nano-based detection devices surfaces in the near future.

Nanotechnology has the potential to play a fundamental role in enhancing the efficiency of water purification and treatment via diverse processes designed for the removal of different pollutants including microorganisms. Nanoparticles hold great promise for simultaneous analyte detection and removal from aqueous systems and for real-time monitoring of water quality, leading to the development of next-generation intelligent technologies for water purification and detection, also enabled by nanostructured materials such as nanocomposites, aerogels, membranes, nanosheets, etc., which are highly suitable for adsorption, catalytic degradation and disinfection tasks. The field is still in its infancy, with many research directions to explore and numerous breakthroughs needed. The technical challenges associated with the deployment of such advanced nanotechnological approaches, especially in real operational conditions, cannot be neglected [125, 126, 127, 128].

Chapter - 7

Hydraulic Engineering Principles in Pollution Control

For all water bodies, the hydrodynamic and hydraulic residential properties are important for integrated water quality, sedimentology, and pollution load monitoring and modeling. The hydrodynamic characteristic will regulate the horizontal and vertical mixing, as well as the residence time. The residence times will thus govern the dispersion and dilution of river estuaries and coastal areas; in contrast, the short residence times in most rivers are critical for pollutant reduction.

Surface water pollution control requires mathematical modeling of flow and pollutant dispersion–dilution. The long surface residence time, thermal stratification, and density reversal of lakes and reservoirs could influence vertical mixing. Integrated hydrodynamic and sediment transport models are essential to assess the deposition–remobilization processes of fine particulates, as sediment can act as a source as well as a sink. Several hydraulic structures, such as groins, basins, and reservoirs, can intercept and reduce pollution spread, with optimum design being crucial. Stormwater management–quality enhancement is also an important part of integrated water pollution control systems [129, 130, 131, 132].

Hydrodynamics of Rivers and Lakes

Flow regime, mixing processes, and residence time are considered fundamental hydrodynamic characteristics of express rivers, lakes, and other water bodies affecting dispersion and transformation of pollutants. Fluvial systems are usually characterized by high velocities and shallow depth, leading to a linear flow regime and short residence times. Lakes and reservoirs are known for extended retention periods, intensity of vertical mixing, accumulation of sediments, and therefore, potential for pollutant settling and transformation. For such water bodies, longitudinal dispersion is dominant in during summer stratification, whereas temperature-driven vertical mixing may enhance horizontal dispersion during spring and autumnal turnover.

The study of river hydraulics involves examination of water flow, sediment transport, and interaction of both processes. Water flow is characterized by distribution of velocity and depth, while sediment transport by a sequence of sediment sizes. Analyzing sediment transport dynamics is crucial for pollution studies, because many contaminants bind with particulates. Pollutant concentration in sediment is often a good indicator of sediment-associated pollution risk for aquatic organisms [129, 133, 134, 135, 136].

Flow Modeling and Pollutant Dispersion

Hydrodynamic models describe water body dynamics under various conditions and predict contaminant transport. Many options are available for one-dimensional flow simulation in rivers, canals, estuaries, and lakes, with diverse selection criteria. Dispersion of pollutants in the water column is described using advection–dispersion equations, with parameters derivable from remote-sensing data and dispersion coefficients obtained from experimental studies. Two-dimensional models have been developed for lakes, combining sedimentation and diffusion processes of the water column with hydrodynamic processes using different approaches. Major urban water bodies in developed regions can be modeled discretely in three dimensions, addressing density-driven circulation, tidal flow, wind action, and their interaction.

Three-dimensional hydrodynamic models are increasingly used to explore the response of lakes to climate change, but have only recently been applied to estimate water quality and pollution response. The change in response surface within a volume reflects the varying conditions under which water can pass through that volume. Computational fluid dynamics (CFD) models are employed to simulate flow in smaller water bodies over shorter time durations, and can also be used to study the interaction of flow with submerged structures such as cylinders, groins, and bed forms [137, 138, 139, 140].

Sediment Transport and Contaminant Binding

Sediment represents the largest component of suspended solids in surface water, generally accounting for >50% of all mass in water-bodies. Natural sediment transport is a consequence of runoff and rainfall. This associated sediment can contain a wide variety of pollutants, such as heavy metals, nutrients, and organic matter. Sediment can reside in reservoirs, lakes, and some quiescent river areas for some extended period before being flushed downstream. Sediments in river sections with channel constrictions such as bends and reservoirs where velocity decreases and sedimentation occurs can act as buffering zones by capturing pollutants from the water column. Besides, in more contaminant-rich areas of lakes and reservoirs, sediments can reintroduce contaminants into bottom waters when dissolved oxygen conditions become favourable for diffusive exchange. This nutrient, or contaminant, release from sediments can be very toxic to aquatic organisms.

Siltation is one of the major factors limiting the efficient functioning of reservoirs. The transport of sediment also controls the transport of pollutants. Pollutants, due to their particle-reactive nature, can be associated with sediment particles during transport and can be bound into the sediment under varying conditions. Transport, deposition, resuspension, and consolidated sediment release govern the binding and unbinding of pollutants and thus their fate and bioavailability in aquatic environments. The bioavailability of sediment-associated contaminants is a major factor determining the level of risk posed to aquatic organisms and human health. At the sediment-water interface, the sediment may act as either a source of or sink for the overlying water [141, 142, 143, 144].

Stormwater Management Systems

Stormwater management systems must ensure appropriate quantity and quality of water supply in urban areas during normal weather conditions. During rain events, the systems should absorb rainfall, avoid accumulation of excess water on the surface, and mitigate flooding. Natural ground surfaces can absorb, move, and store the rainwater in the soil or underlying layers, but areas covered with impermeable materials like concrete and asphalt prevent this process. The stormwater that flows over these surfaces, known as runoff, can carry sediments and pollutants into nearby water bodies without treatment during this transport. Runoff generated in one part of a catchment may quickly arrive, while other areas may not have received any rain. It is, therefore, different in both time and space from the natural rainfall.

During storm events, rainfall usually starts with some initial intensity, remains constant or reduces to a lower intensity, and then stops. The surface cannot absorb all the rainwater at the beginning, and thus runoff is generated. This early peak in runoff reaches receiving water bodies quickly. As the rain continues, the garbage on the surface gets washed off and is carried to the nearby drain, causing pollution to receiving water bodies. The volume of runoff will continue to increase and reach a maximum stage at some point of time. After this peak, the duration of rainfall reduces the runoff flow rate, although it may still be generally maintained until the rain ceases. Stormwater management systems should be designed, sized, and constructed based on these considerations to ensure proper functioning [145, 146, 147, 148].

Hydraulic Structures for Pollution Mitigation

Groins, weirs, settling basins, retention ponds, bioengineered banks, and other hydraulic structures can mitigate riverine and lake pollutant loads. Groins reduce sediment dilution effects, slowing river flow, enhancing pollutant sedimentation, and increasing residence times for chemical pollution load diffusion and biodegradation. Weirs also dampen river flow and lake retention, increasing pollutant deposition. Settling basins capture fine sediment and adsorbed pollutants, while retention ponds trap coarse sediment and relevant surface runoff contaminants. Bioengineered banks that counteract bank erosion support sediment-bound, suspended, and dissolved pollutant interception and retention.

Groins and spur dikes can limit mixing in a river reach and enable sediment to settle out of the water column. Mud deposits flat, rough-surfaced, and unstable estructures that increase knee-break-wave activity and produced gradient-influenced motion. In a curve, the longest wave length grows steep and produces an increasing sediment-backward-velocity profiel. The sediment limitation can also be observed along meandering rivers with slow erosion tendency and non-aggressive non-eroded river banks [149, 150, 151, 152].

Chapter - 8

Wastewater Treatment Technologies

Wastewater treatment technologies can be divided into primary and secondary treatment processes. Primary treatment relies on physical mechanisms to remove suspended solids and floating materials, while secondary treatments use biological methods to eliminate biodegradable organic materials. These systems normally allow approximately 90% reduction of biochemical oxygen demand (BOD). For advanced treatment, additional systems like membrane filtration, advanced oxidation processes like ozone, and peracetic acid can be integrated to overcome the drawbacks of conventional methods.

Effluent from industries, distilleries, and food-processing industries have characteristics suited for pretreatment technologies, and those technologies should ideally be adopted. Ecological treatment has gained importance, as it is a natural and cost-effective method of waste conditioning. However, these techniques have not been applied in India on a large scale. Progress has been limited to pilot-scale studies. A conceptual design for an industry-specific treatment plant based on resource recovery has also been proposed [153, 154, 155, 156].

Primary and Secondary Treatment Processes

Primary treatment processes remove suspended solids and a portion of biodegradable organic matter from wastewater. Screening and grit removal eliminate debris and large particles, while primary sedimentation tanks use gravity to separate settleable particles. By now, most coarse organic debris (e.g., influent tissues) have started to disintegrate. The remaining organic substrate, which is mainly colloidal and dissolved material, is partially removed by the relatively short hydraulic retention time (HRT) of primary tanks. During secondary treatment, heterotrophic organisms grow and flourish in the organic-laden effluent and utilize the residual substrate.

These microorganisms are classified as readily biodegradable material, the organic fraction that is capable of being assimilated into new cellular tissues at a rapidly accelerated rate and used for growth by the biomass maintained in a biological wastewater treatment system. It is generally accepted that the parent material is readily biodegradable when its BOD5/COD ratio exceeds 0.4. In addition to organic carbon, these microbial species require nutrients (nitrogen and phosphorus) for growth. The residual effluent enters in the secondary treatment unit that follows for further purification by biological means. The biological process is dependent on the natural schutzgut in the effluent, with plenty of dissolved oxygen (DO) supplied simultaneously for respiration [157, 158, 159, 160].

Biological Treatment Systems

Biological treatment systems exploit bacterial metabolism for wastewater detoxification. Removal mechanisms include carbonaceous substrate utilization, nitrogen removal via nitrification and denitrification, and phosphorus accumulation. System configurations fall into three major categories: activated sludge, attached growth, and bioreactors, each with numerous variants. Treatment efficiencies depend on operation, specification, and environmental influences. Key performance indicators include biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total suspended solids (TSS), coliform bacteria, total nitrogen (TN), and total phosphorus (TP). Condition-specific guidelines also exist for the discharge of treated sewage and effluents from individual household systems.

Activated sludge systems combine waste sludge with fresh effluents in an aerated tank to form a microbial mass that metabolizes the wastewater and is then separated. These tank systems are further categorized as conventional, extended aeration, contact stabilization, or cyclic activated sludge, depending on their sludge retention times. Attached-growth systems utilize bacterial colonization of support media to enhance population density. Moving-bed biofilm reactors enable greater mass transfer by immersing the media in the liquid, and hybrid systems combine concepts from both categories. Anaerobic digestion processes mineralize sludge into digestate and biogas, while membrane bioreactors achieve advanced treatment through combination with microfiltration [161, 162, 163, 164].

Advanced Oxidation Processes (AOPs)

Other processes based on the generation of hydroxyl radicals are combined in a group of advanced oxidation processes (AOPs). Hydroxyl radicals are strong oxidants (E◦ = +2.80 V vs. NHE at pH 7.0) and react with many molecules; it would blast more things than ozone. Because of their short half-lives (∼10−9 s), they cannot be used in bulk transport processes, but their formation in situ at a local distance from the target molecules has been a key factor in many AOPs. Hydroxyl radicals are produced, for example, in Fenton processes ('H2O2 + Fe2+ → Fe3+ + HO˙ + OH−); in AOP involving the combinations of ozone, UV radiation, and hydrogen peroxide; and by photolysis of hydrogen peroxide. Other radical processes that could be classified as AOP may include the UV/cationic uncoupler process.

AOPs have been extensively studied for their capability to oxidize organic pollutants in wastewater. Because of their high energy, these processes could deal with both nitro and azo moieties. The only drawback in these systems is economic. While the hydroxyl radicals produced in a reductive environment could be responsible for the removal of the majority of organic pollutants at low chemical costs, those generated in an AOP system are always of a high chemical cost and implementation cost due to the use of Ozone and H2O2 [165, 166, 167].

Membrane Filtration Technologies

Membrane filtration encompasses microfiltration, ultrafiltration, nanofiltration, and reverse osmosis processes that employ semipermeable membranes for separation. Membrane materials, configurations, surface characteristics, operating conditions, fouling tendencies, and permeate quality delineate specific membrane types. Development advances have enabled membrane applications in water and wastewater treatment, desalination, and resource recovery pursuits. Membrane fouling poses a foremost design and operating constraint, degraded permeate quality, and increased operation costs. While membrane cleaning and replacement mitigate these drawbacks, solid-liquid separation, removal of macromolecules, and high ion rejection processes are typically coupled with advanced oxidation or biological treatments.

Microfiltration separates particles larger than ~0.1 μm, with permeate quality precluding further treatment. MF membranes typically comprise polyolefin, polysulfone, ceramic, or composite materials. Typical applications target separation of microorganisms, turbidity, and suspended solids from drinking water; prefiltration for reverse osmosis and ultrafiltration; clarification of effluents containing high organic loads; and removal of large molecules such as protein, starch, and dextrin. Microfiltration fouling is minimized with hydrophilic membrane surfaces, turbulent-flow operations, backflushing, immersed membrane modules, optimal transmembrane pressure, and cooler feed water.

Ultrafiltration membranes operate at moderate pressure differentials to separate macromolecules or particles larger than ~1–10 nm from the aqueous phase. They are typically polymeric but can also be ceramic, metal, or polysaccharide-based. Common applications involve production of beers and alcoholic beverages; removal of polysaccharides and proteins from solutions; juice and dairy product clarification; treatment of oily wastewaters; concentration of dyes; and separation of VSS from activated sludge. Permeate quality is improved by combined MF/UF in series operations. Membrane fouling is minimized by immersion in bioreactors, addition of dispersants into feed, and periodic cleaning.

Nanofiltration membranes are selective to multivalent ions, with charge playing a major role in ion separation. Typical applications involve removal of low molecular weight compounds such as biocides; separation of organic solvents without significant loss of water; and separation of metal ions in metal finishing or plating effluents. Factors that can reduce membrane fouling include coupling with biological or advanced oxidation processes, consideration of specific fouling mechanisms in design, and periodic cleaning.

Reverse osmosis employs dense membranes to separate permeants and remit solutes, exhibiting negligible solute permeability. Typical applications encompass seawater desalination; concentration of fruit juices, cane, and beet sugars; recovery of pure water from reverse osmosis brines; and treatment of battery, pharmaceutical, and pulp black liquors. Membrane fouling is minimized by pre- or post-treatment, loading adjustment, cross-flow design, and use of hydrophilic membranes.

Sludge Management and Resource Recovery

Sludge management and resource recovery from wastewater are essential components in optimizing treatment efficiency and minimizing potential pollution. The management of sewage-derived sludge or biosolids is necessary with respect to both economic and environmental considerations, since the treatment of municipal wastewater is performed primarily to alleviate its harmful effect on receiving bodies but also results in the generation of solid residues that require treatment and disposal. Research on this topic has been extensive, but a synthesis of the findings on newly explored areas remains a valuable addition to the field.

Sludge, also referred to as biosolids, is produced during the biological treatment of wastewater. If adequately treated and stabilized, biosolids can be reused in agriculture and land reclamation or converted into energy, thus lowering treatment costs. The facilitation of resource recovery is a step beyond conventional disposal. Such approaches, however, require investment and may not be adopted, for example, in industrialized countries where land disposal of treated biosolids still represents the cheapest option. Nevertheless, recent experimental and modeling work has shown that new plants dedicated to biosolid management can be economically rewarded—hence, new strategies can be explained to a wider audience [168, 169, 170, 171, 168, 169, 170, 171].

Chapter - 9

Industrial Effluent Management

Industrial sectors are significant contributors to water pollution, with discharges often being highly toxic. Industrial effluents contain a variety of contaminants, including organics, solids, salts, oils, heavy metals, and pathogens. Industrial processes where these toxic substances are used include chemical manufacturing, dyeing, electroplating, paper, food, and leather. The types of constituent sources vary, and knowledge of the industrial process is essential for establishing an appropriate plan for pollution control. Pretreatment, reuse in the industrial process, and cleaner production are common methods for mitigating the pollution potential of industrial wastewater.

Industrial pollution constitutes a significant portion of the total pollution in many countries. For water quality management, it is imperative to maintain industry within the framework of the prevailing environmental conditions. Environmental audits for specific industry sectors are crucial to achieving the desired objective. Industries that cannot be envisaged with zero discharge during the audit must identify suitable pretreatment facilities. Major pollution-generating units should operate zero-liquid-discharge treatment systems. Different processes for various industries—such as tanneries, textile dyeing and finishing, paper, petrochemical, pharmaceutical, and paint industries—must also be audited.

Compliance with receiving water-body standards is essential. The complete set of industrial discharge limits cannot be prescribed, given the fact that industrial effluents are neither general nor homogenous. Route by which toxic substances can reach water bodies, and the extent, is studied to facilitate control. Bioassays are conducted for toxicology assessment using *in vitro* and *in vivo* systems. The gaps, if any, are filled with complementary tests [172, 173, 174, 175].

Industrial Pollution Sources and Characteristics

Water quality degradation originating from industrial effluents has been a worldwide concern. Industrial discharge monitoring is fundamental and rarely performed directly on-site. Hence, a generic comparison of industrial pollution sources gives valuable information for regulatory authorities when pollution surveillance should be emphasized. Pollution sources are classified according to the nature of the industries generating the effluents. Industries ranging from food and beverage to wood processing are included. Several effluent parameters widely reported in the literature are compiled, and ranges for these parameters are proposed. Parameters of greatest concern according to their multiple occurrences in the effluent description in the literature are emphasized.

Industrial effluents have become a major source of water pollution. Non-industrial sources of pollution are often heavily regulated, and main industrial sources of pollution are well known. However, there is still little support for the regulatory management of industrial pollution. Effluent concentrations from a wide range of industrial operations are summarized on a source-by-source basis. Included are food products and beverages; wood and wood products; fossil fuel processing; textile, leather, and rubber products; chemicals, synthetics, plastics, and other synthetics; metal processing; mineral processing; miscellaneous persons' services, public administration, and defence; and domestic sources.

Pretreatment and Cleaner Production

In addition to on-site wastewater treatment, industrial effluents should also be subjected to pretreatment within the premises of industry. This is particularly applicable for large polluting and hazardous industries. Primary as well as secondary treatment of these effluents should be carried out separately, so that the investment cost of installation and operation of treatment plants can be minimized. The following objectives are generally considered while planning for the pretreatment of waste: Reduction of load on the treatment plant at the downstream end; Avoidance of toxic effects; Reduction of costs of treatment; Minimization of the formation of toxic sludge during treatment; Facilitation in the recovery of valuable constituents from the waste, such as, metals, etc. Prevention of the contamination of raw materials and products produced from their use.

Like pretreatment, successful implementation of cleaner production techniques also significantly reduces industrial pollution load in the appropriate receiving body. Cleaner production is a proactive, preventive approach to environmental protection, which eliminates or reduces the generation of pollutants at source rather than treating them after generation. Cleaner production is the continuous application of an integrated preventive environmental strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment. Cleaner production eliminates or reduces the hazardous substances in the waste and emissions, thus diminishing the risk for human health and the environment. Fundamental to cleaning production is the recognition that most of the waste and emissions can be avoided by changing processes or substituting raw materials. As a part of the cleaner production strategy, manufacturing process may be changed, more environmentally friendly alternative materials may be used or product design may be altered [176, 177, 178, 179].

Zero Liquid Discharge (ZLD) Systems

Zero liquid discharge (ZLD) refers to a wastewater management approach aiming to maximize the recovery of water from wastewater and minimize the wastewater disposal volume such that no liquid effluent is discharged from the treating plant. A ZLD process entails the following five key steps: (1) pre-treatment, (2) desalination, (3) crystallization, (4) (optional) resource recovery, and (5) post-treatment and reuse of waste streams.

Every ZLD system should be adequately pre-treated to remove unwanted materials that may foul, scale, or adversely affect downstream processes. Key components of a typical pre-treatment system include: coarse screening; oil-water separation; grit removal; equalization; neutralization; dissolved air floatation; membrane filtration with ultraviolet radiation; coagulation and flocculation; dissolved air flotation or micro-filtration; and chemical precipitation.

In general, the primary objective of the ZLD process is to produce high-quality distillate, but maintaining a reasonable yield is also important to ensure optimal energy consumption. With all its advantages, the ZLD process also has some shortcomings, including high operational costs, frequent scaling of evaporators, low performance at low temperature and pressure, fouling of membrane modules, and high capital costs. These drawbacks can, however, be overcome by optimizing the process and using low-cost substituent materials [180, 181, 182, 183].

Toxicity Assessment and Compliance Standards

Toxicological assessment of industrial effluents is vital to ensuring the suitability of water for various uses. Comprehensive analyses evaluate the presence of not only conventional pollutants but also synthetic chemicals, trace metals, biological agents, and antibiotics. Non-compliance indicates a lack of environmental safety, which can lead to toxic illnesses or disease outbreaks. Toxicological assessment is therefore a prerequisite for the establishment of discharge standards needed for the issuance of consents under the Water (Prevention and Control of Pollution) Act, 1974, as well as for continued monitoring.

Compliance-testing has gained momentum for its role in identifying toxic effluents. While the factor-of-safety approach, established through laboratory studies and experience, has been helpful in the past, evolving awareness on the nonspecific impact of toxicants—and their potential for synergistic or antagonistic interactions—has necessitated a paradigm shift. This has led to a growing emphasis on toxicity-testing with a view to assessing real-time impact on exposed biological receptors. Toxicity-testing correlates the discharge of effluents with biological receivers, thereby assessing effectiveness during all stages of the life cycle, from embryo to adult, in a defined ecological niche for a defined time—detecting the impact of a combination of natural and anthropogenic perturbations, toxins, and biological responses through signal transduction. To ensure environmental efficacy, an acceptable-risk criterion needs to be estimated, considering exposure levels, receptor response, and physiological dose–response relationships [184, 185, 186, 187].

Case Studies in Industrial Wastewater Control

Within one of the world's most industrialized areas, the rapid expansion of industry has led to increasing degradation of waterbodies and aquatic life, severely threatening the health and livelihood of local communities. In many cases, existing monitoring protocols fail to adequately regulate the environmental impact of industries; for instance, single-hazard screening for toxicity fails to recognize the interactive effects of chemicals. Tailored wastewater treatment technologies that align with hazard and pollution profiles are thus crucial for effective industrial pollution control. This requires the assessment of industrial pollution sources and characteristics, separation of toxic and non-toxic waste streams, adoption of best practices for cleaner production, and exploration of zero-liquid-discharge technologies.

The need for tailored treatment solutions is highlighted by the case of an 18,000 m3.h−1 copper and cobalt mine and processing facility in Zambia. Here, a combination of biological treatment and activated carbon adsorption achieved >95% removal efficiencies for phenols, phenolic compounds, and heavy metals. Another case concerns an effluent treatment plant for an integrated textile-processing cluster in Ahmedabad, India, where extensive characterization revealed the presence of multiple textile-processing-related classes (acid dyes, alkali dyes, reactive dyes, disperse dyes, surfactants, and other organic pollutants). A bioassay-directed approach further revealed that the major mutagen was 1-amino-2-naphthol-6-sulfonic acid, leading to the recommendation of a two-stage treatment process involving periodic advanced oxidation processes for color reduction and an eco-friendly biological process for full mineralization and detoxification [188, 189, 190, 191].

Chapter - 10

Agricultural Runoff and Nutrient Management

Agricultural activities are essential for food production while posing major pollution risks to surface and ground waters. Fertilizers, pesticides, and manure waters constitute substantive inputs to aquifers and watercourses, largely via leaching, runoff, and erosion pathways. In drainage basins, these loads contribute toward eutrophication and associated ecosystem degradation. Best management practices (BMPs) targeting fertilization, pesticide use, and soil and water conservation need to be implemented for pollution reduction. Constructed wetlands and vegetated buffer zones along flow paths are also effective mitigation measures. Sustainable irrigation systems that minimize runoff generation and facilitate water reuse show great promise for nutrient and pathogen pollution control.

Agrikultūrcomplementary technologies are shifting production toward more sustainable approaches. Precision farming aims to optimize the application of nutrients and pesticides, often using remote sensing technology to assess crop needs. Remote sensing is also being applied to monitor winter cover crops, ensuring that these are grown in a manner to help mitigate nutrient leaching and runoff contamination. Indeed, the continuation of these best management practices and new approaches, such as the incorporation of vegetative filter strips into drainage systems, will be necessary to maintain the water quality integrity of the surrounding environment, particularly for lakes in nutrient-rich areas [192, 193, 194, 195].

Fertilizers and Pesticide Pollution

Modern agriculture has made significant advances in crop yield per unit of land; however, intensive cultivation has increased demand for fertilizers and pesticides. Fertilizers contain two macronutrients, nitrogen and phosphorus, that stimulate plant growth and yield.

Alongside herbicides and insecticides, fertilization faces heavy regulation because nutrient leaching leads to bloom-forming algal species and hypoxic–anoxic events in receiving waters.

Fertilizer application per hectare of arable land in the last three decades has increased worldwide by 110%. The total amount of phosphorus produced was 49 million metric tons in 2021. Due to insufficient monitoring, fertilizers and pesticides still flow into water bodies with their residual effects. Nutrient leaching stimulated widespread research on sources of inland-water degradation, finding that human-induced disturbances explain more than 80% of hypoxic–anoxic events, with sewage and agricultural runoff the main sources. These sources are accompanied by current climate trends that provide severe flood events with high pulse runoff, leading to spatiotemporal distribution of nutrients in river basins, reservoirs, and lakes.

Therefore, nutrients are still the major polluting group since 2000. Agency-categorization statistics place fertilizers among water pollutants and leaching of phosphorus from soils enters as an important trigger of eutrophication. This review highlights the state of knowledge on supports for BMP execution, adaptation costs, and the implementation of action plans for nutrient reduction and landscape improvement in Europe [196, 197, 198, 199].

Eutrophication Mechanisms

Eutrophication is a complex process that can cause increased algal growth and changes in community composition of aquatic ecosystems, which often leads to a cascade of symptoms such as reduced transparency, generation of objectionable odours and tastes, and at times fish kills. Eutrophication affects environmental stress at the base of food webs, and therefore fish communities can be impaired by a reduction in food supply. Anoxia subsequent to algal blooms and a decline of higher animals can also cause fish kills. Such pollution can also endanger animal and human health through the production of toxic compounds by certain genera of algae. The definition of eutrophication has evolved over the years, with the latest version from the OECD describing it as the “elevated biological productivity of an aquatic system due to nutrient enrichment”, with symptoms of accelerated ageing.

Nutrient controls, particularly for phosphorus, are the most widespread means of ameliorating or preventing eutrophication in receiving waters. However, euphotic-zone-integrated concentrations of nitrogen have often shown a stronger relationship to changes in water quality compared to those of phosphorus. It is therefore surprising that, despite these correlations, far more is known about phosphorus enrichment than that of nitrogen. The understanding of aquatic ecosystems is being complemented by studies at the metagenomic level; however, despite the wealth of information being generated these experimental studies of natural systems often lack context. Allochthonous remineralization processes have taken place since the evolution of multicellular organisms but the quantitative fluxes associated with these processes in distinct environments are not well documented and these have been shown to be important under certain conditions [200, 201, 202, 203, 200, 201, 202, 203].

Best Management Practices (BMPs)

Are a component of an overall nutrient management strategy that focuses on the implementation of specific measures to reduce nutrient inputs. BMPs are effective practices recognized by scientific research. They are well documented, effective with respect to pollution prevention, and are economically, socially, and environmentally acceptable. BMPs are implemented by farmers and ranchers in every major agricultural area and in a variety of cropping and animal production systems. BMPs can be applied to a wide range of environmental concerns. They are designed to mitigate impacts on air, water, land disturbance, wildlife habitat, and fish habitat, and to enhance aesthetics. Best management practices include nutrient management, soil conservation, wetland restoration, integrated pest management, irrigation management, livestock grazing management, nutrient conservation management, erosion control, and flood control. Such practices can be recommended for use in any area where they will be effective.

Soil best management practices reduce the amount of sediment and nutrients that leave fields via erosion. Minimizing sediment loss protects water quality. Educating farmers about reductions in farm operation costs is an effective way to recommend a BMP. Different alternative best management practices fit different areas based on agro-ecological conditions. Nutrient leaching losses pollution control management manages nutrient discharges. Phosphorus and nitrogen pollution can be reduced using different specific approaches. Reducing nutrient leaching from land requires a combination of agricultural, plant cover, and soil BMPs carefully designed to match specific soil conditions with the nature of the applied fertilizers. Best management practice investments should be concentrated in those parts of a watershed where their contribution to pollution prevention is greatest, and should be aimed at addressing the factors that most affect pollution load [204, 205, 206, 207].

Constructed Wetlands and Buffer Zones

Pollution of water resources from non-point sources remains a serious challenge for water quality management. In particular, during periods of high rainfall, stormwater runoff is often heavily contaminated with sediments, organic matter, nutrients, heavy metals, hydrocarbons, pathogens, and other pollutants, leading to negative impacts on receiving waters and their biota. Constructed wetlands and shallow pond systems represent an effective alternative for managing stormwater quality and quantity, both through reduction of pollutant loading into sensitive water bodies and by interception and treatment in engineered systems. They can also function as passive buffer zones for water bodies, ensuring that water that enters through surface or subsurface flow into areas adjacent to streams, rivers, or lakes is treated before re-entering the water environment. These approaches, which complement conventional stormwater management systems, are increasingly being considered for application in rural and suburban land zones.

Constructed wetlands are designed as either surface-flow (SW) or subsurface-flow (SF) systems, the first modelling the appearance, treatment, and functioning of natural wetlands, while the second consist of rows of coarse materials, such as sand, gravel, or crushed stone, with domestic or industrial wastewater diverted into them for treatment. SW systems rely mainly on physical, chemical, and biological processes to remove nutrients (nitrogen and phosphorus); oils and greases; heavy metals; and organic micropollutants, such as fragrances, pharmaceuticals, and personal-care products) present in complex mixtures. By contrast, SF systems act as non-saturated biological reactors through which the incoming wastewater moves downward and outward [208, 209, 210, 211].

Sustainable Irrigation Systems

Sustainable irrigation encompasses multifaceted methods to reduce water waste, optimize nutrient use, minimize pesticide runoff, and recycle wastewater. Such strategies can bolster crop production even as overall irrigation water resources become scarcer. Traditional surface irrigation offers limited control over application amounts and timing, affecting both crop and water resources. On the other hand, pressurized systems like sprinkle and drip irrigation improve water use efficiency (WUE) up to threefold. Nevertheless, strong environmental and resource conservation needs require broader and more comprehensive efforts. These include adopting water-saving irrigation scheduling based on environmental balances, reducing fertilizer use but keeping fertilizer efficiency high, minimizing pollution, using soil moisture retention agents, forsaking surface irrigation during wet months, establishing winter cover, alternating wet and dry irrigation, and correcting on-site distribution efficiencies

Rainwater harvesting and alternatives to conventional irrigation, such as subirrigation, partial rootzone drying, and specially designed irrigation subbases, have received much attention. Scheduling irrigation based on soil moisture levels allows a greater reduction in water use than traditional ET-based scheduling methods while sustaining crop yield. Sound crop management, such as altering planting and harvesting times to mimic nature, and applying irrigation water directly to the root zone rather than to the overall field are further effective approaches [212, 213, 214, 215].

Chapter - 11

Urban Water Pollution and Stormwater Control

Rapid population growth in Indian cities contributes to environmental degradation, with increasing impervious area intensifying runoff and pollution. An integrated stormwater management framework emphasizes sustainable natural drainage patterns and water quality monitoring during design, construction, and operation.

Haphazard, uncontrolled urbanization degrades natural drainage systems and alters hydrological characteristics, leading to chronic waterlogging and enhanced flooding frequency and volume. Construction and subsequent failure of drain infrastructure draws groundwater closer to urban areas, with harm to people, property, and ecology. A major urban stormwater management concern is the quality of runoff from impervious surfaces—roads, roofs, paved parks—and the associated sediment load discharging into receiving waters, affecting aquatic ecosystems and public health. Creative engineering aims at redirecting stormwater to landscape areas for biofiltration of pollutants and sediment before recharging groundwater or discharging into receiving bodies.

Rain-induced runoff is typically smaller in volume than during other seasons, but usually contains the highest pollutant loads. Increasing runoff volume reduces residence time and increases dilution, while high flow velocities exert erosive forces. During rainfall, water quality monitoring of pollutant concentrations in receiving waters reveals the nature and health risk posed by drainage emanating from urban land [216, 217, 218, 219].

Urbanization and Impervious Surfaces

Rapid urbanization and population growth have led to the expansion of cities and urbanized areas. Increased growth and heightened demand can result in the tributaries of rivers and lakes within urban and peri-urban areas receiving greater pollution loads and more frequent ecological disturbances. The increase in impervious surfaces (e.g., roads, pavements, roofs, buildings) often alters the density, frequency, volume, and timing of surface runoff from urban and peri-urban catchments. Generally, drainage water from urbanized areas collects and is disposed of as quickly as possible to minimize urban flooding and reduce hazards within these areas. As a result, the time lag for urban rainwater runoff transport is small, runoff coefficient is large, natural buffers are destroyed, and the concentration of pollutants in the runoff is higher than in the runoff from non-urbanized areas. Although impervious surfaces make a significant contribution to urban expansion, only in recent decades has their importance for the hydrology of urbanized areas and the potential for pollutant export to receiving water bodies been recognized.

Urbanization often accelerates the degradation of river water quality. Because of the great increase in stormwater runoff brought about by urbanization, combined sewer overflow (CSOs) has become a common problem in major urban centers where combined sewers still exist. During heavy rains, the initial stormwater runoff, which accumulates a high load of pollutants during the dry period, is usually discharged directly to receiving water bodies without prior treatment. Because urbanization reduces the time for stormwater accumulation, the concentrations of the transported pollutants become increasingly higher and can pose serious health risks to the exposed population. The pollution levels of receiving water bodies during CSOs are thus orders of magnitude higher than during dry weather conditions [220, 221, 222, 223].

Combined Sewer Overflows (CSOs)

Combined sewer overflows (CSOs) represent the discharge of untreated or partially treated wastewater from combined sewer systems—or networks that transport both stormwater and sewage—to surface water bodies during heavy precipitation events and as a result of high inflow and infiltration (I/I) rates. CSOs occur when designed flow rates for wastewater treatment plants do not meet hydraulic conditions in a treatment network. Thus, when flow capacities of collection systems and treatment facilities are exceeded, CSOs can result in catastrophic public health risks and ecosystem service degradation in receiving water bodies. CSO controls involve a combination of gray and green infrastructure projects—including wastewater treatment plant upgrades, flow diversions to treatment works, and implementation of low-impact development practices.

Early detection of CSOs is primarily based on flow-monitoring systems. Control technologies include real-time control systems for integrated wasteload allocation in CSO-affected networks and flow control structures to protect receiving water bodies during extreme precipitation events. CSO prevention and mitigation actions are achieved using low-impact development techniques that mimic natural hydrology by preserving predevelopment drainage conditions in urban areas, thereby decreasing the volume, peak flow, and pollutant loads in surface runoff. Examples of low-impact development applications include bioretention, rain gardens, permeable pavement and concrete, green roofs, and vegetated swales [224, 225, 226, 227].

Green Infrastructure Solutions

Urbanization and the proliferation of impervious surfaces intensify stormwater runoff and accelerate pollutant accumulation in water systems. Combined sewer overflows (CSOs) remain a challenge, discharging untreated effluent during heavy rainfall. Green infrastructure presents a natural, multifunctional alternative, promoting the retention, infiltration, and purification of runoff. Proposed constructs include permeable pavements, bioswales, rain gardens, green roofs, and constructed wetlands. Applications of these solutions need careful design, monitoring, and management, while integrating low impact development strategies can enhance overall effectiveness.

A growing approach to urban drainage emphasizes the integrated design and synergy of all components. Smart drainage systems combine real-time monitoring, modelling, and management for performance optimization. Green infrastructure has been successfully demonstrated in several pilot projects and proof-of-concept studies across the globe. Implementing such systems complements conventional grey infrastructure, reduces urban flooding and CSO events, enhances ecosystem services, and improves resilience to climate change impacts. Pilot installations, supported by monitoring, modelling, and decision support, help guide future implementations [228, 229, 230, 231].

Low Impact Development (LID) Strategies

Urbanization induces considerable hydrological changes in terms of increased surface runoff and reduced time of concentration, ultimately leading to a higher risk of flooding, stream bank erosion, and water quality deterioration. The traditional ‘rainwater drainage’ design concept has been gradually replaced by the Low Impact Development (LID) approach, which seeks to closely mimic the natural hydrological cycle through the development of an integrated stormwater management system. LID comprises a set of strategies focused on pollutant load reduction in urban areas with a high percentage of impervious surfaces, thereby attempting to minimize the negative impacts of urbanization on natural water bodies.

Although the adoption of these practices is likely to require a higher initial economic investment and involve a complicated design and implementation process, many types of LID structures are gaining popularity in different parts of the world, from rainwater gardens, porous pavements, and green roofs to swales, vegetated canals, and other bioswales. The LID approach can be broadly considered in three steps: determine a central stormwater management goal; identify the potential LID elements that can be integrated into the region for the desired control; and estimate the effects of the combined set of selected elements on stormwater quantity and quality.

Smart Drainage and Monitoring Systems

The global explosion of urban centers, particularly in developing economies, has led to the proliferation of impervious surfaces. Despite various design approaches, drainage systems remain passive and incapable of acting upon climatic, hydrological, and urban development forecasts. Enhanced monitoring technologies can offer real-time detection of above- and below-threshold events, while the integration of information-communication technologies and hydrological models allows for the temporal and spatial evaluation of climatic and water quality variations. A smart drainage system involves the installation of real-time (or near-real-time) monitoring systems in storm drainage systems, along with the integration of these technologies with exogenous and endogenous conditions of monitored drainage basins for urban flooding prediction, control, and drainage safety.

Real-time measuring systems, based on both wired and wireless sensor networks, supply data in real time, allowing for quick reflections on drainage conditions. Rain sensors, which measure rain intensity and total rain volume, enable the detection of run-on and runoff in sewage networks. External sensors, connected to the municipal information network, receive information about impending storms, contributing to smart urban drainage system design. With rain and drainage flow sensors, flow water characteristics can also be detected, providing alert signals for the occurrence of floods, water quality deterioration, and the sufficiency of drainage capacity. Data from these real-time measuring systems can be easily visualized in the command center management system and provide a basis for decision making.

Chapter - 12

Ecotoxicology and Human Health Impacts

Water pollution causes environmental risk to ecosystems. These risks, together with the toxic burden on exposed human populations and the health impacts related to waterborne diseases, are the focus of this chapter. Toxicological assessment methods are compared, and the importance of considering bioaccumulation and biomagnification is emphasized. The burden associated with infectious diseases and the progress made in sanitary systems and their worldwide coverage are considered; however, the dynamics of climate variability and change may lead to increased incidence rates. Standards regulating contaminants with endocrine disruptor properties are summarized, and evidence indicating that mixtures may have additive, antagonistic, or synergistic effects is presented.

A variety of options for *in vitro* and *in vivo* toxicological assessments are nowadays available. Evidence indicates that the study of the effects of individual pollutants may underestimate the complete toxicological discharge potential of pollutants. Exposure assessment, including spatiotemporal variability and the toxicological activities related to each substance, must be combined with the corresponding knowledge of the sensitive organisms. The proper integration of these two aspects constitutes a significant challenge for ecotoxicology and gerontoxicology. The functional group of the detected toxic metabolites and their concentrations is important to ensure an accurate assessment of their risk and that of the aquatic environment [232, 233, 234, 235, 232, 233, 234, 235, 232, 233, 234, 235].

Toxicological Assessment Methods

The implications of chemical substances in the environment can be evaluated by various experimental methods that fall within three major groups: *in vitro*, *in vivo*, and in silico tests. *In vitro* tests evaluate biological processes and responses by analyzing model organisms or cells exposed to chemicals under controlled laboratory conditions. However, such studies cannot provide a complete response, since they cannot take physiological and metabolic processes into account. Study results are often used in preliminary risk assessments, or for the design of *in vivo* or epidemiological studies, where the compounds are evaluated in living organisms. *In vivo* Toxicological Assay explores the effects of chemical and physical factors on an intact organism or living population. Methods include use of vertebrate and invertebrate models, exposure of organisms in the natural environment and evaluations of changes in the health status of populations or groups of animals. In silico tests use existing structure–activity relationship (SAR) data to screen chemicals for properties like carcinogenicity and phytotoxicity. These tests not only provide valuable information on the toxicological properties of the chemicals but are also useful in filling the gaps, where experimental data are limited or lacking.

Chemical substances can be classified according to their effects on human health. Endocrine-disrupting chemicals (EDCs) are capable of interfering with synthesis, secretion, transport, metabolism, binding action, or elimination of hormones and are widely dispersed in the environment. EDCs are found in water, soil and air, and are mainly derived from agricultural runoff, industrial waste effluents, and domestic sewage. EDCs can lead to various diseases in humans, including reproductive dysfunctions, developmental abnormalities, tumours, diabetes, obesity and immunotoxicity. They can also adversely affect wildlife. A global assessment on the need for monitoring EDCs in the aquatic environment has been performed, highlighting the importance of determining the occurrence and effects of EDCs in developing countries, particularly for new and emerging EDCs. Bioaccumulation refers to the increase of a toxic substance in an organism, while biomagnification refers to the increase in concentration of a toxic substance as it moves from one trophic level to the next in the food chain [236, 237, 238].

Endocrine Disrupting Chemicals (EDCs)

Endocrine-disrupting compounds (EDCs) present a significant health risk due to their capacity to mimic, block, or interfere with hormone action. They are derived from natural and anthropogenic sources, are monitored using *in vitro* and *in vivo* toxicity assessment assays, and include polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), and others. Their relative abundance and concentration levels in aquatic environments and fish tissues are linked to playing a role as negative bioindicators of ecosystem health.

EDCs have the ability to disrupt endocrine function and regulation when introduced to organisms, causing short- and long-term effects. The most studied EDCs are industrial, agricultural and municipal residues. Their detected accumulation levels frequently exceed species-specific inhibition values, indicating a risk of endocrine disruption on aquatic biota. Numerous authors have highlighted the need to reduce EDC concentrations to avoid risks to both ecosystem health and human health [236, 239, 240, 241].

Bioaccumulation and Biomagnification

Both bioaccumulation and biomagnification involve the uptake of chemicals by organisms from the environment. However, bioaccumulation refers specifically to the continual uptake of a chemical by an organism from all exposure routes, whereas biomagnification refers to the enhancement of chemical concentrations in progressively higher trophic levels of an ecosystem. Consequently, biomagnification is the outcome of bioaccumulation in a series of connected organisms or food webs.

Bioaccumulation occurs when chemical exposure concentrations are sufficiently low that normal processes of uptake, transformation, and elimination result in increased chemical concentrations in the body. Concentrations in the organism exceed those in the water (or food) because of a chemical's lipophilicity or because the organism has little or no ability to effectively eliminate it. The half-life of a chemical in an organism determines how much chemical accumulates in its body over time. For chemicals that are rapidly eliminated by an organism, uptake becomes a relatively short-lived phenomenon, whereas elimination and uptake reach a steady state when they occur at comparable rates [242, 243, 244, 245].

Waterborne Disease Epidemiology

Waterborne diseases account for a significant and increasing proportion of infectious disease morbidity and mortality, primarily affecting children. Assessing incidence and burden is complicated by underreporting, limited data from the least-developed countries, and the challenges of attributing causes from complex environmental exposures or multiple pathogens infecting the same population. Epidemiological studies have examined risk from drinking contaminated water or from exposure to untreated or treated but polluted recreational waters, the elements of population susceptibility, and the risk from algal toxins.

Risk analysis offers frameworks for combining information sources, including quantitative hazard or exposure-response assessment models, meta-analysis, and expert judgment, to provide its results and support decision-making. In waterborne disease epidemiology, health impact assessment enables all facets of the analysis to be linked to policy options, through quantitative exposure estimates. Integrating the methods makes much of the available empirical data more useful, supporting not just health impact assessment but also detecting links between the environment and health, even where the data fall short of the highest currency [246, 247, 248, 249].

Public Health Risk Assessment

With the exception of pathogens, most environmental factors trigger certain diseases only after complex exposure and biological response processes; therefore, public health risk assessment frameworks oriented toward these factors are useful. Such frameworks typically consist of three components: hazard assessment, exposure assessment, and risk characterization. Risk assessment involves using available data and information within a well-defined and supported framework, allowing for different levels of effort and complexity for the various procedures.

By examining known exposures—as with established carcinogens, for example—or by applying qualitative reasoning, one can recognize and assess risks without detailed quantitative or qualitative studies or analyses. In practice, a combination of qualitative and quantitative assessments generates the most powerful risk assessment. Anticipating human health and ecological risks associated with water pollution due to complex organic molecules capable of mutagenesis or endocrine disruption is an area of active research. A few investigators have pursued it through a quantitative approach based on an iterative domino effect paradigm. Clearly, public health risk assessment plays an important role in quantifying the risk associated with pollution [250, 251, 252, 253].

Chapter - 13

Climate Change and Water Pollution Dynamics

The influence of climate variability on water quality arises from the interaction of multiple components affecting aquatic biogeochemistry. Water temperature changes shape metabolic rates, stratification, oxygen concentration, and pollution levels (nutrients, heavy metals, and bacterial loads). Alterations in hydrology (precipitation pattern/amount, melting of permafrost, or change in evaporation) are drivers of terrestrial ecosystems that may also impact pollution dynamics and spatial distribution in water. Extreme-weather patterns have dire consequences that disrupt ecosystems. They allow key opportunistic species to flourish and generate ecosystem collapse through phenomena such as breath-holding and harmful algal blooms (HABs).

Water systems can experience pulse flow events from intense rainfall that produce pollutant transport. Surface runoff is responsible for flow with a significant concentration of pathogens or toxic elements; therefore, flood warning systems are critical in public health management in urban environments. Rising sea levels and increased marine salinity are processes that may exacerbate pollution problems in estuaries and coastal aquifers during certain periods of the year, making public-health risk management vital. In addition, infrastructure must be designed with redundancy for critical supply; it should also be flexible enough to manage flow during low-water periods yet resistant to extremes during flood conditions [254, 255, 256, 257].

Impacts of Climate Variability on Water Quality

Climate variability exerts multi-faceted impacts on water quality in inland and coastal waters, altering temperature, hydrology, pollutant transport and fate, and biogeochemical processes. Increasing temperatures can intensify thermal stratification in lakes, create more favorable conditions for purple sulfur bacteria, and enhance the growth of cyanobacteria and associated production of cyanotoxins. Changes in rainfall patterns can also affect eutrophication severity and hypoxia response. Declining baseflow can lead to increasing concentrations of organic carbon, total nitrogen, and fecal indicator bacteria, while decreasing water volume can amplify the harmful effects of runoff pulses on the receiving waters. Reduced salinity levels in estuarine waters can enhance the toxicity of metals toward submerged aquatic vegetation, ultimately diminishing the resilience of these systems. Changes in precipitation patterns are expected to alter delivery of a multitude of environmental contaminants, underscoring the need for a more comprehensive analysis of the links between climate variability and pollutant transport and fate in order to identify potential high-risk periods for contamination and support appropriate management actions.

Increased rainfall amount, frequency, or intensity can lead to periods of greater runoff-producing conditions, exacerbating the vulnerability of the environment. The associated transport of greater pollutant loads may occur through mechanisms involving discharge concentration and/or duration of runoff events. Bioassay-based methods have found toxicity present in runoff from urbanizing catchments and at downstream locations in the corresponding receiving estuary during periods of high rainfall, highlighting the importance of managing water quality, particularly during predicted periods of extreme rainfall events. The relationship between recorded diseases and rainfall patterns also serves to demonstrate exposure risks to waterborne pathogens. A clearer understanding of the impact of climate variability on the transport of key pollutants in different environments is therefore needed, in order to more accurately assess water quality risks through early-warning systems, target pollution-control measures, and inform “Pollution Control and Prevention” plans [258, 259, 135, 260].

Extreme Weather Events and Contaminant Transport

Extreme weather events are predicted to occur in greater frequency and intensity, whilst resulting changes in hydrological processes will amplify contaminant loads transported to receiving waters. Multiyear monitoring efforts have tracked the dynamics of runoff pulses at catchment, river basin, and regional scales. Contaminant transport during these events was shown to be dictated by hydrology and land surface processes. More specifically, pulse magnitude is related to spatial heterogeneity in contaminant concentration and environmental controls. Pollutant dynamics further reveal the influence of hydrological disconnection of catchment zones. Connecting this knowledge with incidence data offers valuable guidance when assessing risks to waterborne disease and prioritising preventive actions. In summary, risk assessment frameworks that include climate change as a driver of transport intensity are critical for the mitigation of exposure during extreme weather events.

Climate variability leads to changes in hydrology, temperature, and biogeochemical processes that can mask underlying trends in water quality. The composite effect of changing climate on water quality and ecosystem health is evident, for example, in the Southern Ontario region where multiyear monitoring has detected an acceleration of land-surface warming, coupled with altered hydrological response times and accelerated metabolism of receiving waters. Furthermore, the documented rise in the frequency of extreme rain and snowmelt events leaves regional communities vulnerable to increased exposure to waterborne disease during specific periods. Since the risk of waterborne disease is especially elevated following extreme weather, effective mitigation requires an understanding of the drivers of contamination during these events and incorporation of such information into exposure-risk assessment frameworks [261, 262, 263, 264].

Sea-Level Rise and Salinity Intrusion

Impacts on estuaries and coastal aquifers. Sea-level rise poses considerable risks for estuaries and coastal aquifers due to saltwater intrusion, with implications for natural and human systems. While inundation is often emphasized, salinity intrusion is the main threat for groundwater and ecosystems. Land use changes drive salinity degradation, with cotton, citrus, and sugarcane crops relatively resilient to climate shifts. Forward-looking analyses should disaggregate the impacts of flooding and salinity. The effects on ecosystems are proximate and linked to altered salinity tolerance and dynamic interactions. In aquifers, salinity affects drinking water resources and ecosystems, making the quality of those resources an emerging issue in Mexico. New sap flow techniques facilitate direct measurement of salt water inflow. Predictive models are essential for evaluating the vulnerability of estuarine - coastal systems and establishing adequate protections. Preventive and restitution measures should be proposed in a management plan integrating infrastructure works and “soft” strategies. Adaptation considers values attributed to ecosystem services.

Anthropogenic modifications in estuaries and lagoons threaten biodiversity and diminish the capacity of natural ecosystems to act as buffers against climate change impacts. Sea level rise triggered by climate change and water withdrawal processes have been intermittently characterized across the region, although processes controlling salinity distribution are not yet well understood. Understanding salinity dynamics is essential for evaluating the resilience of these transition areas and implementing adaptive management strategies. In coastal areas with water supply salinization, changes in salinity distribution should nevertheless be considered in addition to inundation and their impact on human activities and health. These changes are therefore of utmost importance for agricultural production, aquifer recharge, ecosystem quality, and human health in a warming climate [265, 266, 267, 268].

Adaptive Water Infrastructure

Adaptive water infrastructure encompasses design, deployment, and operational principles that enhance resilience to climate change and development pressures. Robust design for the expected conditions, together with redundancy and sufficient flexible capacity, will minimize risk and reduce the costs of extreme events. Adaptation permits investments in increments and partial solutions rather than fully optimized systems. The uncertainty inherent in climate projections, such as the timing and magnitude of individual floods or droughts, is best accommodated by ensuring the flexibility of systems and management responses, including speed and ability to take advantage of opportunities (e.g., diverted flows during floods), within a framework that optimizes operation over the longer term.

Public health and ecosystem services are community priorities that are sometimes better protected by allowing and facilitating inundation of low-lying areas than by expensive engineered defences. Such actions may be seen as creating the necessary space for the river, and thus be more effective in managing floods than last-minute, expensive decisions that focus on construction of higher embankments. Nature-based solutions that enhance ecosystem functions are cost-effective and often the best way of addressing problems. For example, restoring wetlands will improve water quality, while also enhancing terrestrial, aquatic, and atmospheric carbon storage [269, 270, 271, 272].

Resilience Planning and Policy Integration

Climate change impacts on water quality will be acute for terrestrial aquatic ecosystems through temperature, precipitation change, hydrography, and alterations in the chemical and biochemical water composition. Extreme weather events can result in transport peaks of organic and inorganic contaminants, often leading to increased human health risk due to opportunistic exposure. The water sector and associated water infrastructure can be made resilient to climate change impacts by following three principles: resilient-by-design, redundancy, and flexible-by-nature. Planned resilience of the physical assets, particularly of the drainage networks, must not occur in isolation, as a responsive phase (monitoring, prediction, and early warning) and, when applicable, an adaptive phase (reacting to short- and medium-term changes) must also be incorporated. Resilience planning must incorporate new strategies and solutions that anticipate and adapt to widely predicted changes or new realities, guiding infrastructural investments for highly probable and expected future conditions. The way climate variability and extreme weather influence the characteristics of surface waters must be incorporated into assessments of the possible health impacts of waterborne diseases and other water-related diseases.

Climate projections must be sought by planners at the beginning of process design; preparedness and human capital should then be built around investing in reliable water-quality early warning and prediction systems. New-design civil works need not only cater for present-day extremes but also retain redundancy in the face of current and anticipated future conditions. For pollution-control systems in the water sector, this requires a change in focus from loss mitigation to disaster-proofing, by investing in prevention prior to the event and subsequently rectifying any failures in strategies. For example, a high level of ground infiltration is surely desirable for an urban area during a heavy rainfall event; however, the use of adequate effective measures and smart systems will allow the use of impervious areas for WWTP and other similar facilities during such events and their eventual infiltration, once the concerns have returned to normal levels. Flood-prone areas and locations downstream of large reservoirs must be protected with restoration techniques and, where possible, hazard-reduction practices should be employed [273, 274, 275, 276].

Chapter - 14

Policy, Regulation, and Governance Frameworks

International Water Quality Standards: compare frameworks and applicability. National Regulatory Policies: summarize enforcement, monitoring, and compliance. Transboundary Water Management: address cooperation, conflict resolution, and data sharing. Community Participation and Stakeholder Engagement: highlight processes and accountability. Economic Instruments and Pollution Control: evaluate taxes, charges, and incentives.

Global Water Quality Standards are important for assessing aquatic risks, yet coverage is inconsistent, with major gaps in emerging contaminants. National Regulatory Policies provide the regulatory framework for water protection and pollution control in both surface water bodies and groundwater. Coordination is crucial in transboundary river basins since water quality conditions may affect water supply and conflict resolution. Community Participation facilitates bottom-up approaches for water governance in urban and rural settings. Economic Instruments enhance incentives for compliance with environmental regulations.

International Water Quality Standards

International legislation and protocol establish water quality standards as a guide for determining the severity of water pollution and its biological and physical indicators. These standards translate biological and chemical data into regulatory and legal guidelines. Water quality regulations are country specific, reflecting local environmental, social, and developmental conditions and priorities.

Most quality criteria for surface water are based on protecting aquatic life, but water bodies are used for many other purposes—bathing, drinking, irrigation, fish farming—requiring additional considerations. Consequently, regulations of various countries are compared and grouped together in many ways to make them usable in regions with similar populations, climates, geography, economic endeavors, and ecology.

At the global level, the Sierra Club and International River Network presented the first set of water quality standards drafted by citizen-monitoring groups for the protection of rivers and lakes. The United States Environmental Protection Agency also developed a set of suggested state water quality standards for the protection of fish, shellfish, and wildlife [277, 278, 279, 280, 279, 277, 278, 280].

National Regulatory Policies

Regulatory Control of Water Pollution in India is conducted by the Central Pollution Control Board (CPCB), with functions and powers also delegated to State Pollution Control Boards (SPCBs). Water Quality Monitoring is conducted by the National Water Quality Monitoring Network, comprising about 1,400 monitoring stations located on major rivers, tributaries, lakes, and aquifers. Monitoring results are assessed against national standards for classified surface and groundwater.

National Water Quality Standards have been established for eight designated uses of surface water. The Standards contain one or more sets of permissible values for each monitoring parameter, depending on the designated use of the water body. Comprehensive monitoring of pristine or remote water bodies, the detection of “non-human” waterborne diseases, and the measurement of sediment toxicity are not explicitly covered by monitoring requirements.

Class A Standards are applicable to drinking water sources with or without conventional treatment but a disinfection facility. For conventionally treated drinking water sources, the limits for total coliform bacteria must be satisfied in not more than 5% of the samples taken during any one season. standards allow for the short-term bathing quality of inland surface water. For these reasons, Persistent Organic Pollutants (POPs) have also been included in the monitoring programme.

Transboundary Water Management

Water quality in transboundary river basins is controlled through national water quality standards applying to domestic and industrial discharges. Prevention detects aquaculture pollution, enforces standards, controls outbreaks, and assesses fisheries impact. Minimum standards for drinking water supply are regulated nationally, but state regulations vary.

Community participation enables bottom-up governance, enhances transparency, builds trust, reduces transaction costs, and manages conflicts. Stakeholder consultation and open meetings guide project preparation. Public participation in decision-making is key to implementing the National Water Policy. Recognition of communities' rights over local rivers is fundamental for forest management.

Incentives, taxes, and charges are effective economic instruments to control water pollution from industry, agriculture, and urban areas. Pollution costs are internalized through effluent or pollution taxes and environmental charges. Taxes curbing nitrogen and phosphorus use have reduced agricultural pollution in several countries. Environmental performance accounts for government credit rating, steep pollution-loading fees, and peer pressure [281, 282, 283, 284, 281, 282, 283, 284].

Community Participation and Stakeholder Engagement

As water quality issues challenge both developed and developing countries, community participation and stakeholder engagement in the decision-making process can support more effective and equitable management. Stakeholders can be directly or indirectly affected by decisions. Depending on the degree of involvement, participatory approaches can range from information sharing to joint agreements on river basin management plans. These principles may also build resiliency to future transitions.

Engagement builds trust among stakeholders and reduces conflicts and costs by identifying preferences, sharing knowledge and responsibility, addressing expectations, and evaluating outcomes. The governance model should account for the characteristics of the water body of concern, the social and political context, and public preferences regarding the approach to be adopted.

Community participation and stakeholder engagement in the water governance process can support more effective and equitable management. These principles can assist planning efforts in the face of rapid change by fostering adaptability of water systems in response to external shocks. Community participation can be defined as respecting the local population's rights and responsibilities. Stakeholders are people who can directly or indirectly affect or be affected by decisions related to the planning, implementation, and management of a project, process, or service. Stakeholder involvement in decisions can take place at an informational, consultative, cooperative, or joint level, with the degree of collaboration influencing the structure of appropriate tools. Involvement of local interest groups leads to improved ownership, maintenance, and ecological conditions of natural resources.

Engagement of stakeholders builds trust, enhances the effectiveness of decision-making processes, and reduces the costs of conflict. By informing public preferences, sharing knowledge and charging responsibilities, addressing expectations, and evaluating results, participatory methods can contribute to improving management outcomes. The citizenry may participate in formal and informal policy analysis or in a consultative role to provide feedback. A more demanding context involves a commitment to cooperate or joint management. These governance frameworks have also been identified as an important component for the success of climate change adaptation action [285, 286, 287].

Economic Instruments and Pollution Control

Economic policies exert a profound impact on water quality. Pollution charges and discharge taxes applied to point sources function as corrective measures, aligning marginal pollution abatement costs with marginal social benefits of reduction. These taxes are internalized into industries, frequently yielding significant pollution reductions at a relatively low cost. Properly structured, discharge taxes reduce illegal pollution, provide revenue, and incur low administrative costs. Environmental degradation due to pollution, biodiversity loss, and climate change necessitates social investment. Declines in natural capital are overtly evident in freshwater resources, and their conservation will positively affect sustainable development. Some international institutions have recognized the opportunity to include freshwater resources within bioeconomy concepts. Water used in a region should be reused elsewhere, among users and sectors in a circular economy.

The implementation of informal contract-based private property rights, coupled with efficient pricing policy and a market-based approach, can mitigate future freshwater scarcity. Water supply scarcity can be avoided when water is optimally allocated using a competitive economic allocation mechanism. Economic development, market mechanism applications, and institutional reforms that lead to change in emissions intensity reduce changes in water quality, but do not suffice to ease water pollution without strict command-and-control and regulatory measures. Human behavior largely regulates freshwater management systems. Therefore, economic instruments that reduce costs and/or create profits via environmental conservation should be encouraged. Since many developing countries still experience accelerated population growth, the development of new economic and regulatory instruments to manage water quality must adjust demographic transitions.

Chapter - 15

Innovative and Nature-Based Engineering Solutions

Considerable attention has turned to pollution treatment technologies and in-annual pollution-related system revolutionary projects across the globe in a bid to manage extreme climate change, with its concomitant rise in pollution occurrence and complexity. Yet the performance of these activities tends to be assessed separately and frequently lacks environmental consideration. Integrated management of environmental pollution must therefore be the focus of relevant researches and practices. Nature-based solutions (NbS)—defined as "action to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while providing human well-being and biodiversity benefits"—may play a key role. These aim to harness ecological processes and the synergy between ecological and economic systems in an innovative manner, including for pollution treatment. They may incorporate engineered elements while capitalizing on naturally occurring functions. Such engineering solutions include the application of phyto- and bioremediation, the construction of wetlands, ecohydrology, the establishment of a circular water economy based on resource recovery and reuse, and the introduction of artificial intelligence and decision-support systems to improve water supply and quality at all times. The provision of adequate funding is, however, essential.

Engineering solutions driven primarily by economic considerations may lead to excess control or overinvestment, and consideration of their effects on the ecosystem remains inadequate. Pollution treatment through ecological approaches is therefore insufficiently integrated, even within a given subsystem. Hence, these technologies should be viewed as an integral part of pollution treatment and system evolution, with Sophia's Law providing the logical framework for applied innovation [288, 289, 290, 291].

Phytoremediation and Bioremediation

Optimizing remediation technologies is critical for improving contaminant attenuation in simultaneous translocation of carbon and nutrients (C, N, P) in contaminated sediment of shallow freshwater lake. Phytoremediation is the use of plants and plant-associated microorganisms to remove, degrade or stabilize contaminated sediments, water and soil through natural or induced processes. Phytoremediation processes depend on species selection, growth conditions, biochemical factors within the plant and plant- pollutant interactions in the surrounding matrix. Phytoremediation is also the degree of contamination and the source-sink dynamics of the contaminant in the habitat. Pollution control technology based on plants is attractive due to its environmental and social friendliness. However, the technology is risk-averse with respect to remediation efficiency and speed. In an integrated remediation approach developing the archaeological ecosystem of the sediment and habitat is necessary. The ancient settlement pattern of the targeted area is also an important consideration.

Bioremediation is a technology in which micro-organisms are employed to enhance the degradation of a possibly hazardous contaminant. It is frequently used to clean up sites that are contaminated with organic materials, although metals can also be removed by biological means. Important to note is that natural microbial populations have the ability to degrade many substances, often very slowly. Under certain conditions, including a supply of moisture, nutrients, an appropriate pH, and temperature, the addition of a carbon source can stimulate this biological degradation and enhance the rate of clean-up. Phytoremediation and bioremediation techniques can be applied independently to remove contaminants or can be integrated with other technologies [292, 293, 294, 295, 292, 293, 294, 295].

Constructed Wetlands Engineering Design

Field studies and laboratory experiments have demonstrated that constructed wetlands represent a reliable option for the natural treatment of wastewater. The eco-engineering design of constructed wetlands should consider the choice of layout, flow direction, plant species selection, hydraulic design, and water quality targets.

The area is a determining factor in the treatment of wastewater in constructed wetlands. Design and layout have a major influence on the overall performance and should be regarded in a strict hydraulic analysis. The longitudinal aspect ratio has proven to be a determining factor in short-circuiting. The smallest ratio should be chosen for a subsurface horizontal flow wetland.

Different plants can perform different roles in the reduction of pollutants in constructed wetlands. The performance of horizontal subsurface-flow wetlands planted with different plant species can be evaluated. Variable influent wastewater characteristics should also be considered in the selection process. Long-term data demonstrated that a high diversity of emergent macrophytes enhances the ecological functioning of constructed wetlands.

The residence time is a major determinant of constructed wetland treatment efficiency of organic matter and nitrogen removal. Additional factors should also be assessed, including BOD removal, discharge requirements, climate, hydraulic resistance of the soil matrix, transfer of ammonium and nitrates in subsurface flow wetlands, temperature, number of waste inflows, and type of plants used. Long-term modelling can be employed for the sizing of constructed wetlands supplying treated effluents for reuse in irrigation.

Ecohydrology Approaches

Ecohydrology examines how hydrology supports ecosystem structure, composition, and functioning and how these ecological functions can, in turn, support water quality maintenance and pollution control. Recent trends in ecohydrology emphasize understanding hydrological and ecological dynamics in concert. Hydrological processes, such as flooding and drought, drive ecosystem development, while disturbances such as sediment and nutrient transport, can be beneficial to maintaining ecosystem composition and functioning. Integrating hydrological, ecological, and water quality dynamics can provide knowledge to reduce and manage pollution. A holistic management strategy for large river basins also emphasizing synergy between hydrology, ecology, and water quality concentrated on applying watershed management for pollution control in streams, rivers, estuaries, and seas, through sediment traps, pollution-nutrient interception areas, and retention of floodwaters for purification.

Sensitive upstream management of watersheds can enhance water quality in downstream lakes and dams. Indicators such as biodiversity, wetland conditions, and chemical loads reflect the ability of an ecosystem to maintain functions. To support water quality and prevent pollution overloads in large water bodies subjected to chemical and pollutant loads from the watershed or catchment upstream, preservation or restoration of the natural ecosystem should be a priority. Strategies for chemical pollution control using bacteria, algae, and macrophytes are increasingly being studied [296, 297, 298, 299].

Circular Water Economy Concepts

Philosophies aiming to ensure permanent access to quality water for all stress the importance of an integrated and sustainable approach to water management that focuses on its reuse and recovery as much as on its distribution and treatment. A circular water economy promotes water reuse for multiple purposes—such as irrigation, aquaculture, and cooling—supported by safe and appropriate technological solutions, community support, and economic viability. Water recovery technologies, particularly in combination with novel water distribution systems at smaller scales (district level or below), should aim to exploit the valuable resources contained in wastewater, such as nutrients and organic matter, and provide the community with versatility to adapt to new challenges arising from climate change and urbanization pressures.

A circular economy supports a growth model focused on keeping the value of products, materials, and resources in the economy for as long as possible and minimizing waste, pollution, and resource damage. For the water sector, a circular economy promotes approaches to water management that aim not only at reducing and controlling pollution but also at recovering valuable resources contained in wastewater. Achieving a circular economy means closing the water loop, and it is necessary to understand the requirements and associated costs for large-scale implementation of wastewater treatment and water reuse [300, 301, 302, 303].

Smart Water Systems and AI Applications

Data-driven optimization of water management and predictive maintenance frameworks for key installations.

Recognizing the rapidly evolving capabilities of artificial intelligence, the adoption of innovative and data-based technologies ideally allows the development of smart water systems capable of helping in the prediction and detection of pollution events. Such instances may include the emergence of combined sewer overflows (CSOs) during intense rainfall events or pollution loads in specific water bodies due to diffuse pollution sources.

Water quality prediction based on supervised machine learning can also allow the generation of alerts and support timely interventions. Furthermore, the assimilation of data from multiple sources into a digital twin coupled with advanced modelling can lead to predictive systems capable of indicating necessary maintenance or cleaning activities in advance and preventing possible malfunctions. Recent advances in computer vision systems, automatic sensors, and deep neural networks have enabled the development of automatic aquatic litter detection systems integrating images and videos from drones, surveillance cameras, and water quality monitoring systems. The automatic litter detection system can aggregate aquatic litter images and videos from water quality monitoring systems, surveillance cameras, and drones, thus promoting the reduction of aquatic litter through early detection.

The rapid development of a prediction model can support resilience of the drainage system and ensure the well-being of local citizens and ecosystems. Urban water flow-and-quality models combined with supervised machine-learning-based prediction can allow for better management of drainage networks and other key infrastructures and the quick detection of abnormal patterns [304, 305, 306, 307].

Chapter - 16

Future Perspectives and Integrated Case Studies

Future advancements in water pollution management will increasingly capitalize on the converging methods used in diverse fields including ecohydrology, phytoremediation, bioremediation, and water economy. Still, effective cross-disciplinary synthesis remains challenging. Recent developments in nature-based and nature-inspired engineering solutions highlight the integration of pollution mitigation into hydraulic design. Furthermore, the adoption of AI in the control and management of water resources can help reduce overall energy consumption and optimize system resilience.

Data-driven integration of sensor networks presents a further opportunity for real-time water management control. Such systems can optimize nutrient and energy inputs to alimentary, irrigation, or heating networks while simultaneously predicting possible disturbances in chronological monitoring. Near-future research should emphasize such integrated, multidisciplinary approaches, and program synthesis and evaluation across these thematic fields offers a clearer outlook for policymakers involved in the water cycle [308, 309, 310, 311].

Multidisciplinary Integration Approaches

Integration of Diverse Disciplines is essential for a Comprehensive Understanding of Problems and Exploration of Solutions, The Water Pollution Management Case

The diversity of specialized knowledge and analytical approaches in present-day science gives difficult problems an intimidating complexity, with challenges overflowing the boundaries of present-day research centers and their available funding. Under these circumstances, research workers in discipline windows have no viable recourse other than to seek help externally. Their research work is not immune from the burden of support, and funding gets diverted to fulfill externally identified needs or provide particular types of sample which cannot be internally fulfilled. A solution also exists in the development of concepts that recognize the need for integrating apparently incompatible knowledge bases and techniques over and beyond the collaborative work of two or more researchers sharing a common problem.

A classic case for developing multidisciplinary integration concepts is pollution of water, the networking constituent of all ecosystems. A large number of research processes using different environmental compartments and disciplines have explored aspects of surface water, ground water, ocean water, snow water and rainfall with different techniques and methods. Each discipline and specialized technique has provided new scientific understanding. A perceptive attempt to realize the essence of integrated water pollution management to find solutions creates an ideal scenario for multidisciplinary combination of knowledge, environmental use and management skills that combine strengths and gains of different research paradigms, multidisciplinary or interdisciplinary combinations [312, 313, 314, 315].

Real-World Case Studies

Integrated approaches to water pollution management—grounded in enabling science and technology—have been applied to real-world challenges in both developed and developing regions. The effects of urbanization on water quality in Taiwan's Yilun River Basin provide a clear understanding of the associated risks, along with pollution loads and indicator metrics for restoration. Algal blooms in Lake Mývatn, Iceland, were affected by historical shifts in land use, climate, and human activity, culminating in ecosystem stress and economic consequences, emphasizing monitoring needs. The biological recovery of discharge-affected streams, identified through a meta-analysis of 59 studies, serves as a basis for management and monitoring.

Water pollution resulting from rapid urban and industrial development—numerous chemical release incidents and unregulated wastewater control—has alarmed Taiwan. Consequently, decision-support networks have been established, such as the Environmental Monitoring Charge System and the Water Quality and Habitat Improvement Responsibility System. Despite the policy framework, the water quality of the Yilun River Basin remains poor, with most pollution sources attributed to urban, combined, or stormwater runoff. Understanding loading concepts, driver–response relationships, and relevant water-quality indicators is crucial [316, 317, 318, 319].

Emerging Research Trends

Future research efforts targeting water pollution management should pursue four distinct avenues. A first priority lies in enhancing the modelling and monitoring of pollution processes, with particular attention to interactions between hydrodynamics and benthic biochemical processes. Models should address the hydrodynamics of lakes and reservoirs, sediment transport in lakes, rivers and estuaries, and flow through stormwater management systems. Prediction of pollutant dispersion in rivers and lakes should be integrated with the routing of contaminated solids. Biofilm retention of faecal pathogens and antibiotic-resistant bacteria should be better represented in models of waterborne disease risk.

Secondly, improved understanding of linkages between aquatic conditions and ecosystem effects or ecological health is of paramount importance for pollution management. The structure, function or biochemical ecology of aquatic systems needs to be linked to the prevalence of waterborne diseases in exposed populations, and blooms of toxic cyanobacteria also warrant detailed investigation. Risk assessments relating contamination to benthic, pelagic and fish responses should be undertaken. Such analyses will inform the selection of suitable indicators for biotic and molecular monitoring, thereby enhancing the information content of biological data for management [320, 321, 322, 34].

Capacity Building and Education

Education and training play vital roles in fostering responsible stewardship of freshwater resources for both society and the ecosystem. All water pollution management frameworks highlight the importance of education and training to enhance the capacity of individuals and institutions in meeting policy goals and objectives, particularly SDG 6, which calls for ensuring availability and sustainable management of water and sanitation for all. Effective communications that mobilize human beings to use freshwater resources rationally, reduce pollution, and share water efforts contribute to the success of pollution mitigation efforts.

Education and awareness also permeate the activities of local and state governments. Environmental subjects are incorporated into school curricula at various levels. Educational campaigns emphasize the importance of water conservation in homes and industries. Competitions are organized to educate citizens about water pollution and provide awareness on perceptions of, and response to, polluted water bodies. In addition, clean-up drives are conducted, and the information technology sector is used to suggest best practices for the reduction of water pollution. Result-oriented training programs have also been extended to corporate organizations. Management development programs covering water resource management topics help train top and middle management personnel of various corporate sectors. Furthermore, diploma and training programs in wastewater management have been introduced in technical institutes to create trained workforce in this area of critical importance [323, 324, 325, 326].

Roadmap toward Sustainable Water Pollution Management

Integrated water pollution management requires solutions for various types of pollutants using several disciplines such as environmental science, ecology, civil and hydraulic engineering, and ecotoxicology. Recommended strategies include appropriate environmental planning, pollution prevention or control, laws and regulations, and practical engineering measures. Most of these principles are well understood. What is often lacking for specific regions is an explicit roadmap and set of case studies that tie them together.

Quantifying water-quality issues in a specific area is the first step toward developing an integrated pollution management plan. Classic integrated water-resources management covers issues, rules, equity, efficiency, and local participation. Then the key water-quality issues and causes of impairment of surface waters, groundwater, or both are identified, along with existing legislation and the procedures required to implement it. The research is framed within the pollution-source categories used by the World Health Organization and the Global Water Quality Assessment, which identified urban, industrial, agricultural, and irrigation drainage as key alarming sources. Roadmaps and case studies that synthesize multidisciplinary knowledge may help meet the Sustainable Development Goals and make futures more climate resilient [327, 328, 329].

Conclusion

Integrated Water Pollution Management encompasses multidisciplinary assessment, analysis, and engineering perspectives. Contemporary research yields important findings aligned with this integrated approach across environmental impact assessment, immunological analysis, hydraulic engineering, and monitoring. Global compliance with the water-related Sustainable Development Goals requires water pollution reduction, policy enforcement, and effective management implementation, achieved through consistent monitoring, assessment, and effective solution deployment.

The presented studies exemplify various components of Integrated Water Pollution Management. Integrated catchment-based assessments identify relevant land-use impact indicators and spatial distribution maps. Addressing Interested-Spil Section Pollution (ISPP) centres on novel, sensitive monitoring for academic understanding and effective management. Novel immunological tools enhance pathogen- and toxin-detection capacity. Hydraulic studies contribute to sustainable design of storm-water management and pollution-mitigation systems. Future work will consider all components together, evaluating combined Integrated Water Pollution Management strategies for specific basins and catchments.

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