PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9412

eISSN 2348-1900

REVIEW ARTICLE

Integrating traditional and emerging technologies for enhanced water quality monitoring and sustainable resource management

A Barath[1], S Selvakumar[2*], V Ravikumar[2], U Sivakumar[3] & K Boomiraj[4]

[1]Department of Soil and Water Conservation Engineering, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Environmental Science, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - selvaswc@tnau.ac.in

Received: 11 May 2025; Accepted: 30 June 2025; Available online: Version 1.0: 01 August 2025

Cite this article: Barath A, Selvakumar S, Ravikumar V, Sivakumar U, Boomiraj K. Integrating traditional and emerging technologies for enhanced water quality monitoring and sustainable resource management. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9412

Abstract

Global water quality is increasingly threatened by industrial expansion, urbanization and climate change, necessitating robust and adaptive monitoring systems. This review critically examines the evolution of water quality assessment methodologies, transitioning from traditional field-based approaches to advanced technologies such as Artificial Intelligence (AI), constructed wetlands, remote sensing and Internet of Things (IoT)-enabled monitoring systems. Emphasis is placed on the evaluation of key water quality parameters, including physicochemical, bacteriological and heavy metal contaminants, across both surface and groundwater systems. Analytical tools such as the Water Quality Index (WQI), Geographic Information Systems (GIS), hydrus modelling, Multivariate Statistical Analysis (MSA) and regression-based machine learning models-including Artificial Neural Networks (ANN) and Hammerstein-Wiener (HW) models are reviewed in terms of their applicability and effectiveness. Bibliometric analysis is employed to uncover current research trends, interdisciplinary linkages and geographic hotspots in water quality research. The primary objective of this review is to synthesize current advancements, identify methodological gaps and propose an integrated framework that combines traditional techniques with modern analytics to enhance sustainable water resource management strategies.

Keywords: GIS; remote sensing; sustainable water resource management; WQI; water quality monitoring

Introduction

Water quality assessment is an important step toward ensuring the long-term viability and safety of water resources for human use, agriculture and industry. Among several pollutants, water pollution becomes especially important for sustainable management as a major hazard to human life, health, also the most notable concern (1), Poor water quality poses serious threats to human health, ecosystems and economic activities, making its evaluation essential for sustainable development. Global changes, including climate variations and human activities such as agricultural runoff, wastewater discharge, landfill leachate and excessive fertilizer application, have significantly contributed to water quality degradation. Surface water quality is deteriorating due to both natural and anthropogenic factors, including soil erosion, landslides, GLOF (Glacial Lake Outburst Flood) events, sediment movement, urban development, industrial, mining and agricultural operations (2). Groundwater is an important water source for the agricultural purposes, industrial sectors and majorly used as potable water in India, groundwater resources, which supply approximately 43 % of agricultural water, are under severe pressure due to urbanization, industrialization, overconsumption and poor management practices (3- 6).

Water quality monitoring programs, typically conducted through field measurements and laboratory analysis, help in assessing the physical, chemical and biological characteristics of water (7). One of the widely used assessment tools is the WQI, which integrates multiple water quality parameters to provide a composite rating of water suitability. While WQI is extensively used for drinking water assessment, limited research has been conducted on its application for agricultural water evaluation (8). Additionally, the presence of heavy metals like arsenic (As), lead (Pb), copper (Cu) and iron (Fe) in water sources poses significant health risks through bioaccumulation in food chains (9).

Advanced analytical approaches such as MSA and GIS techniques have been instrumental in assessing spatial and temporal variations in water quality (6). The combination of remote sensing, GIS and water quality approaches enables a thorough understanding of water quality dynamics, spatial patterns and trends across time. This integrated strategy helps make educated decisions about water source management, pollution control and conservation measures (10). Surface water detection is evaluated using standard water indices including NDWI, MNDWI, WRI and NDVI (11). For the sake of sustainable development, IoT-enabled AI for water quality monitoring is highly pertinent (12). These methodologies enhance the ability to identify pollution sources, track trends and develop effective management strategies. This review aims to provide a comprehensive evaluation of water quality assessment methodologies, water quality models and their applications. By analysing various parameters, sources of pollution and modern assessment techniques, this study seeks to contribute to the development of sustainable water management practices that ensure the safety and reliability of global water resource.

Bibliometric analysis

To provide a quantitative overview of the current state of the research, we conducted a bibliometric study using the VOSviewer software. When we extracted bibliographic data from Scopus, we concentrated on publications up to 2024. Overlay and density visualizations of term co-occurrence were created using this data, exposing significant trends and advancements in the field. The size of each node represents the frequency of keyword occurrence, while the thickness of the connecting lines indicates the strength of co-occurrence relationships presents a keyword co-occurrence network generated using VOSviewer, illustrating the thematic structure of research on water quality (Fig. 1) (13).

Discussion

Within the larger study landscape pertaining to environmental studies and water quality, the bibliometric visualization identifies clear theme clusters. These clusters show interrelated areas of research concentration and are created by closely linked terms that commonly occur together in scholarly papers.

At the centre of the map lies the Water Quality & GIS cluster, characterized by keywords such as "water quality", "GIS", "statistical analysis" and "spatial analysis." This cluster represents a core theme where geospatial technologies are extensively applied to monitor, model and manage water quality parameters. The integration of GIS tools with statistical and multivariate analysis methods enables researchers to assess spatial variations in water quality across different regions, facilitating better decision-making in water resource management. The hydrochemistry & groundwater cluster, which includes phrases like "hydrochemistry", "groundwater quality", "ion exchange" and "aquifer" appears in the lower left section. This team investigates factors including pH, alkalinity, hardness and the presence of ions and trace elements to characterize groundwater resources chemically. To comprehend the mechanisms determining groundwater composition and to evaluate its suitability for a variety of applications, including drinking and irrigation, studies in this cluster frequently employ methods like factor analysis and hydrogeochemical modelling. With phrases like "health risk assessment", "water pollutants, chemical", "heavy metals" and "drinking water" the human risk & pollution cluster is clearly visible on the right side of the map. Assessing the effects of chemical pollutants on human health, including lead, arsenic, cadmium and nitrates, is the focus of this theme area. Health risk models are being used more in recent studies in this field to estimate exposure hazards and guide public health initiatives, especially in areas with substantial sources of anthropogenic pollution. Finally, the upper portion of the map is occupied by the remote sensing & land use cluster, which includes phrases such as "remote sensing", "land use", "satellite imagery" and

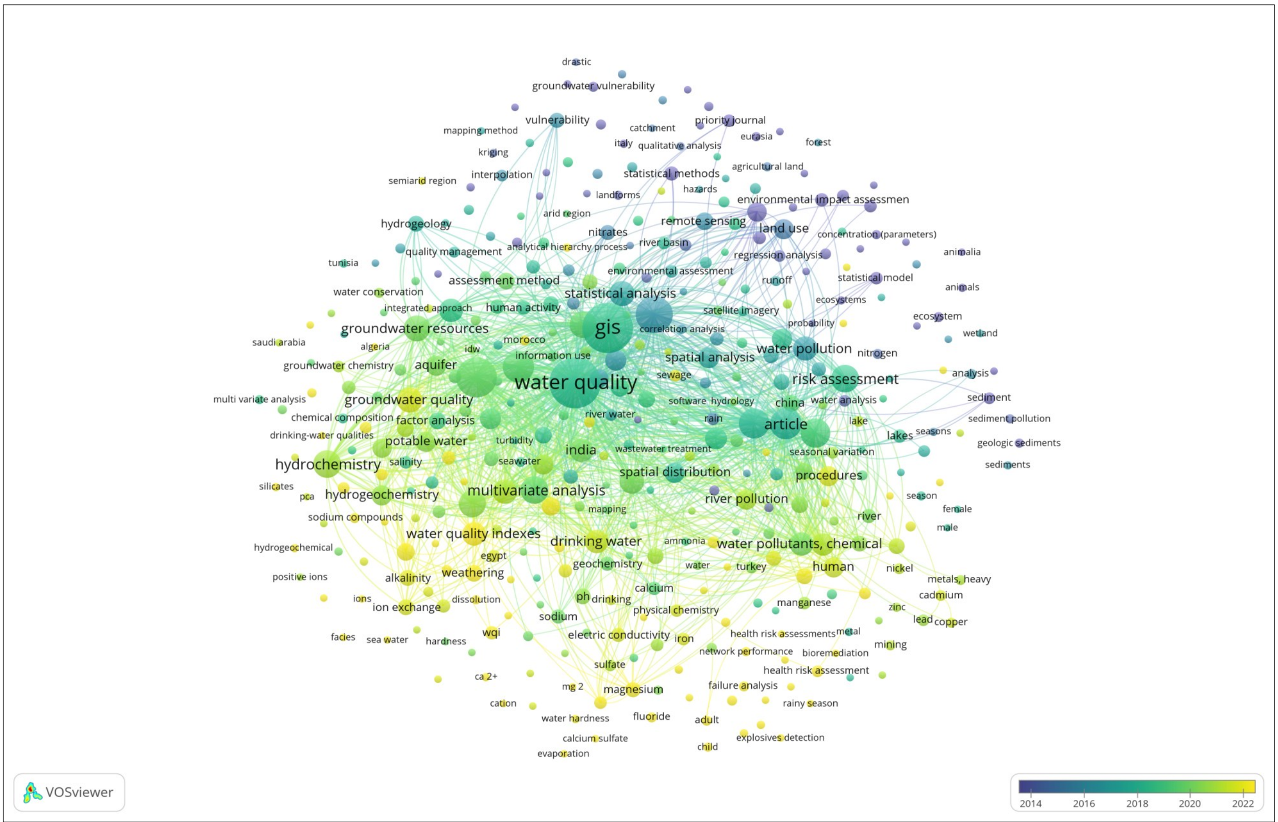

Fig. 1. Visualization of keyword co-occurrence in overlay.

(VOSviewer software was used to create the figure. The software's default setting is the font style) (13) "environmental impact assessment." This cluster focuses on the application of remote sensing technology and land use analysis to investigate environmental changes impacting water systems. Researchers may evaluate the impact of land cover dynamics, agricultural expansion, deforestation and urbanization on water quality, watershed health and ecosystem services using satellite data.

Collectively, these clusters offer a thorough understanding of the interdisciplinary character of water-related research, emphasizing how public health concerns, environmental monitoring, water quality analysis and GIS techniques are all integrated into modern scientific investigation.

Sources of water pollution

Water pollution can originate from two sources: 1. A point source; 2. A non-point source. Sources of water pollution are shown in Table 1 (14). Point sources of pollution are those with a direct identifiable source, such as a factory pipe, oil spill from a ship, or industrial effluents. Non-point sources of contamination originate from various non-identifiable sources and infiltrate groundwater or surface water through multiple pathways. Rainwater is a natural source of water pollution as it dissolves contaminants from the air and transports particulate debris. For example, acid rain occurs when acid gasses, such as sulfur and nitrogen oxides, dissolve in raindrops. Dry deposition, or direct deposition of particulate matter by gravity, is a contributing factor to water contamination (15).

Water quality improvement techniques

Membrane filtration technologies (e.g., ultrafiltration, reverse osmosis)

These technologies are effective in removing pathogens, suspended solids and chemical contaminants from water. They are widely used in both drinking water and wastewater treatment. Studies show ultrafiltration membranes effectively remove viruses and bacteria, making them suitable for decentralized water treatment (16).

Constructed wetlands

Constructed wetlands improve water quality by using natural processes involving wetland vegetation, soil and microbial activity to treat wastewater. This approach is sustainable and low-cost, especially suitable for rural and peri-urban areas (17).

Advanced Oxidation Processes (AOPs)

AOPs like ozonation, UV/H_2O_2 and photocatalysis effectively degrade organic contaminants and micropollutants in water. They are particularly useful for removing pharmaceutical residues and pesticides from water supplies (17).

Electrocoagulation

This process uses electric current to remove pollutants such as heavy metals, dyes and suspended solids from water. Electrocoagulation is considered efficient, cost-effective and environmentally friendly compared to chemical coagulation (18).

Nanotechnology based approaches

Nanomaterials, such as nano-adsorbents and nano-membranes, offer high surface area and reactivity, improving the removal of pollutants at low concentrations. These approaches are promising for removing heavy metals and organic pollutants from water (16).

Water quality monitoring and assessment techniques

Field measurements and laboratory analysis

Field measurements and laboratory analysis are critical in water quality assessment. The key parameters analyzed in water quality assessment include Chemical Oxygen Demand (COD) which is the amount of oxygen required to oxidize organic and inorganic materials (12, 19, 20). Biochemical Oxygen Demand (BOD) is the amount of oxygen required by microorganisms to break down organic materials. pH is the acidity or alkalinity of water. Dissolved Oxygen (DO) is the amount of oxygen dissolved in water. Turbidity refers to cloudiness in water caused by suspended particles. Electrical Conductivity (EC) measures the flow of electricity and indicates dissolved ions. Temperature affects chemical and biological processes. Oxidation-Reduction Potential (ORP) which measures the oxidation status of water. Salinity is the concentration of salt in water. Total Nitrogen (TN) and Total Phosphorus (TP) the Indicators of Eutrophication and Nutrient

Table 1. Sources of water pollution (14)

Category	Natural sources of pollution	Anthropogenic sources of pollution
Sediment pollution	Soil erosion from natural processes like rainfall and riverbank collapse	Deforestation and agricultural expansion leading to soil erosion
Nutrient pollution	Natural mineral leaching from rocks and soil	Excessive use of fertilizers in agriculture leading to eutrophication
Organic pollution	Decomposition of organic matter like plant material and animal waste	Industrial and agricultural waste discharge containing organic pollutants
Heavy metal pollution	Natural weathering of rocks and volcanic activity	Industrial effluents from factories, mining and waste disposal
Microbial pollution	Natural microbial activities in soil and water	Untreated sewage discharge and runoff from livestock farms
Chemical pollution	Natural leaching of elements like arsenic and fluoride	Industrial effluents containing chemicals like pesticides, detergents and hydrocarbons
Salinity pollution	Natural salt deposits and seawater intrusion	Irrigation practices and industrial wastewater discharge

Pollution.

Conventional vs. modern monitoring methods

Conventional method: Central Water Commission operates as an example of a traditional technique. Certain places gather water samples within the processing and distribution system, examined in state-of-the-art laboratories (21). Found that traditional water quality monitoring methods, such as i) Manual sampling and laboratory analysis, involve significant human effort. ii) Labor intensive and time-consuming techniques make large-scale monitoring difficult. iii) Samples are collected at discrete locations and times, which may not capture dynamic water quality changes, making them susceptible to human error and providing limited spatial-temporal coverage. Conventional approaches typically include collecting and tracking water samples, which are then analysed in the laboratory (22). Mistakes may occur while processing samples in the lab (21).

Modern monitoring methods: Modern approaches combine real-time data collecting, automation and advanced analytics to improve monitoring efficiency. These methods address the limitations of traditional sampling and lab-based testing by enabling continuous, remote and intelligent analysis of water bodies.

IoT and smart sensors: IoT enables real-time monitoring of water from anywhere in the world with portable sensors, digital computer devices and communication mediums (23). IoT-based sensors continuously monitor pH, turbidity, conductivity and temperature. Data is sent to cloud systems for instant analysis from the study emphasize the importance of IoT in water quality monitoring by enabling wireless, real-time assessments (12).

Remote sensing and GIS applications: Research conducted in Malaysia used satellite imagery from Malaysian Tiungsat-1 to map water quality on Penang Island (24). The study aimed to assess Total Suspended Solids (TSS) and create a water quality map (25). Satellites and drones are used to monitor surface water quality metrics as chlorophyll-a, TSS and turbidity. Water quality at Omerli Dam in Turkey was examined using satellite data and GIS techniques (26).

AI and machine learning: AI-based models such as ANN and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) forecast water quality trends. AI models can examine enormous datasets, identify abnormalities and anticipate outcomes. The application of AI models such as ANN and ANFIS to monitor and assess water quality has been examined (12). The HW model, a machine learning-based system identification technique primarily used for regression tasks, has been effectively applied in modelling DO concentration (27).

Automatic Water Quality Monitoring Stations (AWQMS): These stations continuously monitor important parameters and send real-time data. Used for river, reservoir and coastal monitoring programs. The importance of automated methods in improving data collection and addressing monitoring gaps has been emphasized in previous studies (28). The AWQMS2 station features an autonomous winch system for measuring water quality throughout the water column (29). Korea's AWQMS water pollution alarm criteria follow "the principle of establishing alarm criteria for each parameter" (Ministry of Environment, 2008). The criteria take into account the overall water quality of each site, including drinking water and water from rivers with or without industrial effluent (30).

SWOT comparison between traditional and emerging water quality monitoring methods

Traditional water quality monitoring methods have notable strengths, including high accuracy in controlled laboratory conditions and reliance on well-established, standardized protocols. These methods provide reliable baseline data and are widely accepted in regulatory frameworks. However, they also face significant weaknesses, such as being time-consuming, labour-intensive and offering low sampling frequency, which limits their ability to detect sudden pollution events or real-time changes.

In contrast, emerging technologies such as IoT-enabled devices, AI-driven models and remote sensing combined with GIS offer the strength of real-time, continuous and remote monitoring capabilities. They allow integration with predictive analytics and early warning systems, significantly improving responsiveness to pollution threats. Nevertheless, these methods come with weaknesses such as high initial installation and maintenance costs, challenges with data interoperability and concerns over data privacy and cybersecurity.

Looking at opportunities, traditional methods can be used to benchmark and validate the newer technologies, ensuring scientific rigor and regulatory acceptance. Meanwhile, emerging technologies offer vast potential for scalability, especially in smart city planning and integrated environmental management systems.

Finally, traditional methods face threats such as becoming obsolete in fast-evolving monitoring environments and being inadequate for rapid response scenarios. On the other hand, emerging technologies are vulnerable to technical failures, sensor calibration drift and dependence on uninterrupted internet connectivity, which could affect data reliability.

WQI and their applications

WQI is a mathematical tool used to summarize large amounts of water quality data into a single value, making it easier to understand and compare water quality across different locations and time periods (31). WQIs serve several purposes:

i) Simplifying complex water quality data into an understandable form (32)

ii) Monitoring water quality over time to identify trends (9)

iii)Helps policymakers and the public (33)

Applications

River and surface water monitoring: River pollution from industrial and urban sources has been evaluated using WQI. Urbanization in Nepal's Bagmati River has reduced water quality from 71 (good) to 47.6 (poor) at its discharge (33).

Groundwater assessment: Used to measure the impact of agricultural and industrial operations on groundwater. In Bangladesh, WQI indicated that most groundwater sources near mining regions were acceptable for drinking, although some were contaminated (34).

Urban and industrial pollution assessment: WQI was used in Canada's Mackenzie River basin to analyse industrial pollution from suspended sediments and metals (35).

Climate change and hydrological impact studies: Adjusting WQI models to include climate change impacts on water bodies (36).

Physicochemical and biological parameters of water quality

Standard methods were adapted for the analysis of various water quality parameters APHA-AWWA-WPCF(1989) (37). Physicochemical and biological parameters of water quality are shown in Table 2 (38). pH, specific conductance, temperature, Total Dissolved Solids (TDS) and Total Solids (TS) are the first five factors. Total alkalinity, DO, COD, BOD, total hardness and nutrients.

pH

pH is an important factor regulating the solubility of minerals and heavy metals in water. Water's pH indicates its acidity or alkalinity. The acidic and alkaline ranges are 0-6 and 8-14, respectively. pH levels between 6.5 and 8.5 are considered optimal. It is measured using electrometry and pH electrodes. It has a strong correlation with EC, total hardness, sulphates and TSS (20). The optimal pH range for drinking and surface water is 6.5-8.5, found mildly acidic pH values in the Oban Massif of Nigeria, presumably due to rock weathering and agricultural activity (39).

Conductivity

The ability of an aqueous solution to convey an electric current is expressed numerically as conductivity. This capability is contingent upon the existence of ions, their mobility, relative concentrations, valence and total concentration, as well as the liquid's temperature (38).

Temperature

It influences the chemistry of water. Higher temperatures accelerate chemical reactions, allowing minerals from nearby rocks to dissolve more easily, particularly in groundwater (23). Water temperature influences chemical reactions and biological activity in aquatic ecosystems. Seasonal changes in the water temperature of the Karnaphuli River in Bangladesh were observed, ranging from 22 °C to 30 °C (40).

TDS

Water quality is primarily measured by TDS, water contains both organic and inorganic soluble solids, including cations like magnesium, calcium, sodium and potassium (23). TDS levels above 300 mg/L are unsuitable for drinking. The permissible TDS range is 500 mg/L (41).

Turbidity

Water that is turbid is hazy or cloudy, primarily due to suspended particles that are undetectable to the human eye, such as fine organic and inorganic materials, silt and clay, algae, or soluble coloured organic compounds (23). A study conducted in the Ankober district of Ethiopia found that turbidity values ranged from 0.05 to 8.99 NTU, with higher values observed in areas near agricultural runoff (42).

Total hardness and salinity

Water hardness is determined by measuring the concentrations of dissolved calcium and magnesium salts, primarily in the form of bicarbonates, carbonates, sulphates and chlorides. The optimal limit for total Hardness is 200 mg/L, while the highest allowed value is 600 mg/L (41). Salinity affects water classification and agricultural appropriateness. TDS levels in the dams of the Albaha region in Saudi Arabia were found to exceed acceptable limits, indicating increased salinity (43).

DO

DO represents the dissolved gaseous form of oxygen. Fish and other aquatic species rely on it for breathing (38).This shows oxygen's solubility in water. Water absorbs oxygen from the atmosphere and creates it through photosynthesis and it is

Table 2. Physicochemical and biological parameters of water quality (38)

Study area	Physicochemical parameters analyzed	Bacteriological parameters analyzed	Key findings & role in water classification	Key findings & role in geochemical processes
Nsukka, Nigeria	pH, DO, BOD, Chloride, Total Hardness, TDS, Sulphate, Nitrate	Total Bacteria Count and Coliform Count	Classified water as unfit for drinking due to bacterial contamination; good physicochemical attributes	Presence of nitrates and sulphates linked to agricultural runoff and natural weathering processes
Vaigai River, India	pH, EC, DO, BOD, COD, Total Hardness, Nitrate, Chloride	Total Coliform and Fecal Coliform	High EC and TDS indicate pollution; not suitable for drinking	Elevated BOD and COD suggest organic pollution from urban and industrial sources
Karnaphuli River, Bangladesh	pH, EC, BOD, COD, TDS, TSS	Total Coliform and Fecal Coliform	High contamination levels, unsuitable for consumption	Industrial discharge and sewage inflow identified as primary contributors to pollution
Oban Massif, Nigeria	pH, EC, Turbidity, TDS, BOD, DO	Total Coliform and Fecal Coliform	Water mostly within permissible limits, except for bacteriological contamination	Ion concentrations suggest geogenic sources with some anthropogenic influences
Samaru, Nigeria	pH, EC, DO, Chloride, Nitrate, Hardness	Total Bacteria and Coliforms	High bacterial load renders water unsafe	Nitrate and phosphate pollution linked to agricultural activities
Albaha, Saudi Arabia	pH, TDS, NO_3, SO_4, Fe, Mn	Coliform Bacteria	Some dam water exceeded permissible levels for pH and dissolved solids	High NO_3 and SO_4 concentrations linked to agricultural runoff
Ankober, Ethiopia	pH, EC, DO, Alkalinity, Hardness, Major Ions	Total Coliform and Fecal Coliform	Water is mostly safe, with localized contamination concerns	Seasonal variation affects ion concentrations due to weathering and dilution
Kidd's Beach, South Africa	pH, Temperature, EC, Salinity, Turbidity	Enterococcus and Total Coliform	High bacterial contamination poses health risks	Anthropogenic influences such as sewage discharge contribute to microbial contamination

crucial for aquatic life. It is typically measured using an electrometric meter or Winkler titration (20). DO levels in the surface waters of Oban Massif, Nigeria, were found to range from 4 to 6.5 mg/L, which are suitable for fish survival (39).

BOD

BOD quantifies the breakdown of organic matter. BOD levels in the Vaigai River in India were reported to range from 4.5 to 22.6 mg/L, indicating organic contamination due to wastewater discharge (44). BOD can be found in a variety of sources, such as leaves and woody debris, dead plants and animals, animal manure, wastewater treatment plant effluents, feedlots, food processing facilities, pulp and paper mills, failed septic systems and urban storm water runoff.

COD

The amount of oxygen needed for the chemical oxidation of organic materials with the aid of a potent chemical oxidant is measured by COD (45). Elevated COD could lead to oxygen depletion brought on by microbial breakdown to a point where it is harmful to aquatic life. COD levels in the Karnaphuli River ranged from 25.7 mg/L to 86.7 mg/L, exceeding the WHO limit of 10 mg/L and underlining industrial pollution (40).

Nutrients

Ammonia and inorganic nitrogen are two forms of nitrogen that can infiltrate lakes and streams. Aquatic systems have a plentiful amount of accessible nitrogen because nitrogen can enter them in a variety of ways (38). Eutrophication and algal blooms result from excessive nitrogen levels. Nitrate concentrations in the Vaigai River were found to range from 4.51 to 7.51 mg/L, suggesting possible contamination from agricultural runoff (44).

Heavy metals in water and their health implications

Heavy metals are major environmental pollutants because of their persistence, toxicity and bioaccumulation in ecosystems. The most frequent heavy metals found in water sources are arsenic (As), lead (Pb), copper (Cu), chromium (Cr), manganese (Mn), iron (Fe) and nickel (Ni). These metals come from both natural and manmade sources, including industrial waste, mining operations and agricultural runoff.

Arsenic (As)

Natural geological formations, mining operations, industrial effluents and pesticide applications are the main causes of arsenic contamination in water (46). Groundwater systems frequently include arsenic, which can linger because of the natural weathering of minerals that contain it (47).

Lead (Pb)

Lead contamination is primarily caused by leached old plumbing systems, industrial pollutants, battery waste and mining activities (48). Lead accumulates in drinking water when deteriorated pipes emit lead particles, posing a considerable risk to water users (47).

Copper (Cu)

Copper enters water through industrial effluents, deteriorated pipes and agricultural runoff (49). Copper contamination is commonly associated to acid mine drainage and chemical manufacturing operations, which discharge excessive copper into aquatic systems in the study (46).

Chromium (Cr)

Electroplating, textile, leather tanning and industrial waste sectors are the primary sources of chromium pollution (50). Trivalent (Cr III) and hexavalent (Cr VI) forms of chromium are both extremely toxic and carcinogenic (47).

Manganese (Mn)

Mining operations, industrial waste discharges and natural deposits all contribute to manganese contamination (51). Groundwater systems frequently have elevated manganese levels in drinking water, especially in regions with significant natural manganese reserves (49).

Iron (Fe)

Natural sources, industrial effluents and deteriorated pipelines are the main causes of iron contamination (5). Despite being a necessary nutrient, too much iron in drinking water can cause discoloration and a metallic taste (47).

Nickel (Ni)

Nickel pollution comes from metal plating, mining and fossil fuel burning (52). Nickel contamination in urban water sources has been related with industrial discharge and atmospheric deposition (46).

Statistical and geospatial techniques for water quality assessment

Remote sensing provides a spatial and temporal view of surface water quality, allowing for more efficient monitoring and quantification of concerns (19). In water quality evaluations, multivariate statistical methods including Cluster Analysis (CA), Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) are frequently employed. PCA was applied to identify the origins of the trace elements in the surface waters of Kizilirmak River (53). Relationships between optical (NDVI, NDWI and MNDWI) and non-optical (TDS, BOD, hardness and DO) water quality measures were examined in this work using Pearson correlation and scatter plots (11). Regression modelling was utilized to predict non-optical using the factors that were chosen using PCA. The water quality metrics (EC, TDS, Ca, Mg and total hardness) of a few chosen tanks were analysed spatially and temporally using box plots. By converting correlated variables into a collection of uncorrelated components, PCA is used to simplify huge datasets. PCA was employed by to identify the main causes of water contamination, including household wastewater, agricultural runoff and industrial effluents (54). Prioritizing intervention options is made easier by the major components that were identified from the data, which show the primary pollutants influencing water bodies.

Water quality assessment in the some previous studies used multivariate analysis (PCA, CA) to find connections and descriptive statistics to summarize parameters (11, 55). Whereas ANOVA or t-tests assess changes, regression analysis looks at affecting factors. GIS methods such as overlay analysis evaluates environmental effects and spatial interpolation (Kriging, IDW) forecasts water quality. Hotspots for pollution are seen by thematic mapping and hydrological influences are better understood through watershed modelling. These techniques improve precision and facilitate efficient water management. A statistical technique called HCA is used to organize water quality data into hierarchical categories. To support the design of targeted water management plans, a study demonstrated how HCA can be used to group water samples with similar pollutant characteristics (54). The study was conducted in the Oued Laou Mediterranean Watershed in Morocco. Sampling stations were geographically classified using the Euclidean distance and Ward's linkage method to assess similarity and dissimilarity. HCA was employed to validate the results of PCA (56).

Integration of PCA, HCA and GIS in real-world water quality monitoring

To ensure reproducibility and enhance real-world applicability, many water quality studies now combine multivariate statistical methods like PCA and HCA with spatial tools like GIS. This integrated approach allows for both data reduction and pattern recognition (via PCA/HCA) and spatial visualization and decision-making support (via GIS).

PCA

PCA reduces the dimensionality of complex water quality datasets by identifying the most influential variables, helping to uncover key pollution sources and seasonal trends. For example in a study of the Ganges River, PCA was applied to surface water quality parameters to identify the dominant factors controlling pollution such as organic load and agricultural runoff-simplifying a dataset of 15+ variables into 3-4 meaningful components. This allowed environmental managers to focus interventions on the most critical pollutants. In China's Taihu Lake Basin, PCA helped separate natural from anthropogenic sources of pollution by showing how components like nitrate and phosphate aligned with urban discharge zones. By highlighting which variables explain the most variance, PCA ensures efficient monitoring design and reduces redundancy.

HCA

HCA is used to group monitoring sites or sampling periods based on similarities in water quality. This clustering enhances interpretability and helps prioritize regions with similar pollution profiles. For instance: In a study of groundwater in Iran, HCA grouped 20 wells into three distinct clusters based on their chemical composition and contamination levels, enabling focused groundwater protection strategies. Another example from the Danube River Basin showed that HCA effectively grouped upstream and downstream locations based on pollutant concentrations, guiding localized management plans. HCA strengthens site classification and decision targeting, reducing monitoring and treatment costs.

GIS

GIS facilitates the spatial mapping and visualization of water quality indicators, enabling better communication with policymakers and the public. It also allows integration with land use, hydrological and pollution source data. Key applications include: in Malaysia, GIS was used with satellite data to map suspended solids and chlorophyll-a concentrations across Penang Island, helping visualize hotspot areas for marine pollution control. In Turkey's Omerli Dam, GIS combined with PCA and HCA allowed for spatial interpretation of pollutant sources and risk zones, optimizing where monitoring stations should be installed. GIS ensures that statistical findings are translated into actionable spatial insights for regional water resource management.

Challenges and future aspects in water quality management

Challenges in water quality management arise from increasing pollution levels due to domestic, agricultural and industrial sources, making treatment more difficult. Emerging contaminants, such as heavy metals, microplastics and pharmaceuticals, further complicate water purification efforts (57). Rising temperatures, shifting precipitation patterns and extreme weather events driven by climate change exacerbate water quality issues and pose challenges for sustainable water management (58). Uneven enforcement of policies and a lack of international cooperation create significant gaps in regulations, hindering effective water management (59). The absence of proper wastewater treatment and monitoring systems in many regions highlights the inadequacy of infrastructure for effective water management (60). High costs and limited access to advanced water treatment technologies create significant technological and financial constraints, hindering effective water management (61). For a future-oriented perspective on water quality protection, public awareness and participation through education and community involvement are essential (59). A holistic approach to sustainability, known as Integrated Water Resource Management (IWRM), integrates land and water management to ensure long-term resource efficiency (57). Water purification and quality control can be greatly enhanced by advanced treatment methods, such as membrane filtration, bioremediation and nanotechnology (62). Additionally, leveraging big data, remote sensing and real-time monitoring can enhance decision-making and improve water management efficiency. Raising awareness and actively engaging local communities in conservation efforts remain crucial for sustainable water management (60).

Conclusion

Water quality assessment is an important part of long-term water resource management, especially considering rising anthropogenic demands and climate change. This overview discusses the many physical, chemical and biological factors used to assess water quality, as well as commonly used classification systems and indices. It also includes an overview of several water quality models, which are useful tools for modelling and predicting water quality dynamics in various aquatic habitats. Each model has a distinct structure, strengths and limits, so it is critical to choose an appropriate model based on specific goals, data availability and catchment features. While traditional monitoring methods are accurate, they are typically time-consuming and costly, underlining the growing need for robust, user-friendly modelling approaches.

To improve the precision and application of water quality evaluations, future research should concentrate on incorporating cutting-edge technologies including real-time data collection, machine learning and remote sensing. For policymakers, academics and water resource managers seeking to preserve and restore water quality across diverse ecosystems, a hybrid strategy that combines field observations with model simulations can provide thorough insights.

Acknowledgements

The authors would like to extend their sincere gratitude to chairperson and advisory committee members.

Authors' contributions

AB conducted the review work, including literature collection and analysis. SS contributed to the conceptualization, supervision and work planning of the review. VR assisted in refining and structuring the review content. US and KB contributed to writing the manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflict of interest.

Ethical issues: None

References

1. Huchhe MR, Bandela N. Study of water quality parameter assessment using GIS and remote sensing in DR. BAM University, Aurangabad, MS. International Journal of Latest Technology in Engineering, Management & Applied Science. 2016;5(6):46-50.
2. Kc A, Chalise A, Parajuli D, Dhital N, Shrestha S, Kandel T. Surface water quality assessment using remote sensing, GIS and artificial intelligence. Technical Journal. 2019;1(1):113-22.
3. Singh P, Tiwari AK, Singh PK. Hydro chemical characteristic and quality assessment of groundwater of Ranchi township area, Jharkhand, India. Current World Environment. 2014;9(3):804.
4. Chandra S, Singh PK, Tiwari AK, Panigrahy BP, Kumar A. Evaluation of hydrogeological factors and their relationship with seasonal water table fluctuation in Dhanbad district, Jharkhand, India. ISH Journal of Hydraulic Engineering. 2015;21(2):193-206.
5. Tiwari AK, Singh PK, Singh AK, De Maio M. Estimation of heavy metal contamination in groundwater and development of a heavy metal pollution index by using GIS technique. Bulletin of Environmental Contamination and Toxicology. 2016;96:508-15. https://doi.org/10.1007/s00128-016-1850-6
6. Sanad H, Moussadek R, Dakak H, Zouahri A, Oueld Lhaj M, Mouhir L. Ecological and health risk assessment of heavy metals in groundwater within an agricultural ecosystem using GIS and multivariate statistical analysis (MSA): A case study of the Mnasra region, Gharb Plain, Morocco. Water. 2024;16(17):2417. https://doi.org/10.3390/w16172417
7. Japitana MV, Burce MEC. A satellite-based remote sensing technique for surface water quality estimation. Engineering, Technology & Applied Science Research. 2019;9(2):3965-70.
8. Al-Dahhan NAA, Al-Atwi AKH, Al-Zubaidi MGM, editors. Water quality index for surface water assessment by using remote sensing and GIS techniques, Al-Najaf, Al-Manathera district, Iraq. Journal of Physics: Conference Series; 2019.
9. Badar MS, Ali S, Daniyal, Akram MW, Faheem K, Khan SU, et al. GIS -based assessment of groundwater vulnerability to heavy metal contamination via water quality pollution indices in urban Aligarh, India. Water Practice & Technology. 2024;19(2):419-34. https://doi.org/10.2166/wpt.2024.071
10. Adilakshmi A, Venkatesan V. Effective monitoring of Noyyal River surface water quality using remote sensing and machine learning and GIS techniques. Desalination and Water Treatment. 2024;320:100630. https://doi.org/10.5004/dwt.2024.100630
11. Ramachandran R, Kannan B, Sivasubramanian K, Arunadevi K, Patil S. Spatio-temporal analysis of surface water quality on urban tanks in Coimbatore. Plant Science Today. 2025;12:5919. https://doi.org/10.14719/pst.5919
12. Ighalo JO, Adeniyi AG, Marques G. Internet of things for water quality monitoring and assessment: a comprehensive review. In: Hassanien AE, Bhatnagar R, Darwish A, editors. Artificial intelligence for sustainable development: theory, practice and future applications. 2021:245-59. https://doi.org/10.1007/978-3-030-51920-9_13
13. Van Eck N, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2010;84(2):523-38. https://doi.org/10.1007/s11192-009-0146-3
14. Singh MR, Gupta A. Water pollution-sources, effects and control. Centre for Biodiversity, Department of Botany, Nagaland University. 2016:1-16.
15. Singh J, Yadav P, Pal AK, Mishra V. Water pollutants: Origin and status. In: Sensors in water pollutants monitoring: Role of material. 2020:5-20.
16. Khan NA, Singh S, López-Maldonado EA, Méndez-Herrera PF, López-López JR, Baig U, et al. Emerging membrane technology and hybrid treatment systems for the removal of micropollutants from wastewater. Desalination. 2023;565:116873. https://doi.org/10.1016/j.desal.2023.116873
17. Al-Jabri K, Al-Mulla Y, Melgani F, Stefanakis A. Remote sensing analysis for vegetation assessment of a large-scale constructed wetland treating produced water polluted with oil hydrocarbons. Remote Sensing. 2023;15(24):5632. https://doi.org/10.3390/rs15245632
18. Yadav P, Singh RP, Singh G, Verma H, Singh SK, Dahiya P, et al. Contamination removal from waste water using electrochemical approaches. Advances in Chemical Pollution, Environmental Management and Protection. 2024;10:261–73. https://doi.org/10.1016/bs.apmp.2023.08.004
19. Gholizadeh MH, Melesse AM, Reddi L. A comprehensive review on water quality parameters estimation using remote sensing techniques. Sensors. 2016;16(8):1298. https://doi.org/10.3390/s16081298
20. Ahmed U, Mumtaz R, Anwar H, Mumtaz S, Qamar AM. Water quality monitoring: from conventional to emerging technologies. Water Supply. 2020;20(1):28-45. https://doi.org/10.2166/ws.2019.070
21. Babatunde A. A study on traditional water quality assessment methods. Risk Assessment and Management Decisions. 2024;1(1):41-52.
22. Amrita CM, Babiyola D. Analysing the water quality parameters from traditional to modern methods in aquaculture. International Journal of Science, Environment and Technology. 2018;7(6):1954-61.
23. Jan F, Min-Allah N, Düştegör D. IoT based smart water quality monitoring: Recent techniques, trends and challenges for domestic applications. Water. 2021;13(13):1729. https://doi.org/10.3390/w13131729
24. Lim H, MatJafri M, Abdullah K, Saleh N, AlSultan S, editors. Remote sensing of PM10 from LANDSAT TM imagery. Acrs; 2004.
25. Usali N, Ismail MH. Use of remote sensing and GIS in monitoring water quality. Journal of Sustainable Development. 2010;3(3):228.
26. Alparslan E, Aydöner C, Tufekci V, Tüfekci H. Water quality assessment at Ömerli Dam using remote sensing techniques. Environmental Monitoring and Assessment. 2007;135(1):391-8.
27. Lowe M, Qin R, Mao X. A review on machine learning, artificial intelligence and smart technology in water treatment and monitoring. Water. 2022;14(9):1384. https://doi.org/10.3390/w14091384
28. Behmel S, Damour M, Ludwig R, Rodriguez M. Water quality monitoring strategies-a review and future perspectives. Science

of the Total Environment. 2016;571:1312-29. https://doi.org/10.1016/j.scitotenv.2016.07.069

29. Rouen M, George G, Kelly J, Lee M, Moreno-Ostos E, editors. High-resolution automatic water quality monitoring systems applied to catchment and reservoir monitoring. Freshwater Forum; 2010.

30. Lim BJ, Hong EY, Kim HO, Jeong ES, Heo WM, Kim YH. Establishment of Alarm Criteria for Automatic Water Quality Monitoring System in Korea. Korean Journal of Ecology and Environment. 2008;41(4):423-30.

31. Aljanabi ZZ, Al-Obaidy A-HMJ, Hassan FM, editors. A brief review of water quality indices and their applications. IOP Conference Series: Earth and Environmental Science; 2021.

32. Sutadian AD, Muttil N, Yilmaz AG, Perera B. Development of river water quality indices-a review. Environmental Monitoring and Assessment. 2016;188:1-29. https://doi.org/10.1007/s10661-016-5395-1

33. Kannel PR, Lee S, Lee Y-S, Kanel SR, Khan SP. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environmental Monitoring and Assessment. 2007;132:93-110. https://doi.org/10.1007/s10661-006-9506-4

34. Howladar MF, Al Numanbakth MA, Faruque MO. An application of Water Quality Index (WQI) and multivariate statistics to evaluate the water quality around Maddhapara granite mining industrial area, Dinajpur, Bangladesh. Environmental Systems Research. 2018;6:1-18.

35. Lumb A, Halliwell D, Sharma T. Application of CCME water quality index to monitor water quality: A case study of the Mackenzie River basin, Canada. Environmental Monitoring and Assessment. 2006;113:411-29.

36. Zahraa Z, Abdul-Hameed M, Al-Obaidy J, Hassan F, editors. A brief review of water quality indices and their applications. IOP Conference Series: Earth and Environmental Science; 2019.

37. Alam MJ, Islam MR, Muyen Z, Mamun M, Islam S. Water quality parameters along rivers. International Journal of Environmental Science & Technology. 2007;4:159-67.

38. Gorde S, Jadhav M. Assessment of water quality parameters: a review. J Eng Res Appl. 2013;3(6):2029-35.

39. Ugbaja A, Ephraim B. Physicochemical and bacteriological parameters of surface water quality in part of Oban Massif, Nigeria. Global Journal of Geological Sciences. 2019;17:13-24.

40. Dey S, Uddin MS, Manchur MA. Physicochemical and bacteriological assessment of surface water quality of the Karnaphuli River in Bangladesh. Journal of Pure and Applied Microbiology. 2017;11(4):1721-8.

41. Kothari V, Vij S, Sharma S, Gupta N. Correlation of various water quality parameters and water quality index of districts of Uttarakhand. Environmental and Sustainability Indicators. 2021;9:100093.

42. Kassegne AB, Leta S. Assessment of physicochemical and bacteriological water quality of drinking water in Ankober district, Amhara region, Ethiopia. Cogent Environmental Science. 2020;6(1):1791461.

43. Albaggar AKA. Investigation of some physical, chemical and bacteriological parameters of water quality in some dams in Albaha region, Saudi Arabia. Saudi Journal of Biological Sciences. 2021;28(8):4605-12. https://doi.org/10.1016/j.sjbs.2021.06.057

44. Mallika S, Umamaheswari R, Krishnamoorthy S. Physico-chemical parameters and bacteriological study of Vaigai river water Madurai district, Tamilnadu, India. International Journal of Fisheries and Aquatic Studies. 2017;5(1):42-5.

45. Dohare D, Deshpande S, Kotiya A. Analysis of ground water quality parameters: A review. Research Journal of Engineering Sciences. 2014;3(5):26-31.

46. Latif M, Nasim I, Ahmad M, Nawaz R, Tahir A, Irshad MA, et al. Human health risk assessment of drinking water using heavy metal pollution index: a GIS-based investigation in mega city. Applied Water Science. 2025;15(1):12. https://doi.org/10.1007/s13201-024-02473-9

47. Fallahzadeh RA, Ghaneian MT, Miri M, Dashti MM. Spatial analysis and health risk assessment of heavy metals concentration in drinking water resources. Environmental Science and Pollution Research. 2017;24:24790-802. https://doi.org/10.1007/s11356-017-01029-5

48. Shirkhanloo H, Mirzahosseini SAH, Shirkhanloo N, Moussavi-Najarkola SA, Farahani H. The evaluation and determination of heavy metals pollution in edible vegetables, water and soil in the south of Tehran province by GIS. Archives of Environmental Protection. 2015;41(2).

49. Bux RK, Haider SI, Mallah A, Shah Z-u-H, Solangi AR, Moradi O, et al. Spatial analysis and human health risk assessment of elements in ground water of District Hyderabad, Pakistan using ArcGIS and multivariate statistical analysis. Environmental Research. 2022;210:112915. https://doi.org/10.1016/j.envres.2022.112915

50. Arnous MO, Hassan MA. Heavy metals risk assessment in water and bottom sediments of the eastern part of Lake Manzala, Egypt, based on remote sensing and GIS. Arabian Journal of Geosciences. 2015;8:7899-918. https://doi.org/10.1007/s12517-015-1976-8

51. Şener Ş, Şener E, Davraz A. Assessment of groundwater quality and health risk in drinking water basin using GIS. Journal of Water and Health. 2017;15(1):112-32. https://doi.org/10.2166/wh.2016.202

52. Tiwari AK, De Maio M, Singh PK, Mahato MK. Evaluation of surface water quality by using GIS and a heavy metal pollution index (HPI) model in a coal mining area, India. Bulletin of Environmental Contamination and Toxicology. 2015;95:304-10. https://doi.org/10.1007/s00128-015-1558-9

53. Cüce H, Kalıpcı E, Ustaoğlu F, Kaynar I, Baser V, Türkmen M. Multivariate statistical methods and GIS based evaluation of the health risk potential and water quality due to arsenic pollution in the Kızılırmak River. International Journal of Sediment Research. 2022;37(6):754-65. https://doi.org/10.1016/j.ijsrc.2022.03.005

54. Mohseni U, Patidar N, Pathan AI, Agnihotri P, Patel D. An innovative approach for groundwater quality assessment with the integration of various water quality indexes with GIS and multivariate statistical analysis- a case of Ujjain City, India. Water Conservation Science and Engineering. 2022;7(3):327-49. https://doi.org/10.1007/s40899-022-00606-8

55. Uslu A, Dugan ST, El Hmaidi A, Muhammetoglu A. Comparative evaluation of spatiotemporal variations of surface water quality using water quality indices and GIS. Earth Science Informatics. 2024;17(5):4197-212. https://doi.org/10.1007/s12145-023-00924-x

56. Azhari HE, Cherif EK, Sarti O, Azzirgue EM, Dakak H, Yachou H, et al. Assessment of surface water quality using the water quality index (IWQ), multivariate statistical analysis (MSA) and geographic information system (GIS) in Oued Laou Mediterranean Watershed, Morocco. Water. 2022;15(1):130. https://doi.org/10.3390/w15010130

57. Bekele E, Page D, Vanderzalm J, Kaksonen A, Gonzalez D. Water recycling via aquifers for sustainable urban water quality management: Current status, challenges and opportunities. Water. 2018;10(4):457. https://doi.org/10.3390/w10040457

58. Grady CA, Weng SC, Blatchley ER. Global potable water: current status, critical problems and future perspectives. In: Potable water: Emerging global problems and solutions. 2014:37-59.

59. Dalu T, Froneman PW. Diatom-based water quality monitoring in southern Africa: challenges and future prospects. Water SA. 2016;42(4):551-9. https://doi.org/10.4314/wsa.v42i4.11

60. Parris K. Impact of agriculture on water pollution in OECD countries: recent trends and future prospects. Water Quality Management. 2014:33-52.

61. Chen J, Chen S, Fu R, Li D, Jiang H, Wang C, et al. Remote sensing big data for water environment monitoring: Current status, challenges and future prospects. Earth's Future. 2022;10 (2):e2021EF002289. https://doi.org/10.1029/2021EF002289

62. Araújo SO, Peres RS, Ramalho JC, Lidon F, Barata J. Machine learning applications in agriculture: current trends, challenges and future perspectives. Agronomy. 2023;13(12):2976. https://doi.org/10.3390/agronomy13122976

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.