J. Indian Inst. Sci.
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

Check for updates

REVIEW ARTICLE

Bangalore Lakes Information System (BLIS) for Sustainable Management of Lakes

T. V. Ramachandra[1,2,3,4], K. S. Asulabha[1], V. Sincy[1], Abhishek Baghel[1] and S. Vinay[1]*

Abstract | Wetlands (lakes, tanks, ponds, etc.), transitional lands linking hydrologically the terrestrial ecosystem with aquatic ecosystems with biophysical interactions, are the most productive and diverse ecosystems and provide numerous ecological, economic, and social benefits for human well-being. These vital ecosystems sustain ecological processes to provide services such as nutrient cycling, water purification, reducing pollution, carbon sequestration, groundwater recharge, provision of fish, fodder, fuel, and water, flood reduction, erosion control, aquatic biota habitats, education opportunities, aesthetics, and recreation. However, due to globalization, these fragile ecosystems are vulnerable to unplanned developmental activities and rapid urbanization, leading to large-scale land cover changes and hydrologic regimes. The sustained inflow of untreated wastewater (from the industrial and domestic sectors) into wetlands has altered the chemical integrity, which necessitates inventorying, mapping, and regular wetland monitoring to evolve conservation strategies. Integrating spatial and non-spatial data, analysis, and visualization with decision models through decision support systems enables informed decisions. In this context, the Bangalore Lake Information System (BLIS) is designed with information on water quality, biodiversity (microalgae, zooplankton, ichthyofauna, macrophytes, and birds), threats (encroachments, inflow of untreated sewage, etc.) and ecosystem services of lakes in Bangalore, Karnataka State, India. Rapid large-scale land use changes have resulted in an alteration in the hydrologic regime, the loss of habitats, and the disappearance of native species. BLIS empowers decision-making through knowledge of lake distribution in terms of the physical, chemical, and biological aspects and the value of ecosystem services, which is crucial for evolving strategies for prudent management of water bodies in Greater Bangalore.

Keywords: *BLIS, Lakes, Urbanization, Biodiversity, Restoration, Ecosystem services*

[1] Energy and Wetlands Research Group [CES TE15], Centre for Ecological Sciences, Indian Institute of Science, New Bioscience Building, Third Floor, E-Wing, [Near D-Gate], Bangalore 560012, India.
[2] Centre for Sustainable Technologies (ASTRA), Indian Institute of Science, Bangalore 560012, India.
[3] Centre for Infrastructure, Sustainable Transportation and Urban Planning (CiSTUP), Indian Institute of Science, Bangalore 560 012, India.
[4] Department of Civil Engineering, Alva's Institute of Engineering and Technology, Moodbidire, India.
**tvr@iisc.ac.in, envis.ces@iisc.ac.in*

1 Introduction

The freshwater ecosystems include lakes, ponds, streams, rivers, wetlands, springs, and groundwater. Wetlands (and lakes) constitute the most productive ecosystems, with a wide array of goods and services. These ecosystems serve as life support systems and habitats for a variety of organisms, including migratory birds, for food and shelter. They aid in bioremediation or removing contaminants and are aptly known as 'kidneys of

Springer IISc PRESS

the landscape'. Major services include flood control, wastewater treatment, arresting sediment load, drinking water, protein production, and, more importantly, recharging of aquifers, apart from aiding as sinks and climate stabilizers. The wetlands provide a low-cost way to treat the community's wastewater while functioning as a wild fauna sanctuary with public access. Due to their rich biodiversity, these ecosystems are valuable for education and scientific endeavors.

Wetlands (lakes) are crucial for sustaining the regional hydrological cycle and providing ecosystem services (provisioning, regulating, and cultural services) such as food, water provision, water purification, microclimate regulation, habitat provision, erosion control, flood mitigation, groundwater recharge, carbon sequestration, aesthetics, and recreation[1]. Complex natural processes like vegetation cover, climatic variability, hydrologic regime, agricultural run-off, anthropogenic activities like industrial and sewage discharge, and land use dynamics[2–4] govern the quality and quantity of water in water bodies.

Physical, chemical, and biological factors influence water quality in freshwater bodies. The chemical integrity of waterbodies is altered with the discharge of untreated industrial effluents, agricultural run-off, soil erosion, farming in wetland areas, mining, and associated anthropogenic activities[5]. Many waterbodies have recently been severely contaminated due to the sustained inflow of untreated or partially treated domestic sewage and industrial effluents and rapid urbanization coupled with the increase in industrial expansion and population[6–8]. The influx of untreated wastewater has decreased dissolved oxygen (DO), affecting biota. Water quality degradation has recently raised a lot of concern due to its detrimental effects on social, economic, and health aspects, which have been a significant concern at the local, regional, and international levels. The River Ganga in India, which provides vital habitats to 350 fish species, is seriously threatened by rapid urban development and wastewater run-off from agricultural and industrial activities[9]. High nutrient load in Amirkalayeh wetland, Northern Iran, has raised the trophic level and hyper-eutrophication conditions[10]. Wastewater from industrial and agriculture sectors contributes wastewater laden with heavy metals, which causes toxicity, persistence, and biomagnification in biological organisms, which would lead to the contamination of the human food chain with severe health implications for society[11,12], which necessitates assessing the cost of ecosystem degradation with the sustained discharge of untreated wastewater. Factors like light, water temperature, habitat conditions, climate, and substrate composition influence the composition and distribution of aquatic species. Wetlands serve as habitat for microalgae, zooplankton, fish, macrophytes, and water birds. The decline of biodiversity in aquatic ecosystems is due to habitat alteration, habitat loss, alteration in chemical integrity due to pollution, introduction of exotic species, overexploitation of aquatic organisms, etc.

Geoinformatics, with the availability of spatial data acquired through space-borne sensors at regular intervals and advancements in the Geographic Information System (GIS), has been useful in assessing landscape dynamics, which provides vital insights for the prudent management of wetlands[13–18].

Bangalore city (Karnataka State, India) has been experiencing unprecedented urbanization and sprawl due to concentrated developmental activities in recent times, with an impetus on industrialization for economic development. This concentrated growth has increased population and consequent pressure on infrastructure and natural resources, ultimately giving rise to a plethora of serious challenges, such as climate change, enhanced greenhouse gas emissions, a lack of appropriate infrastructure, traffic congestion, and a lack of basic amenities (electricity, water, and sanitation) in many localities, etc. Temporal data analyses of five decades (1973–2023) reveal that there has been a 1055% increase in paved surfaces (built-up, etc.) with a decline in vegetation (88%) and water (79%). The urban heat island phenomenon is evident in a large number of localities with higher local temperatures. The city once enjoyed a salubrious climate (about 14–16 °C during peak summer–May month in the early eighteenth century), but now it has been experiencing higher temperatures (34–37 °C) with an altered microclimate and frequent flooding during rainy days. The study reveals the haphazard pattern of growth in Bangalore and its implication on local climate (an increase of ~ 2 to 2.5 °C during the last decade) and also on natural resources, necessitating appropriate strategies for the sustainable management of natural resources (water bodies, tree cover, etc.). The frequent flooding (since 2000, even during normal rainfall) in Bangalore is a consequence of the increase in impervious areas with the high-density urban development in the catchment and the loss of wetlands and vegetation[19].

Urban ecosystems are the consequence of the intrinsic nature of humans as social beings live together. Unplanned urbanization and consequent urban sprawl have posed serious challenges to the decision-makers in the city planning and management process, involving a plethora of issues like inadequate infrastructure, traffic congestion, lack of basic amenities (electricity, water, and sanitation), loss of vegetation cover, decline in water bodies (quality and quantity), decline in groundwater table, recurring instances of floods, heat islands, enhanced greenhouse gas (GHG) footprint, etc. In this context, detailed field investigations were carried out in the existing lakes of Bangalore to understand the physical, chemical, and biological integrity through (a) assessment of the spatial dynamics of the lakes, (b) water quality encompassing physical and chemical aspects, (c) documentation of biodiversity (flora and fauna), and (d) assessment of threats. Based on these, the BLIS, or Bangalore Lake Information System, was designed for informed decision-making and prudent management. The present study bridges the information gap concerning lakes in Bangalore through the provision of information (lake-wise water quality, microalgae, zooplankton, fish, ecosystem services, threats- encroachments, etc.) based on the sustained ecological research on lakes of Bangalore over two decades.

2 Materials and Methods

2.1 Study Area

Greater Bangalore, with a spatial extent of 741 km^2, is the principal administrative, cultural, commercial, industrial, and educational capital of the state of Karnataka. Bangalore is located at 12° 59′ N latitude and 77° 57′ E longitude, almost equidistant from both the eastern and western coasts of the South Indian peninsula, and is situated at 920 m above mean sea level. The mean annual total rainfall is about 900 mm. The summer temperature ranges from 18 to 38 °C, while the winter temperature ranges from 12 to 25 °C. Thus, Bangalore enjoyed a salubrious climate all year with its numerous parks and abundant greenery, known as the 'Garden City' of India. Bangalore has an average annual rainfall of 859 mm, and temperatures range from 14 °C (December–January) to 33 °C (highest from March to May). There are two rainy seasons: June to September (southwest monsoon) and November to December (northeast monsoon)[20,21].

The Bangalore landscape is located over ridges, forming three watersheds. The undulating terrain in the region has facilitated the creation of a large number of interconnected lakes. Bangalore has grown spatially more than 10 times since 1951. There have been reorganizations with respect to the zones and wards within the corporation, rising from 50 divisions in 1949 to 95 wards in the 1980s, 100 wards in 1995, and now about 150 wards. With the 2006 notification, the Bangalore City Corporation is now reorganized as Greater Bangalore City Corporation with 198 wards (for decentralized administration at the local level as per the 74th Amendment of the Indian Constitution). The city is now known for its growth in information technology (IT)-based industries. With economic liberalization since the early 1990s, Bangalore has taken the lead in service-based industries, fueling its economic and spatial growth. As a cosmopolitan city, Bangalore attracts people and businesses from across the globe, making it a leading player in the IT industry[20,21]. With undulating terrain, the Bangalore landscape forms three major watersheds: Koramangala-Challaghatta Valley, Vrishabhavathi Valley, and Hebbal Valley.

2.2 Landscape Dynamics

Temporal remote sensing data (corresponding to the post-monsoon period–November month) were geo-referenced, geometrically and radiometrically corrected, and cropped to conform to the spatial extent of the study area. Geo-referencing of remote sensing data (landsat multispectral sensor—MSS, thematic mapper—TM and operational land imager—OLI) was done using ground control points collected from the field using a pre-calibrated Global Positioning System (GPS) and also considering known location points (such as road intersections, etc.) collected from geo-referenced topographic maps published by the Survey of India (https://surveyofindia.gov.in/). Land-use classification using remote sensing data involved (a) generation of false color composite (FCC), which helped in identifying and locating heterogeneous patches of landscapes, (b) selection of training data from the FCC corresponding to heterogeneous patches (covering at least 15% of the total area and uniformly distributed over the study area), (c) loading of these training data sites as polygon features to a GPS for compiling attribute information for the training data from the field and online portal with higher spatial resolution data (earth.google.com), (d) land-use analysis through supervised pattern classifier based on the Gaussian maximum

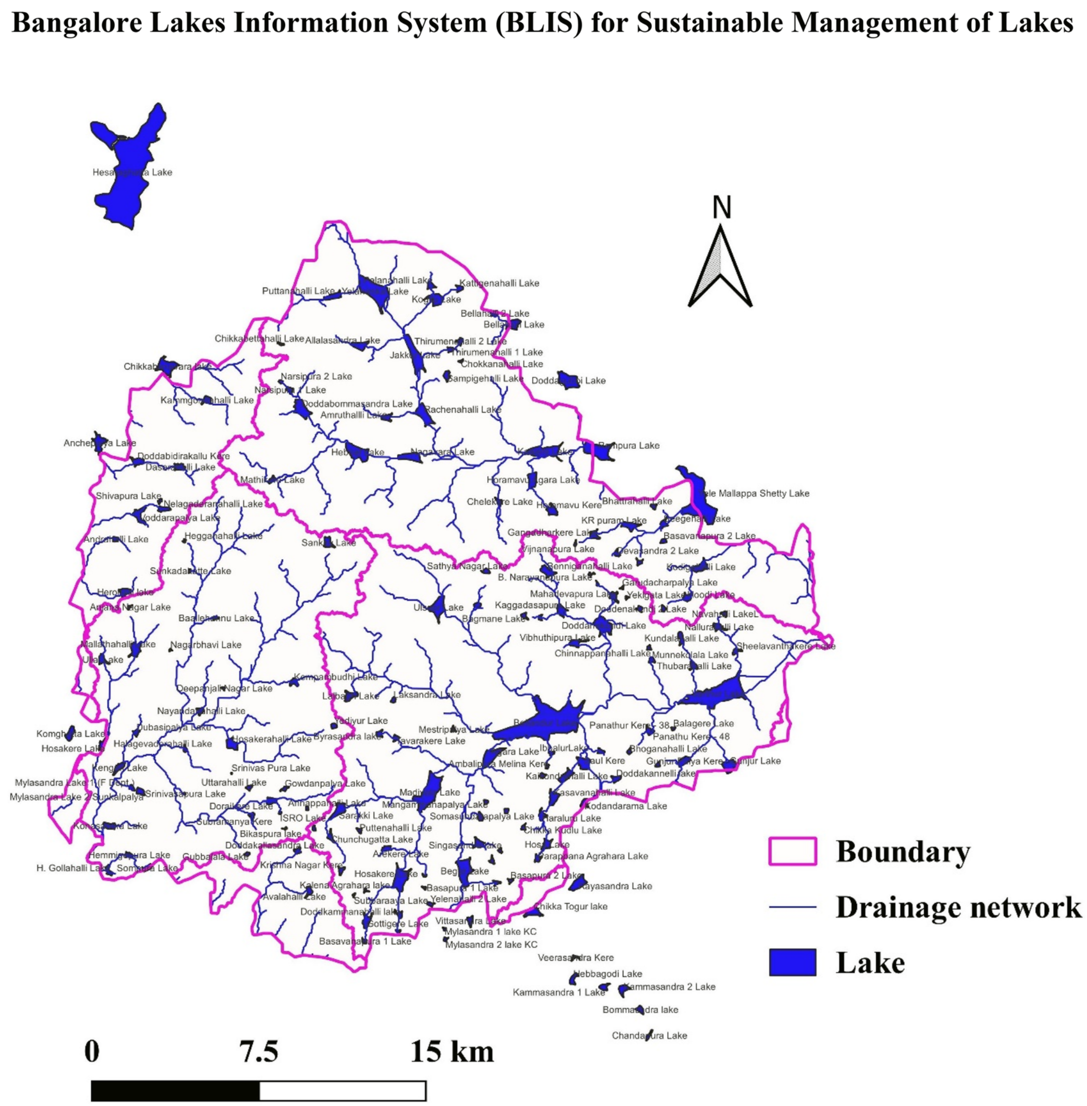


Figure 1: Lakes of Bangalore, Karnataka

likelihood algorithm considering training data (60%, chosen randomly representing all land uses), and (e) accuracy assessment considering training data (40%) through computation of overall accuracy, producer accuracy, user accuracy, and kappa statistics.

2.3 Spatial Distribution of Wetlands

Wetland delineation was carried out using (1) temporal remote sensing data, (2) field data collected from the field with a hand-held pre-calibrated GPS, and (3) digitizing wetlands from the geo-referenced topographic maps of the Survey of India. Google Earth data served in the pre-and post-classification processes and validation of the results. Figure 1 depicts the spatial distribution of interconnected lakes in Bangalore that have been meeting the water demand of domestic, irrigation, livestock rearing, fishing, etc.

Figure 2 outlines the method adopted for the design of BLIS, which entailed (1) compilation of lake information from literature and field survey, (2) assessment of chemical integrity through water quality analyses, (3) assessment of alteration in the physical integrity through encroachment mapping, (4) inventorying biodiversity, and (5) quantification of wetland ecosystem services (of 175 lakes) during the study period 2013–2023, and (6) implementation of BLIS. Sampling locations in each lake (of 115 lakes in Bangalore city) were at (1) inlets, (2) centre, and (3) outlets based on accessibility, water availability, etc.

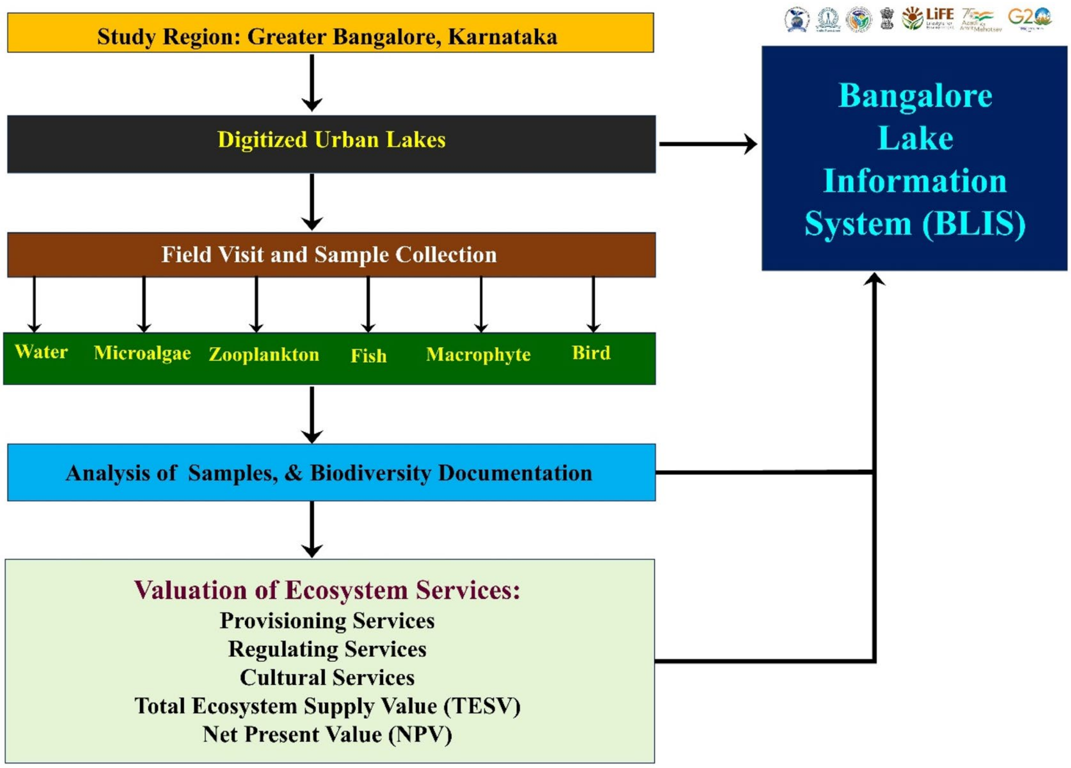


Figure 2: Method for monitoring lakes of Bangalore

2.4 Water Quality Analyses

Monitored quarterly 115 lakes in Bangalore city (Fig. 1) since 2013 to understand ecological and environmental status. Sampling locations in each lake were chosen at (1) inlet, (2) centre and (3) outlet based on accessibility, water availability, etc. Surface water samples were collected and stored in 2 L sterile polypropylene bottles for and physicochemical analysis at the laboratory. Parameters such as water temperature, pH, dissolved oxygen, electrical conductivity, and total dissolved solids were measured at the sampling location using hand-held multi-meter probes. Dissolved oxygen in water samples is estimated through Winkler method. Parameters such as total alkalinity, total hardness, calcium, magnesium, chloride, biochemical oxygen demand, chemical oxygen demand, turbidity, orthophosphate, and nitrate were assessed as per the standard protocol[22] at the Aquatic Ecology Laboratory (Energy and Wetlands Research Group, CES TE15, Indian Institute of Science). These values (mean value of three-time sampling) were incorporated in BLIS. Biological specimen were identified based on morphological keys (referring standard taxonomic literature and online data portals) in consultation with the subject experts.

2.5 Documentation of Biodiversity

2.5.1 Microalgae Sampling and Identification

Microalgae were collected from lake surface water by filtering 50 L using a plankton net, fixed with a 4% Lugol iodine solution, and concentrated to 50 mL. They were stored in labeled plastic bottles and transported to a laboratory for taxonomic analysis. Standard morphological keys[23–25] were used to identify specimens, which were enumerated using an optical microscope at 10 × and 40 × magnifications. Three subsamples were counted for each lake sample. Images of microalgae were taken using a camera attached to a microscope (Olympus).

2.5.2 Zooplankton Sampling and Identification

Zooplankton were collected by filtering 50 L of water using a plankton net. Samples were stored in plastic bottles and transported for taxonomic analysis. Zooplankton specimen were identified up to species level[26] and enumerated using an optical microscope at 10 X and 4 × magnifications. Three subsamples were counted for each lake sample. Photographs of zooplankton were captured with an Olympus camera mounted in the microscope.

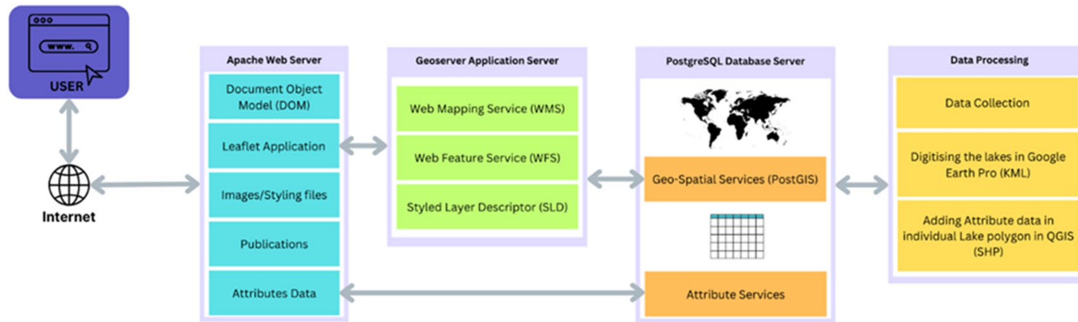


Figure 3: Framework for BLIS

2.5.3 Ichthyofauna Sampling and Identification

Ichthyofauna (fish) specimens were collected using gill nets or cast nets. Locations were recorded using the Garmin Etrex Global Positioning System (GPS), and species were identified using morphological keys and literature. Unidentified specimens were preserved in a 10% formaldehyde solution. Taxonomic analyses were conducted using standard keys in consultation with reference books[27–29]. Photographs were taken using a digital camera.

2.5.4 Macrophyte Collection and Identification

Macrophytes samples were collected randomly through quadrats (100 cm × 100 cm). These samples were washed, separated, and analyzed in a laboratory. Macrophytes were classified based on habitat as emergent, rooted, floating, submerged, and free-floating. Species were identified using standard morphological keys and literature[30,31]. Photographs of macrophyte species were taken using a digital camera.

2.5.5 Bird Diversity Documentation

Birds encountered during fieldwork were recorded and archived digitally through a digital camera. The birds were identified by referring to the field guide and Avibase (https://avibase.bsc-eoc.org/avibase.jsp).

2.6 Bangalore Lakes Information System (BLIS)

An information system is conceptualized and implemented using Geoserver, PostgreSQL with PostGIS extension, and Leaflet. With the spatial information (as per OGC standards) of Bangalore lakes, the Bangalore Lakes Information System (BLIS) provides geo-visualization of information about lakes in Hebbal-Nagavara, Koramangala-Challaghatta, and Vrishabhavathi watersheds of Bangalore city from 2013 to 2023 through Web Map Service (WMS) and Web Feature Service (WFS). Figure 3 outlines the schema of BLIS with a comprehensive database of attributes pertaining to physical, chemical, and biological aspects, including supplementary details such as biodiversity, encroachment, and restoration efficacy.

The Bangalore Lakes Information System (BLIS) consists of a comprehensive database (spatial and attribute), which is crucial for monitoring and managing lake health (Figs. 3, 4). The front end of BLIS is implemented through HTML (HyperText Markup Language), CSS (cascading style sheets), and JavaScript for interactivity, data retrieval, and map manipulation. The backend hosts a data server, which serves as a gateway for communication. Interactive spatial information for visualization is implemented through a JavaScript library (Leaflet). GeoServer is an open-source server that enables users to share and edit geospatial data, and Leaflet is used to create visually appealing and informative maps (Fig. 3). BLIS (https://wgbis.ces.iisc.ac.in/sdss/BLIS/) provides valuable insights for informed decision-making by researchers, policymakers, and stakeholders.

3 Results and Discussion

3.1 Landscape Dynamics

Temporal land use, depicted in Fig. 5, reveals that the landscape of Bangalore has transitioned from a porous landscape (with 68% vegetation cover, 274 lakes/wetlands, and < 8% built-up) to a paved contiguous surface (< 3% vegetation cover, 193 lakes, 86% paved surface) with the loss of vegetation cover (88%), and water cover (79%).

Unplanned developmental activities during the post-2000s, due to concentrated developmental activities for IT parks and SEZ's development

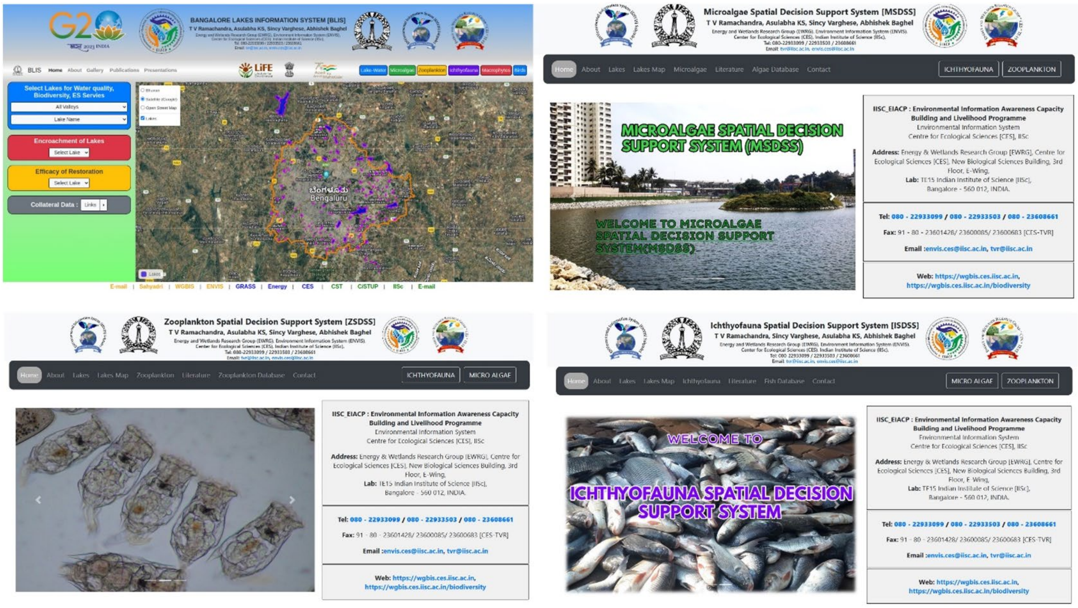


Figure 4: Decision support system (DSS) for water quality and aquatic biodiversity in Bangalore lakes

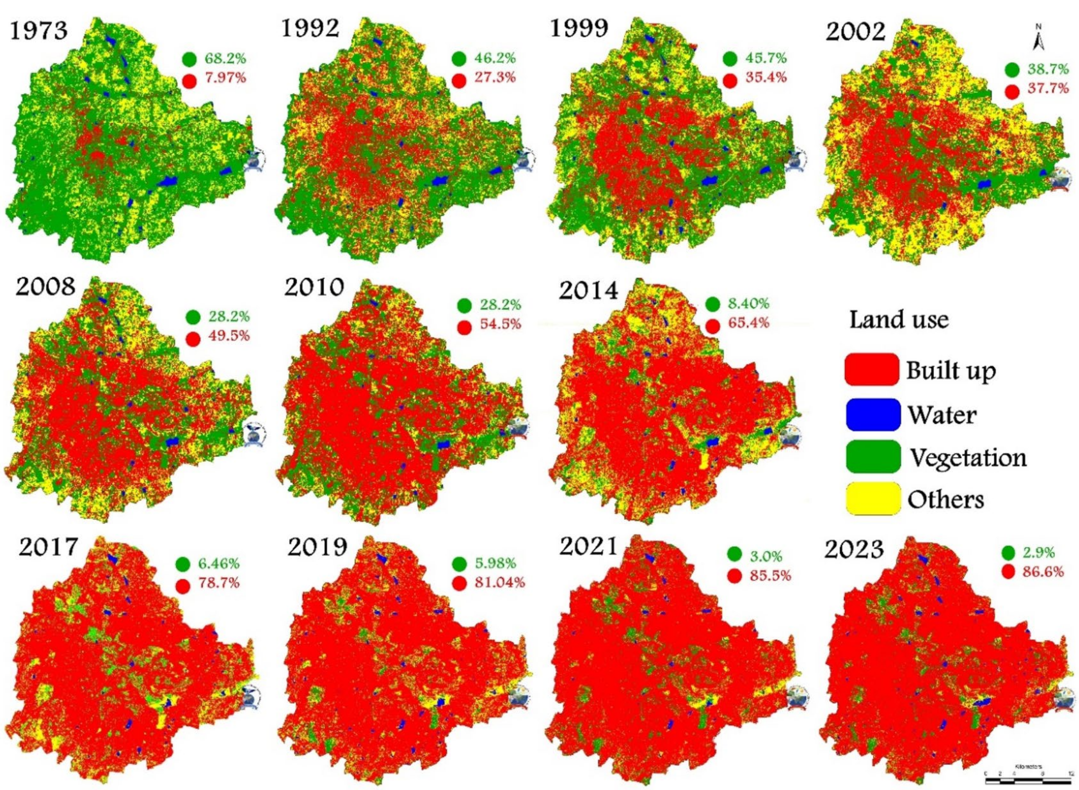
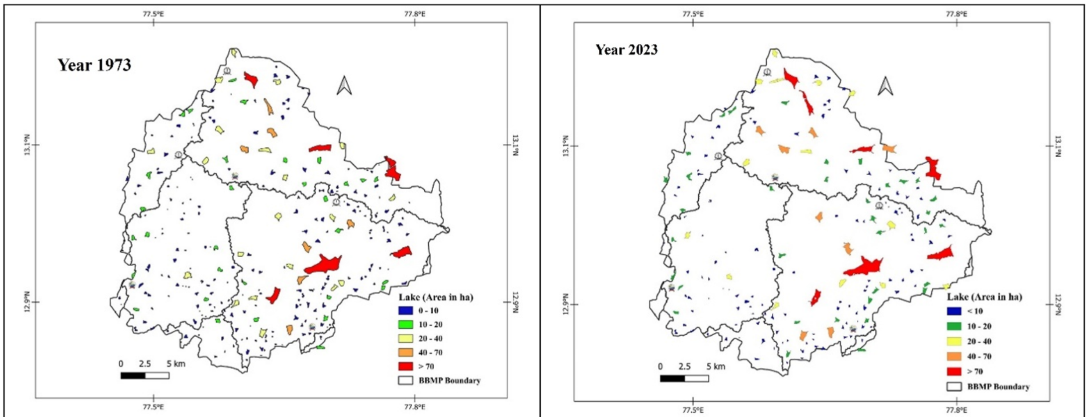


Figure 5: Land use dynamics in the rapidly urbanizing landscape of Bangalore during 1973 to 2023

in the city, have given impetus to rapid urbanization with drastic and unrealistic land use changes. The growth has surpassed the carrying capacity, which is evident from the acute scarcity of natural resources (oxygen deficiency, water table decline, declining environmental quality, etc.), inadequate infrastructure, and basic amenities.



(a) Spatial distribution of lakes in 1973 (as per the Survey of India topographic maps)

(b) Spatial distribution of lakes (2023) based on the field survey

Figure 6: Spatial distribution of lakes in 1973 and 2023

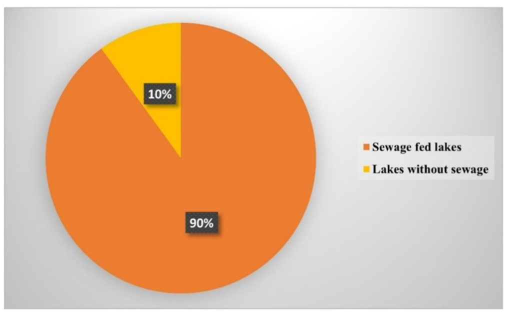


Figure 7: Water quality of Bangalore lakes

3.2 Spatial Analyses of Wetlands

Figure 6 illustrates the sharp decline (by 70.4%) in the number of waterbodies from 1973 to 2023.

The decline in water bodies in Bangalore is mainly due to intense urbanization and urban sprawl. Field survey reveals that lakes (98%) have been encroached on for illegal buildings (high-rise apartments, commercial buildings, slums, etc.), nearly 90% of lakes are sewage-fed (Fig. 7), slums surround 38% of lakes, and 82% are wetlands, showing a sharp decline in vegetation cover in the catchment. Also, lake catchments have been used as dumping yards for either municipal solid waste or building debris. Multi-story buildings have come up in many lake beds, and stormwater drains hinder the natural catchment flow. The decline in wetlands is correlated with the increase in built-up area due to the concentrated growth model (focusing on Bangalore) adopted by the state executive system, which severely affects open spaces, particularly water bodies. Rapid urbanization has resulted in land use changes with encroachments and a loss of interconnectivity among lakes, apart from the sustained inflow of untreated wastewater into lakes, resulting in pollution that has affected aquatic biodiversity, evident from the decline of native species[32,65,68].

3.3 Water Quality of Bangalore Lakes

In Bangalore city, the water quality results reveal that 90% of lakes are fed with sewage and only 10% are devoid of sewage (Fig. 7). Assessment of water quality in 105 lakes in Bangalore revealed that about 25 lakes were found to be in a very bad state (lakes had little or no water)[32,65,68].

The physicochemical characteristics of 80 lakes were assessed to understand the prevailing condition of lakes in Bangalore. The water quality results revealed that lakes such as Andrahalli, Baallehannu, Doraikere, Hebbal, Hemmigepura, Herohalli, Hesaraghatta, Jakkur, Kaikondrahalli, Kogilu, Lalbagh, Nagavara, Narsipura 1, Rachenahalli, and Yediyur fall under Class D and E. In contrast, all the other 63 lakes fall under Class E based on the Classification of Inland Surface Water (CPCB, Central Pollution Control Board). Lakes in Koramangala-Challaghatta Valley are more polluted than the lakes in Vrishabavathi Valley and Hebbal Valley. About 79% of lakes monitored in Bangalore belong to class E, 19% to classes D and E, and 2% belong to class A. Lakes like Bellandur, Chelekere, Chikkabegur, Chunchugatta, Hebbagodi, Kalkere, Kammasandra Lake-1, Kengeri, Mallathhalli, Maragondanahalli, Nallurahalli, Rampura, Varthur, and

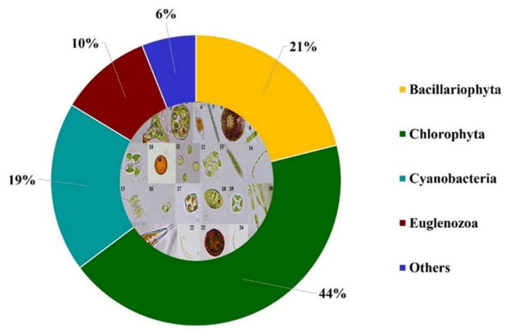


Figure 8: Microalgae diversity in lakes of Bangalore

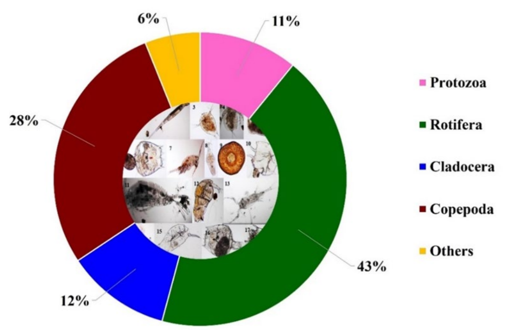


Figure 9: Zooplankton diversity in lakes of Bangalore

Yelemallappachetty receive an enormous amount of untreated sewage water[32,65,68].

Lakes with the profuse growth of algae, i.e., Cyanophyceae (due to continuous sewage inflow and high nutrients), are Sankey, Dasarahalli, Bagmane, Ulsoor, Anchepalya, Bommasndra, Kammasandra 1 and Kammasandra 2. About 25 lakes were extensively used for solid and liquid waste dumping and were fully covered with invasive species of macrophytes due to the excessive amount of nutrients. Lakes such as Lakasandra had completely turned into barren land due to the dumping of building debris[32,65,68].

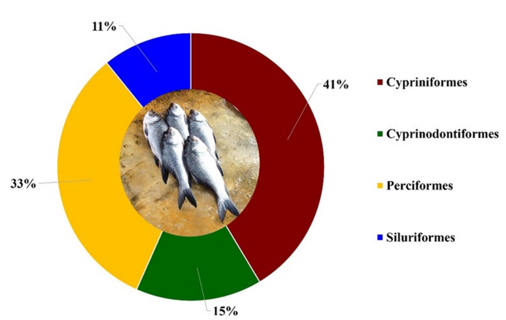


Figure 10: Ichthyofauna diversity in lakes of Bangalore

3.4 Biodiversity in Bangalore Lakes

Lakes provide habitat for numerous aquatic organisms. Globally, freshwater biodiversity is threatened due to factors such as overexploitation, water pollution, habitat destruction or degradation, flow modification, and invasion by exotic species[33].

3.4.1 Microalgae Diversity

Microalgae (or phytoplankton) are primary producers (photosynthetic organisms) and bioindicators in water bodies. They provide food and transfer energy to the various trophic levels. The wide applications of microalgae are in the pharmaceutical and nutraceutical industries[34]. Chlorophyta, which makes up 44% of the total algae in Bangalore lakes, constitutes the most prevalent phylum of algae (in Fig. 8), followed by Bacillariophyta (21%), Cyanobacteria (19%), Euglenozoa (10%), and Others (6%, which include Ochrophyta, Glaucophyta, and Charophyta). The water quality of lakes largely determines the variations in species composition and diversity. Microalgae are useful as bioindicators because of their swift response to environmental changes. Microalgae efficiently utilize nutrients, aiding in remediation[35].

3.4.2 Zooplankton Diversity

Zooplankton are primary consumers, feeding on microalgae or phytoplankton. Like microalgae, zooplankton also serve as effective bioindicators of water quality[36]. Rotifera is the most dominant group of zooplankton (Fig. 9), accounting for 43%, followed by Copepoda (28%), Cladocera (12%), Protozoa (11%), and others (6%, Ostracoda and Chironomid larvae). Rotifer abundance and richness are high on complex macrophytes, providing habitat, food, and protection against predators. Submerged macrophytes provide refuge for small zooplankton and potential predators[37].

3.4.3 Ichthyofauna or Fish Diversity

Fish are excellent sources of protein, vitamins, and minerals. Changes in biotic and abiotic factors affect habitat quality and may, in turn, affect the growth, reproduction, and survival of fish[38]. The present study records 18 species of ichthyofauna. Cypriniformes (43%) is the most dominant order (Fig. 10), followed by Perciformes (33%), Cyprinodontiformes (15%), and Siluriformes (11%). A total of ten fish species are of least concern (LC), which include *Catla catla*, *Clarias batrachus*, *Clarias gariepinus*, *Labeo fimbriatus*, *Labeo rohita*, *Parambassis ranga*, *Cirrhinus mrigala*, *Heteropneustes fossilis*, *Puntius ticto*, and *Gambusia affinis*. Two species are classified as not evaluated (*Ctenopharyngodon idella* and *Oreochromis niloticus*), one species is near threatened (NT), and one species is vulnerable (*Cyprinus carpio communis*).

3.4.4 Macrophyte Diversity

Macrophytes are aquatic plants growing in the shallow euphotic zone of freshwater. Aquatic macrophytes significantly increase habitat complexity, impacting the taxon richness and density of organisms in plant beds. Fish and other aquatic macroinvertebrates find refuge from macrophytes, which also mobilize mineral elements from the bottom sediments. The most dominant order is Poales (29%), which includes species like *Typha angustata*, *Cyperus rotundus*, *Typha* sp., *Cyperus alternifolius*, *Cyperus articulates*, *Cyperus papyrus*, *Chrysopogon zizanioides*, *Echinochloa colona*, *Eleocharis* sp., and *Paspalum* sp. Others (31%) include Salviniales, Lamiales, Zingiberales, Ceratophyllales, Poales, Commelinales, Apiales, Solanales, Myrtales, Proteales, Nymphaeales, and Asterales and occur very few in number (Fig. 11).

3.4.5 Bird Diversity

Birds provide several ecosystem services such as pollination (ornithophily), seed dispersal, nutrient cycling, food (meat, eggs) provision, scavenging, pest control, and ecotourism[39,40]. Waterbirds are efficient bioindicators of ecological conditions, control pests[41], and act as sentinels of potential disease outbreaks[42]. Bangalore urban lakes provide habitat for a variety of birds, which include Paddy field pipit or Oriental pipit (*Anthus rufulus*), Purple gallinule (*Porphyrio martinicus*), White-breasted waterhen (*Amaurornis phoenicurus*), Red-wattled lapwing (*Vanellus indicus*), Brahminy kite (*Haliastur indus*), Black kite (*Milvus migrans*), Little cormorant (*Microcarbo niger*), Little egret (*Egretta garzetta*), and Cattle egret (*Bubulcus ibis*). Lakes in Bangalore, such as Jakkur, Lalbagh, Madiwala, Kaikondrahalli, Kasavanahalli, etc., are home to pelicans and painted storks (Fig. 12).

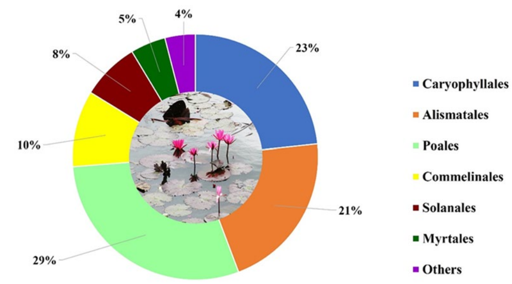


Figure 11: Macrophyte diversity in lakes of Bangalore

3.5 *Ecosystem Services from Bangalore lakes*

Wetlands are the most diverse and productive ecosystems, which provide several ecological, economic, and social benefits to society. Wetlands provide vital ecosystem services and processes, such as nutrient cycling, water purification, reducing pollution, carbon sequestration, groundwater recharge, flood reduction, erosion control, habitats for aquatic flora/fauna, opportunities for education, aesthetics, and recreation. Provisioning services (products obtained from ecosystems) include water, food, fuel, fibre, genetic resources, biochemical components, and medicines. Regulating services (benefits from various ecosystem processes) include water regulation, climate regulation, water purification, disease regulation, erosion control, carbon sequestration, and flood control. Cultural services (nonmaterial benefits) include recreation, aesthetic experiences, spiritual value, and ecotourism. The valuation of ecosystem services (Fig. 13) was done through the residual value and benefit transfer methods[1]. The provisioning services provided by Lakes of Bangalore ranged from Rs. 0.731–1472.23 lakhs per year depending on the spatial extent and condition of ecosystems. The regulating services ranged from Rs. 2.66–5353.779 lakhs per year. The cultural services ranged from Rs. 0.512–1031.24 lakhs per year. The total value of provisioning, regulating, and cultural services provided by the lakes of Bangalore is Rs. 6829.531 lakhs per year, Rs. 24,835.659 lakhs per year, and Rs. 4783.821 lakhs per year, respectively. The TESV (total ecosystem supply value) of Bangalore lakes amounts to Rs. 36,449.004 lakhs per year (Rs. 3.904–7857.248 lakhs per year), and the NPV (net present value) is Rs. 93,782.4 million (10.0–20216.5 million). Natural capital accounting and valuation of ecosystem services aid in accounting for degradation

Figure 12: Winter visitors to Bangalore lakes

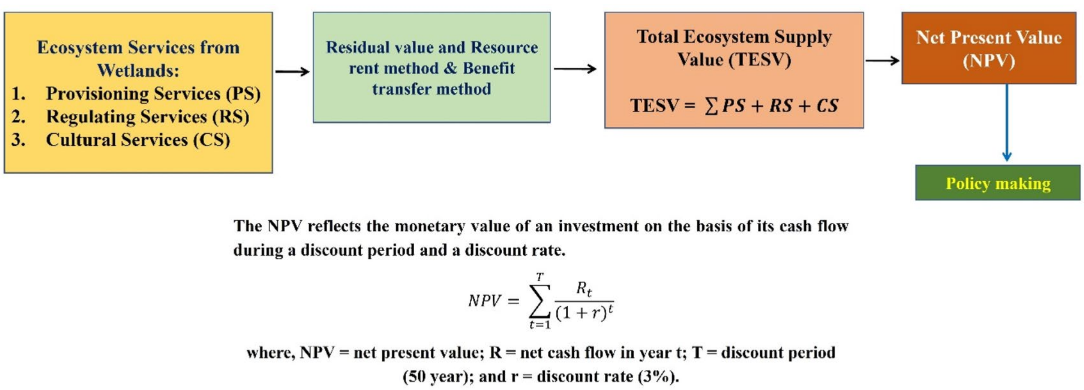


Figure 13: Methods for valuing the ecosystem services of wetlands

costs in development, which is crucial for developing appropriate policies toward the prudent management of fragile life-support ecosystems. The instances of decline in wetland goods and services as a result of mismanagement leading to serious water pollution have affected the livelihood of the dependent people as well as the economic development of a region, as in the case of Amruthalli Lake, which provides goods worth Rs. 20/ha/day compared to the pristine wetland (Rachenahalli Lake) of Rs. 10,435/ha/day, which highlights the need for prudent management of wetlands to sustain the livelihood of the dependent local population[43].

3.6 Threats to Wetlands of Bangalore

Unplanned developmental activities leading to rapid urbanization and urban sprawl have led to increased migration (with improved job opportunities), leading to pressure on infrastructure, inadequate basic amenities, and challenges like escalating pollution, traffic congestion, higher instances of chronic diseases (such as respiratory ailments, cancer, kidney failure, etc.), inadequate drainage systems, waste (solid and liquid) mismanagement, encroachment of stormwater drains, floodplains, lakebeds, a decline of natural flood-storage locations, the loss of permeable/pervious areas, recurring instances of flooding, etc.[44]. Industrialization coupled with the burgeoning population has increased wastewater, which is being discharged indiscriminately to surface water bodies, resulting in water pollution that poses a health hazard to aquatic biota and humans. Land cover changes leading to land degradation and deforestation have contributed to siltation, resulting in sedimentation, which has reduced the storage capacity of waterbodies and caused a decline in groundwater recharge. The loss of lakes and the removal of vegetation cover in the watershed have lowered the water retention capacity of the watershed. Urbanization has resulted in the decline of native biodiversity (flora and fauna), migrating bird populations, and groundwater table. Changes in land use and land cover (LULC) in wetland catchments are causing environmental concerns such as biodiversity loss, water and soil pollution, and climate change[45]. An analysis of Land Surface Temperature (LST) in Greater Bangalore indicated increased temperatures in urbanized regions (built-up areas) and decreased temperatures in regions covered with vegetation and water bodies[20]. Variations in LST for different LULC types were evident during different seasons. It was found that LST and Normalized Difference Vegetation Index (NDVI) were negatively correlated[46,47].

3.6.1 Depletion of Groundwater

The loss of water bodies in Bangalore has resulted in a sharp decline in the groundwater table. Over 20 years following the reclamation of the lake and its watershed for commercial purposes, the water table has dropped to 200 m in five years from 28 m. After two decades of lake reclamation, the local community has lost groundwater, which is evident from the absence of water even at a depth of 600–700 m. Furthermore, the groundwater table in densely populated areas like Whitefield has decreased below 400–500 m[44]. Surface water and groundwater (SW-GW) are vital components of the water cycle, and their interactions are primarily controlled by groundwater depth, local geology, proximity to other freshwater sources, and seasonal variation in precipitation. These, in turn, affect ecosystem health, quantity, and quality of water[48]. Water movement between ground and surface water sustains water during the post-monsoon period in surface water bodies, and it facilitates chemical transfer between terrestrial and aquatic systems, impacting carbon, oxygen, nutrients, and biogeochemical processes, ultimately affecting aquatic systems' biological and chemical characteristics[49]. The changes in climate due to the sustained onslaught of anthropogenic activities have significantly altered SW-GW interactions due to a lack of infiltration during monsoons (due to land degradation), which impaired the functioning of lakes. With the increase in temperature and alteration in the hydrologic regime, the spatial extent of the water spread area has declined with the decline in levels of groundwater and surface water[50].

3.6.2 Loss of Interconnectivity of Lakes

The interconnectivity among lakes is lost due to unauthorized occupation or dumping of solid waste (building debris) in the lake bed, and stormwater drains have hindered the movement of water across lakes, resulting in recurring instances of floods even during periods of regular rainfall[44]. The loss of interconnectivity among lakes has also affected the movement of fauna and water quality (due to the lack of aeration).

3.6.3 Alteration in the Chemical Integrity Due to the Sustained Disposal of Untreated Domestic Sewage and Industrial Effluents into Lakes

Wastewater from commercial, industrial, residential, and agricultural sectors containing organic and inorganic materials is being discharged directly into storm water drains and lakes, altering the chemical composition of lakes[51]. The sustained inflow of wastewater has led to nutrient enrichment, resulting in eutrophication with algal blooms, a decline of dissolved oxygen (DO), the generation of malodorous gases, and the widespread proliferation of invasive macrophytes, which hinders the functioning of lakes. Sewage contains carbon (C), nitrogen (N), and phosphorus (P)[52], which enhances organic contaminants and chemical constituents, resulting in the loss of biodiversity, microbial community structure, disease vectors, pathogens, and flies, which causes waterborne diseases[53]. Health implications are evident from several cases of fever, diarrhea, and skin disorders in the Varthur Lake catchment due to eutrophic status[54]. A similar situation prevails in Hebbal Lake, with a poor overall water quality index[55]. The high levels of phosphates in Varthur and Bellandur lakes manifested in eutrophic conditions with foam formation, abundant growth of invasive macrophytes, and higher levels of chemical pollutants and nutrients (N and P) were reported in foam samples[56].

3.6.4 Water and Land Contamination Due to the Sustained Dumping of Municipal Solid Waste and Blockage of Storm Water Drains with the Disposal of Construction and Demolition (C&D) Waste

Municipal solid waste contributes to global greenhouse gas (GHG) emissions. The total methane emissions from municipal solid waste account for 0.9 Tg/year[57]. The leachate released had a high concentration of organic and inorganic constituents and trace metals contaminating the surface and groundwater[58]. Sustained dumping of solid wastes in water bodies and stormwater drains has

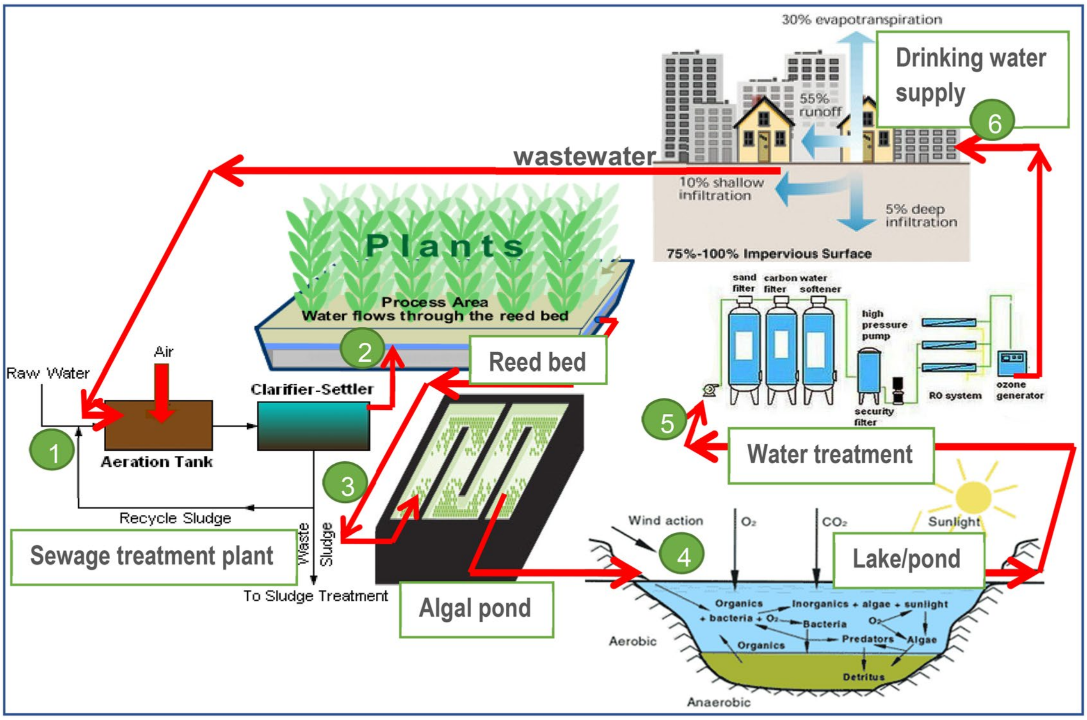


Figure 14: Integrated wetland system

hindered water movement and contaminated the air, land, and water environment.

3.6.5 Recurring Instances of Fish Mortality

Fish mortality in Sankey, Ulsoor, and Devarabisanahalli lakes in Bangalore was due to asphyxiation, with a decline in dissolved oxygen (DO) levels and an increase in ammonia due to the sustained inflow of untreated sewage[59–62].

3.6.6 Introduction of Exotic Species

The introduction of exotic species impairs the native food chain, resulting in the disappearance of native or indigenous species. Exotic fish species prevalent in Bangalore wetlands are *Ctenopharyngodon idella*, *Cyprinus carpio*, *Oreochromis* sp., *Clarias gariepinus*, *Gambusia affinis*, and *Hypophthalmichthys molitrix*[38]. The profuse growth of invasive exotic plant species and exotic fish with the sustained discharge of nutrient-rich wastewater has contributed to the extinction of native faunal species[54]. The exotic fish species compete with the native fish, prey on native fish, introduce new diseases and parasites, alter trophic structure, and cause genetic erosion of indigenous species[63]. Exotic species of macrophytes, such as *Salvinia molesta* and *Eichhornia crassipes*, have choked watercourses and threatened the sustainability of lakes[64].

3.6.7 Inappropriate Restoration of Lakes

Lake restoration entails (1) arresting pollutants, (2) decontaminating the lake, (3) desilting to remove accumulated silt and enhance water storage capacity, (4) improving water percolation to enhance groundwater recharge, (5) maintaining the physical integrity of the lake, (6) re-establishing the habitat quality of aquatic organisms, and maximizing aquatic biodiversity. An environmental audit of the efficacy of rejuvenation revealed that most of the lakes had a poor water quality index, WQI (53% of lakes fell under very poor water quality, 37% under poor water quality, and only 10% had good water quality), which indicates inappropriate decontamination and poor maintenance of restored lakes. The current rejuvenation of lakes faces several gaps, including a lack of understanding of functional aspects such as ecological, hydrological, and remediation aspects; a focus on utilizing allocated funds without scientific evaluation; failure to decontaminate the lake (partial removal of contaminated silt); not arresting fresh pollutants; continued inflow of partially treated or untreated sewage and industrial effluents; and the removal of riparian vegetation. The emphasis of the current rejuvenation endeavor is on converting the lake to a "cement bowl" rather than restoring the ecology and improvement of hydrologic regime.

The creation of jogging paths and beautification rather than ecological restoration contributes to the challenges faced in lake rejuvenation[65]. Appropriate ecological restoration strategies based on natural principles are crucial to restoring and safeguarding physical, chemical, and biological integrity of wetlands.

3.7 Wastewater Treatment Based on Nature-Based Principles

Conventional wastewater treatment options are energy and capital-intensive, apart from their inability to remove nutrients altogether and generate concentrated waste streams necessitating environmentally sound disposal. Compared to this, an integrated wetland system (Fig. 14) would help in the cost-effective tertiary treatment (removal of N, P, and heavy metals), which prevents contamination of lake water and groundwater resources. Algae grow rapidly and uptake nutrients (C, N, and P) in the wastewater. Algae convert nitrate into organic compounds (proteins, lipids) through photosynthesis. Algae exhibit higher growth rates than other plants due to their extraordinarily efficient light and nutrient utilization. Algal bacterial symbiosis is very effective as algae generate O_2 (during photosynthesis), which aids in the efficient oxidation of organic matter with the help of the chemo-organotrophic bacteria and provides algae with an enriched supply of CO_2, minerals, and nutrients.

The integrated wetland system (1.6 ha) consists of an STP (Upflow Anaerobic Sludge Blanket Reactor (UASB) with an extended aeration system) integrated with the constructed wetlands and algal pond, which has helped cost-effectively remove nutrients and chemical ions. Emergent macrophytes (such as typha) act as filters to remove suspended matter and avoid anaerobic conditions caused by root zone oxidation and algae taking the dissolved nutrients. Four to five days of residence time help remove pathogens apart from nutrients. The macrophytes in the wetland area and at the outfalls of the lake include *Typha augustata* species (54%), followed by *Alternanthera philoxeroides* (28%). Floating macrophytes like *Eicchornia crassipes* (84%) were restricted to the outlet reaches. A nominal residence time (~5 days) would help remove pathogens apart from nutrients. Replication of this model in Bangalore would help meet the water demand and also help in recharging groundwater sources without any contamination[51,66,67]. Measures required to mitigate the current water crisis are: (1) rainwater harvesting (15 TMC) at decentralized levels through rejuvenated lakes would help in improving the groundwater table; (2) an integrated wetlands ecosystem consisting of constructed wetlands and algal ponds helps treat wastewater through bioremediation. Replicating the Jakkur wetland ecosystem would help treat and reuse water. Rejuvenating lakes will have the added advantage of maintaining groundwater quality in the vicinity. The integrated wetland system at Jakkur provides an opportunity to assess treatment efficacy and insights for replicating similar systems to address the impending water scarcity in the rapidly urbanizing city of Bangalore.

3.8 Sustainable Management of Bangalore Lakes

Despite good environmental legislation, the loss of ecologically sensitive wetlands is due to the uncoordinated pattern of urban growth happening in Bangalore. The principal reason is a lack of good governance and decentralized administration, evident from a lack of coordination among many para-state agencies, which has led to unsustainable use of land and other resources. Failure to deal with water as a finite resource leads to the unnecessary destruction of lakes and marshes that provide us with water. This failure, in turn, threatens all options for the survival and security of plants, animals, humans, etc.

The sustainable management of lakes at disaggregated levels would help maintain the groundwater table, apart from other ecosystem services. Good governance at decentralized levels with informed decision-making requires the organisation of data and knowledge from disparate sources through decision-support systems, which enhances the decision-making capabilities. Bangalore Lakes Information System (BLIS) is designed by taking advantage of recent advances in information and open-source web technologies through the integration of spatial with the attribute information (physical, chemical, and biological aspects) of Bangalore lakes at disaggregated levels, which helps in prudent management while enhancing governance transparency and meeting societal needs.

Web-based BLIS available online (https://wgbis.ces.iisc.ac.in/sdss/BLIS/) is designed by integrating free and open-source software (GeoServer, PostgreSQL, PostGIS, and Leaflet) and the integration of spatial information according to Open Geospatial Consortium (OGC) standards to carry out a multiple criteria analysis. Features such as Web Map Service (WMS) and Web Feature Service (WFS) would help in the effective

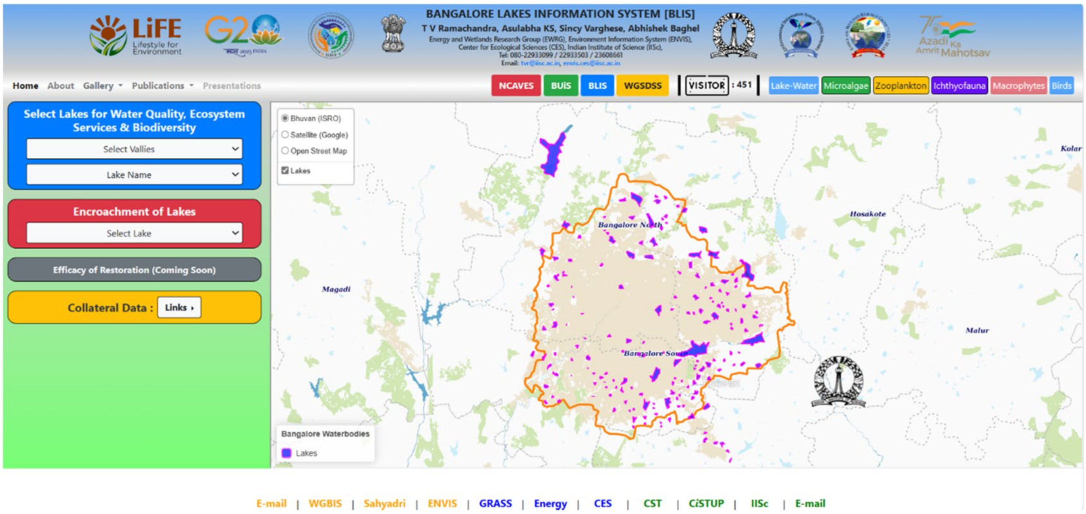


Figure 15: Bangalore Lake Information System (BLIS)

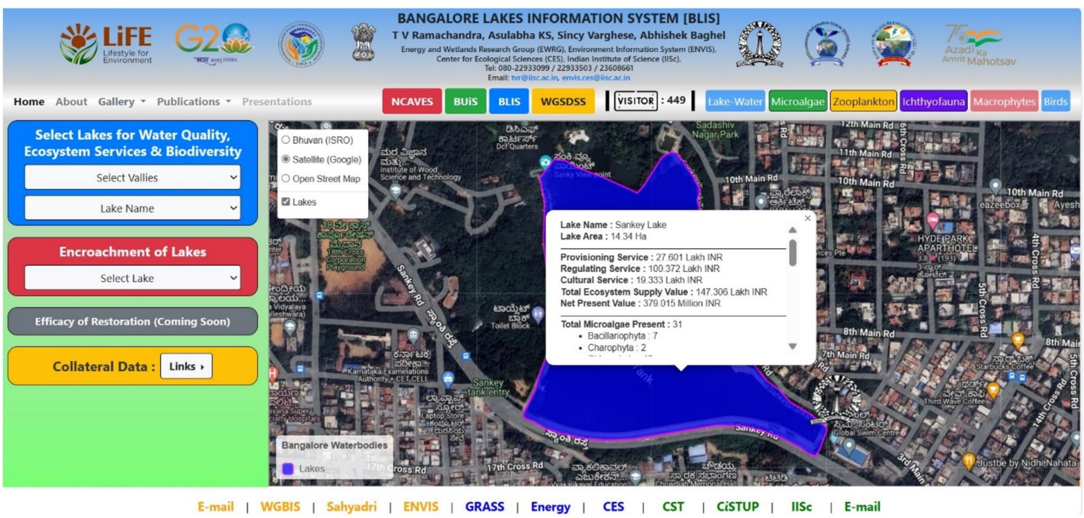


Figure 16: WMS and WFS option of a chosen lake in BLIS

dissemination of information about Bangalore lakes pertaining to water quality, ecosystem services, biodiversity (microalgae, zooplankton, ichthyofauna, macrophytes, and birds).

The Graphic User Interface (GUI) of the Bangalore Lakes Information System (BLIS), as depicted in Fig. 15, consists of (i) a navigation bar and options for WMS and WFS. Interactive options include selecting lakes based on valley and provide details of water quality, biodiversity, and ecosystem services (Fig. 16).

BLIS contains the identification keys, ecological importance, economic importance, and photographs (maximum 6) of all species of microalgae, zooplankton, ichthyofauna, macrophytes, and birds of Bangalore city. BLIS aids in the prudent management of natural resources as per Sustainable Development Goal 6 (SDGs) of the United Nations (2015), focusing on ensuring a clean, stable water supply and effective sanitation for all people by 2030, and helps in ensuring intergeneration equity by maintaining clean air, land, and water.

4 Recommendations

Recommendations for prudent management of waterbodies are:

1. Inventorying, mapping, and monitoring of valley zones and removing encroachments in lake beds, stormwater drains (and rajakaluves/major water drains).
2. Re-establish interconnectivity among lakes to mitigate flooding in regions.
3. Maintaining the riparian vegetation and the integrity of floodplains and buffer zones.
4. Prohibit practices include hunting wild animals, dumping solid waste, directly discharging untreated sewage, converting lakes for uses other than as lakes, and reclaiming lakes.
5. Control any activity that impedes regular run-off and associated biological processes in the buffer zone 200 m from the lake's edge or flood plains.
6. Restrict the inflow of untreated sewage into lakes. Allow only treated water to enter lakes to minimize pollution. It is better to implement the polluter pays principle for polluters to maintain the chemical integrity through pollution reduction.
7. Restrict dumping of municipal solid waste as well as construction and demolition (C&D) wastes in lake beds, storm water drains, and valley zones.
8. Flood mitigation involves restoring lakes, removing drainage blockages, removing encroachments, preventing waste disposal in stormwater drains and lake beds, restoring lake catchment, and restoring lake connectivity to prevent flooding.
9. Prohibit the introduction and cultivation of exotic species of flora and fauna that reduce the population of native species.
10. Promote afforestation activities, i.e., plant native species of flora in the lake catchment.
11. Adopt measures to control the overgrowth of aquatic plants or weeds in lakes through manual operations.
12. Public awareness as well as awareness among educational and business institutions, are necessary for the conservation of these lakes to be successful in the long run. Education is necessary for site managers as well as policymakers at different levels.
13. Stakeholders, the local community, and the corporate sector should be involved in the effective management plan, requiring continuous monitoring of wetland systems. Research is essential to understanding the dynamics of these ecosystems and formulating national policy.

5 Conclusion

Lakes serve numerous functions, including nutrient recycling, water purification, flood mitigation, erosion control, and providing habitat. However, population growth, rapid urbanization, and industrial development in Bangalore have led to the discharge of untreated domestic sewage, industrial effluents, and agricultural runoffs (fertilizers, insecticides), which have been posing serious threats to these ecosystems. The Bangalore Lakes Information System (BLIS) is designed based on the monitoring of 175 lakes in Hebbal-Nagavara, Koramangala-Challaghatta, and Vrishabhavathi watersheds and their biodiversity (microalgae, zooplankton, ichthyofauna, macrophytes, and birds). Rapid urbanization in Bangalore has contributed to changes in wetland hydrology, catchment area loss, habitat loss, increased run-off, flooding instances, pollution, land encroachment, and overuse of resources. The aquatic biodiversity of Bangalore is under threat due to pollution, habitat loss, the introduction of exotic species, overexploitation, the extinction of native species, and other anthropogenic activities. The bioaccumulation of contaminants, particularly heavy metals, has contributed to contamination in the food chain or food web. Even though lakes provide various ecosystem goods and services, their quality is deteriorating mainly due to the sustained inflow of untreated wastewater (of nutrients, organic matter, and heavy metals), which would affect the health of aquatic life and the dependent population. Geographic Information System (GIS) technology is used to map surface water bodies and biodiversity. Thus, integrating GIS and web-based spatial decision support system (SDSS) technologies helps understand the status of lakes and devise strategies for prudent management and conservation of wetlands. BLIS empowers policymakers and other stakeholders to make informed decisions to protect ecologically, economically, and socially significant wetlands.

Publisher's Note

solely governed by the terms of such publishing agreement and applicable law.

Acknowledgements

We thank the EIACP-ENVIS Division, The Ministry of Environment, Forests and Climate Change, the Government of India, and the Indian Institute of Science (IISc) for their sustained support of ecological research. We are grateful to Sudarshan P for field sampling and macrophyte identification and to local fishermen who helped during fish sampling and provided local use information.

Author contributions

Conceptualization, development of methods, soft computing, field investigation, validation, writing, formatting, and reviewing were carried out by all authors. All authors have read and agreed to the published version of the manuscript.

Funding

Field research is funded by the EIACP (ENVIS) division, the Ministry of Environment, Forests and Climate Change, Government of India, and infrastructure support is provided by the Indian Institute of Science.

Data availability

Data are archived at our data portal https://wgbis.ces.iisc.ac.in. Data used in the analyses are compiled from the field. Data is analyzed and organized in the form of tables, which are presented in the manuscript. Also, synthesized data are archived at http://wgbis.ces.iisc.ac.in/.

Data statement

Data used in the analyses are compiled from the field. Data is analyzed and organized in the form of tables, which are presented in the manuscript. Also, synthesized data are archived at http://wgbis.ces.iisc.ac.in/.

Declarations

Conflict of interest

Authors do not have any conflicts of interest, either financial or non-financial.

Ethical approval

All authors have read, understood, and have complied as applicable with the statement on 'Ethical responsibilities of Authors' as found in the Instructions for Authors.

Compliance with ethical standards

The research does not involve either humans, animals, or tissues.

Received: 28 April 2024 Accepted: 11 September 2024
Published online: 24 October 2024

References

1. Ramachandra TV, Sincy V, Asulabha KS (2021) Accounting of ecosystem services of wetlands in Karnataka State, India. JRED 18(1–2):1–26
2. Ramachandra TV, Sudarshan PB, Mahesh MK, Vinay S (2018) Spatial patterns of heavy metal accumulation in sediments and macrophytes of Bellandur wetland, Bangalore. J Environ Manag 206:1204–1210. https://doi.org/10.1016/j.jenvman.2017.10.014
3. Näschen K, Diekkrüger B, Evers M, Höllermann B, Steinbach S, Thonfeld F (2019) The impact of land use/land cover change (LULCC) on water resources in a tropical catchment in Tanzania under different climate change scenarios. Sustainability 11(24):7083. https://doi.org/10.3390/su11247083
4. Bera T, Kumar V, Sarkar DJ, Devi MS, Behera BK, Das BK (2022) Pollution assessment and mapping of potentially toxic elements (PTE) distribution in urban wastewater fed natural wetland, Kolkata, India. Environ Sci Pollut Res 29:67801–67820. https://doi.org/10.1007/s11356-022-20573-8
5. Singh Y, Singh G, Khattar JS, Barinova S, Kaur J, Kumar S, Singh DP (2022) Assessment of water quality condition and spatiotemporal patterns in selected wetlands of Punjab, India. Environ Sci Pollut Res 29:2493–2509. https://doi.org/10.1007/s11356-021-15590-y
6. Ramachandra TV, Asulabha KS, Lone AA (2014) Nutrient enrichment and proliferation of invasive macrophytes in urban lakes. J Biodivers 5(1–2):33–44
7. Bassi N, Kumar MD, Sharma A, Pardha-Saradhi P (2014) Status of wetlands in India: a review of extent, ecosystem benefits, threats and management strategies. J Hydrol Reg Stud 2:1–19. https://doi.org/10.1016/j.ejrh.2014.07.001
8. Rowe GL, Reutter DC, Runkle DL, Berkman JAH, Janosy SD, Hwang LS (2004) Water quality in the Great and Little Miami River Basins, Ohio and Indiana, 1999–2001 (No. 1229). US Geological Survey
9. Kamboj V, Kamboj N, Sharma AK, Bisht A (2022) Fish diversity associated with environmental parameters in impacted area of Ganga River, India. Proc Natl Acad Sci

India Sect B Biol Sci 93(1):79–90. https://doi.org/10.1007/s40011-022-01393-9
10. Rahimi M, Zarei M, Keshavarzi B, Golshani R, Zafarani SGG (2023) Water quality stress to Amirkalayeh wetland, Northern Iran. Environ Monit Assess 195(1):49. https://doi.org/10.1007/s10661-022-10691-8
11. Ramachandra TV, Sudarshan P, Vinay S, Asulabha KS, Varghese S (2020) Nutrient and heavy metal composition in select biotic and abiotic components of Varthur wetlands, Bangalore, India. SN Appl Sci 2:1–14
12. Hong Z, Zhao Q, Chang J, Peng L, Wang S, Hong Y, Liu G, Ding S (2020) Evaluation of water quality and heavy metals in wetlands along the Yellow River in Henan Province. Sustainability 12:1300. https://doi.org/10.3390/su12041300
13. Ramachandra TV, Shivamurthy V, Subramanian AK, Varghese S, Setturu B, Aithal BH (2022) Appraisal of environmental health and ecohydrology of free-flowing Aghanashini River, Karnataka, India. Water 14(6):977. https://doi.org/10.3390/w14060977
14. Samal DR, Gedam S (2021) Assessing the impacts of land use and land cover change on water resources in the Upper Bhima River basin, India. Environ Chall 5:100251. https://doi.org/10.1016/j.envc.2021.100251
15. Sun T, Cheng W, Abdelkareem M, Al-Arifi N (2022) Mapping prospective areas of water resources and monitoring land use/land cover changes in an arid region using remote sensing and GIS techniques. Water 14(15):2435. https://doi.org/10.3390/w14152435
16. Aghsaei H, Dinan NM, Moridi A, Asadolahi Z, Delavar M, Fohrer N, Wagner PD (2020) Effects of dynamic land use/land cover change on water resources and sediment yield in the Anzali wetland catchment, Gilan, Iran. Sci Total Environ 712:136449. https://doi.org/10.1016/j.scitotenv.2019.136449
17. Cao W, Bowden WB, Davie T, Fenemor A (2009) Modelling impacts of land cover change on critical water resources in the Motueka River catchment, New Zealand. Water Resour Manag 23:137–151. https://doi.org/10.1007/s11269-008-9268-2
18. Liu Y, Wang D, Gao J, Deng W (2005) Land use/cover changes, the environment and water resources in Northeast China. Environ Manag 36:691–701. https://doi.org/10.1007/s00267-004-0285-5
19. Ramachandra TV, Mondal T, Setturu B, Aithal BH (2023) Environmental consequences in the neighbourhood of rapid unplanned urbanisation in Bangalore City. AEER 4(4):052. https://doi.org/10.21926/aeer.2304052
20. Ramachandra TV, Kumar U (2008) Wetlands of greater Bangalore, India: automatic delineation through pattern classifiers. Electron Green J 26:2
21. Sudhira HS, Ramachandra TV, Subrahmanya MB (2007) Bangalore. Cities 24(5):379–390. https://doi.org/10.1016/j.cities.2007.04.003
22. APHA, AWWA, WEF (2012) Standard methods for examination of water and waste water, 22nd edn. American Public Health Association, Washington DC
23. Desikachary TV (1959) Cyanophyta. Indian Council for Agricultural Research, New Delhi
24. Prescott GW (1970) How to know freshwater algae, 2nd edn. W.C. Brown, Dubuque
25. AlgaeBase (2023). https://www.algaebase.org/. Accessed 22 Feb 2024
26. Zooplankton Database. https://www.dfo-mpo.gc.ca/science/data-donnees/plankton-plancton/basedonnees-zooplankton-database-eng.html. Accessed 22 Feb 2024
27. Jayaram KC (1999) The fresh water fisheries of Indian region. Narendra Publishing House, New Delhi
28. Talwar PK, Jhingram AG (1991) Inland fishes of India and adjacent countries. Oxford and IBH co. Private limited, New Delhi
29. Fish Base (2023). https://fishbase.mnhn.fr/home.htm. Accessed 22 Feb 2024
30. Cronk JK, Fennessy MS (2001) Wetland plants. CRC Press, Boca Raton
31. Ramaswamy SV, Razi BA (1973) Flora of Bangalore district. Kapila Power Press, Mysore
32. Ramachandra TV, Asulabha KS, Sincy V, Bhat S, Aithal BH (2016) Wetlands: treasure of Bangalore. ENVIS technical report 101, Environmental Information System, Centre for Ecological Sciences (CES), Indian Institute of Science, Bangalore 560012
33. Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny ML, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev 81(2):163–182. https://doi.org/10.1017/S1464793105006950
34. Asulabha KS, Jaishanker R, Sincy V, Ramachandra TV (2022) Diversity of phytoplankton in lakes of Bangalore, Karnataka, India. 10th Chapter. In: Majige S (ed) Biodiversity challenges: a way forward. Daya Publishing House, New Delhi, pp 147–178
35. Ramachandra TV, Mahapatra DM, Bhat SP, Joshi NV (2015) Biofuel production along with remediation of sewage water through algae. In: Singh B, Bauddh K, Bux F (eds) Algae and environmental sustainability. Developments in applied phycology, vol 7. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2641-3_4
36. Sincy V, Asulabha KS, Ramachandra TV (2016) Bio-monitoring of lentic ecosystems through zooplanktons. In: Vinod TR, Sabu T, Thrivikramji KP, Ambat B (eds) Proceedings of Kerala environment congress 2016. Published by Centre for Environment and Development, Thiruvananthapuram, Kerala, India
37. Ejsmont-Karabin J, Karpowicz M (2021) Rotifera in lake subhabitats. Aquat Ecol 55:1285–1296. https://doi.org/10.1007/s10452-020-09818-1
38. Sincy V, Jaishanker R, Asulabha KS, Ramachandra TV (2022) Diversity of phytoplankton in lakes of Bangalore,

Karnataka, India. 10th Chapter. In: Majige S (ed) Biodiversity challenges: a way forward. Daya Publishing House, New Delhi, pp 115–146

39. Gaston KJ (2022) Birds and ecosystem services. Curr Biol 32(20):R1163–R1166
40. Whelan CJ, Şekercioğlu ÇH, Wenny DG (2015) Why birds matter: from economic ornithology to ecosystem services. J Ornithol 156:227–238. https://doi.org/10.1007/s10336-015-1229-y
41. Yusa Y, Sugiura N, Wada T (2006) Predatory potential of freshwater animals on an invasive agricultural pest, the apple snail *Pomacea canaliculata* (Gastropoda: Ampullariidae), in southern Japan. Biol Invas 8:137–147
42. Green AJ, Elmberg J (2014) Ecosystem services provided by waterbirds. Biol Rev 89(1):105–122. https://doi.org/10.1111/brv.12045
43. Ramachandra TV, Rajinikanth R, Ranjini VG (2005) Economic valuation of wetlands. J Environ Biol 26(2):439–447
44. Ramachandra TV, Aithal BH, Kumar U (2012) Conservation of wetlands to mitigate urban floods. JRED 9(1):1–22
45. Ramachandra TV, Meera DS, Alakananda B (2013) Influence of catchment land cover dynamics on the physical, chemical and biological integrity of wetlands. Environ We Int J Sci Technol 8(1):37–54
46. Arsiso BK, Tsidu GM, Abegaz NT (2023) Impact of land use and land cover change on land surface temperature over Lake Tana Basin. J Afr Earth Sci 207:1–16. https://doi.org/10.1016/j.jafrearsci.2023.105047
47. Muro J, Strauch A, Heinemann S, Steinbach S, Thonfeld F, Waske B, Diekkrüger B (2018) Land surface temperature trends as indicator of land use changes in wetlands. Int J Appl Earth Observ Geoinf 70:62–71. https://doi.org/10.1016/j.jag.2018.02.002
48. Johnstone C, Bedaso ZK, Ekberg M (2022) Characterizing surface water and groundwater interaction for sustainable water resources management in southwestern Ohio. Sustain Water Resour Manag 8:1–16. https://doi.org/10.1007/s40899-021-00598-6
49. Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground water and surface water: a single resource, vol 1139. US geological Survey
50. Wu X, Ma T, Wang Y (2020) Surface water and groundwater interactions in wetlands. J Earth Sci 31(5):1016–1028. https://doi.org/10.1007/s12583-020-1333-7
51. Ramachandra TV, Sincy V, Asulabha KS, Mahapatra DM, Bhat SP, Aithal BH (2018) Optimal treatment of domestic wastewater through constructed wetlands. J Biodivers 9:81–102
52. Mahapatra DM, Chanakya HN, Ramachandra TV (2011) Assessment of treatment capabilities of Varthur lake, Bangalore, India. Int J Environ Technol Manag 14(1–4):84–102
53. Paruch L, Paruch AM, Eiken HG, Sørheim R (2019) Faecal pollution affects abundance and diversity of aquatic microbial community in anthropo-zoogenically influenced lotic ecosystems. Sci Rep 9(1):19469. https://doi.org/10.1038/s41598-019-56058-x
54. Ramachandra TV, Alakananda B, Rani A, Khan MA (2011) Ecological and socio-economic assessment of Varthur Wetland, Bengaluru (India). J Environ Sci Eng 53(1):101–108
55. Sudarshan P, Mahesh MK, Ramachandra TV (2019) Assessment of seasonal variation in water quality and water quality index (WQI) of Hebbal Lake, Bangalore, India. Environ Ecol 37(1B):309–317
56. Ramachandra TV, Asulabha KS, Sincy V (2021) Phosphate loading and foam formation in urban lakes. G P Glob Res J Chem 5(1):33–52
57. Ramachandra TV, Shwetmala (2012) Decentralised carbon footprint analysis for opting climate change mitigation strategies in India. Renew Sustain Energ Rev 16(8):5820–5833. https://doi.org/10.1016/j.rser.2012.05.035
58. Naveen BP, Mahapatra DM, Sitharam TG, Sivapullaiah PV, Ramachandra TV (2017) Physico-chemical and biological characterization of urban municipal landfill leachate. Environ Pollut 220:1–12. https://doi.org/10.1016/j.envpol.2016.09.002
59. Ramachandra TV, Sincy V, Asulabha KS, Bhat S, Rahaman MF (2016) Recurring fish mortality episodes in Bangalore Lakes: sign of irresponsible and fragmented governance. ENVIS technical report 105, Environmental Information System, Centre for Ecological Sciences (CES), Indian Institute of Science, Bangalore 560012
60. Benjamin R, Chakrapani BK, Devashish K, Nagarathna AV, Ramachandra TV (1996) Fish mortality in Bangalore lakes, India. Electron Green J 1(6):1–8
61. San Diego-McGlone ML, Azanza RV, Villanoy CL, Jacinto GS (2008) Eutrophic waters, algal bloom and fish kill in fish farming areas in Bolinao, Pangasinan, Philippines. Mar Pollut Bull 57(6–12):295–301. https://doi.org/10.1016/j.marpolbul.2008.03.028
62. Hoyer MV, Watson DL, Willis DJ, Canfield DE Jr (2009) Fish kills in Florida's canals, creeks/rivers, and ponds/lakes. J Aquat Plant Manag 47(1):53–56
63. Sarkar UK, Dubey VK, Singh AK, Gupta BK, Pandey A, Sani RK, Lakra WS (2012) The recent occurrence of exotic freshwater fishes in the tributaries of river Ganga basin: abundance, distribution, risk, and conservation issues. Environmentalist 32:476–484. https://doi.org/10.1007/s10669-012-9412-7
64. Prasad SN, Ramachandra TV, Ahalya N, Sengupta T, Kumar A, Tiwari AK, Vijayan VS, Vijayan L (2002) Conservation of wetlands of India—a review. Trop Ecol 43(1):173–186
65. Ramachandra TV, Sincy V, Asulabha KS (2020) Efficacy of rejuvenation of lakes in Bengaluru, India. Green Chem Technol Lett 6(1):14–26
66. Ramachandra TV, Mahapatra DM, Vinay S, Sincy V, Asulabha KS, Bhat SP, Aithal BH (2017) Bellandur and

Varthur Lakes rejuvenation blueprint. ENVIS technical report 116, Environmental Information System, Centre for Ecological Sciences (CES), Indian Institute of Science, Bangalore 560012

67. Mahapatra DM, Joshi NV, Ramachandra TV (2018) Insights to bioprocess and treatment competence of urban wetlands. J Environ Manag 206:1179–1191

68. Ramachandra TV, Aithal BH, Setturu B, Vinay S, Asulabha KS, Sincy V (2024) Natural capital accounting and valuation of aquatic ecosystem services in Karnataka, India. In: Natural capital accounting and valuation of ecosystem services, Karnataka State, India. Springer, Singapore. https://doi.org/10.1007/978-981-97-2405-5_5

T.V. Ramachandra , FIE, FIEE (UK), FNIE obtained Ph.D. in Ecology and Energy from the Indian Institute of Science. At present, Coordinator of Energy and Wetlands Research Group, Convener of Environmental Information System (ENVIS: http://wgbis.ces.iisc.ac.in) at Centre for Ecological Sciences (CES) and associate faculty at Centre for Sustainable Technologies, Indian Institute of Science. During the past twenty five years he has established an active school of research in the area of energy and environment (http://wgbis.ces.iisc.ac.in/energy). He is a member of Karnataka State Wetland Authority, Kerala Wetland Authority, National Wetland Committee, GoI., and Karnataka State Audit Advisory Committee. Apart from this TVR is serving in many committees of NGT (National Green Tribunal) related to wetlands of Bangalore. TVR features in the recent global ranking of top 2% of scientists (developed by Stanford University) with ranking in Environment: 0.1887, Energy: 0.2138, Enabling & strategic technologies: 0.2642). TVR is a recipient of Johny Biosphere Award for Ecology and Environment (2004), Satish Dhawan Young Scientist Award, 2007 of the Karnataka State Government, Karnataka State Parisara Award, 2017–18 (Environment Award, Government of Karnataka). TVR's research interests are in the area of aquatic ecosystems, biodiversity, ecological modeling, Western Ghats ecology, energy systems, renewable energy, energy conservation, energy planning, geo-informatics, environmental engineering education research and curriculum development at the tertiary level. He has published over 355 research papers in the reputed peer-reviewed international and national journals, 92 book chapters, 343 papers in the international and national symposiums as well as 22 books. He has guided 178 students for Master's dissertation and nineteen students for Doctoral degrees.

K. S. Asulabha is currently a research scholar in Ecoinformatics working in the Microalgae spatial decision support system at at the Energy and Wetlands research Group, CES TE15, Indian Institute of Science, Bangalore. Her areas of interest are monitoring aquatic ecosystems, water quality assessment, wetland ecosystem evaluation, soil quality assessment, algal culturing, algae, fish, and zooplankton documentation, and open source GIS. She has published over 7 research papers in reputed peer-reviewed international and national journals, 19 papers in international and national symposiums, one strategy paper, 20 technical reports, and 2 book chapters.

V. Sincy is currently a Research Scholar in Ecoinformatics working in the Ichthyofauna spatial decision support system at the Energy and Wetlands research Group, CES TE15, Indian Institute of Science, Bangalore. Her areas of interest are wetland ecosystem evaluation, monitoring of aquatic ecosystems, water quality assessment, soil quality assessment, algal culturing in wastewater, fish, algae, and zooplankton, and open-source GIS. She has published over 6 research papers in reputed peer-reviewed international and national journals, 19 papers in international and national symposiums, 1 strategy paper, 21 technical reports, and 2 book chapters.

Abhishek Baghel is currently working as computer analyst at the Energy and Wetlands research Group, CES TE15, Indian Institute of Science, Bangalore. His areas of expertise are design of spatial decision support system, computer analytics.

S. Vinay is an Associate Professor in the Department of Civil Engineering, Alva's Institute of Engineering and technology, Moodbidri, Karnataka, India. He has received PhD from Visvesvaraya Technological University, Belagavi, India. He was a post-doctoral fellow at RCGSIDM, IIT Kharagpur, India. Since 2013 he is associated as a researcher at EWRG, CES, IISc. His research interest areas are Environmental flows, Hydrology, applications of Remote Sensing and GIS in disaster risk assessment, visualisaiton of landscape, spatial modelling for forecasting, Climate, Environment aspects. He has published over 100 articles as journals, conferences, book chapters, conference proceedings. He has been reviewer in national, international journals and conferences.