

Integrated Water Quality and Microplastic Pollution Assessment in Urban Freshwater Systems Using Statistical and Geospatial Approaches

M.Tech. Thesis

By

SHIKSHA SINGH (2402104017)



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Integrated Water Quality and Microplastic Pollution Assessment in Urban Freshwater Systems Using Statistical and Geospatial Approaches

A THESIS

*Submitted in partial fulfilment of the
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SHIKSHA SINGH



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled “ **Integrated Water Quality and Microplastic Pollution Assessment in Urban Freshwater Systems Using Statistical and Geospatial Approaches**” in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF CIVIL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2024 of joining the M.Tech. program to May 2026 under the supervision of Dr. Mayur Shirish Jain, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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(SHIKSHA SINGH)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

(22/05/2026)
(Dr. Mayur Shirish Jain)

Shiksha Singh has successfully given her M.Tech. Oral Examination held on **15th May**.

Signature(s) of Supervisor(s) of M.Tech. thesis

Date: 22/05/2026

Convener, DPGC (Acting)

Date: 22/05/26

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Shiksha Singh (2402104017)

Date: 22/05/2026

CERTIFICATE

This is to certify that the Project Work entitled “INTEGRATED WATER QUALITY AND MICROPLASTIC POLLUTION ASSESSMENT IN URBAN FRESHWATER SYSTEMS USING STATISTICAL AND GEOSPATIAL APPROACHES” is bonafide work of Ms. Shiksha Singh in partial fulfilment of the academic requirements for the award of Post Graduate Program in Water, Climate and Sustainability (WCS). This work is carried out by her under my guidance and supervision.



Signature of Guide

Dr. Mayur Shirish Jain

DEDICATION

This thesis is dedicated to **my beloved parents**, whose unwavering love, enduring sacrifices, and constant encouragement have been the guiding force behind every step of my academic journey.

Abstract

Rapid urbanization, increasing wastewater discharge, and land-use transformation have significantly degraded freshwater ecosystems, particularly urban rivers and wetlands that continuously receive untreated sewage, stormwater runoff, industrial effluents, and solid waste. In recent years, emerging contaminants such as microplastics have become an additional environmental concern because of their persistence, transport behavior, and ecological risks. The present study focuses on the integrated assessment of physicochemical pollution, heavy metals, microplastic contamination, and landscape-level influences in the Kahn River and Sirpur Wetland, Indore, India.

The study was conducted through systematic field investigations, laboratory analyses, statistical evaluation, and geospatial assessment. Water samples were collected from multiple locations along the Kahn River and Sirpur Wetland to evaluate physicochemical parameters, nutrients, and heavy metals using standard APHA methods and instrumental techniques, including ICP-OES and AAS. Microplastics were extracted, quantified, and characterized using stereomicroscopy, FESEM, and ATR-FTIR analysis. In addition, Entropy Weighted Water Quality Index (EWQI), multivariate statistical analysis, and GIS-based Land Use Land Cover (LULC) assessment were performed to examine pollution behavior and the influence of surrounding landscape characteristics on water quality and microplastic distribution.

The results revealed severe deterioration in water quality along the urban stretches of the Kahn River, with several parameters exceeding permissible limits for drinking water and ecological suitability. Statistical analysis indicated strong positive correlations among organic pollution indicators, nutrients, and microplastic abundance, reflecting the influence of untreated sewage discharge and urban runoff. A total of 475 microplastic particles ($>200\ \mu\text{m}$) per liter were identified across the sampling locations, with fibers being the dominant morphology, accounting for nearly 52% of the total MPs, followed by fragments and films. FESEM analysis revealed irregular, weathered particle surfaces, while ATR-FTIR identified dominant polymer types, including polyethylene and polypropylene. Spatial analysis further demonstrated that increasing settlement density, urban fragmentation, and reduced vegetation cover within 500 m and 1000 m buffer zones significantly influenced pollutant distribution and landscape-level degradation.

The study highlights that urban freshwater pollution is multidimensional and cannot be adequately understood through conventional water quality analysis alone. The integrated approach adopted in this work provides a comprehensive understanding of the interactions

between urbanization, land-use change, physicochemical deterioration, and emerging pollutants in urban river–wetland ecosystems. The findings can support sustainable freshwater management, pollution mitigation, and restoration planning in rapidly urbanizing regions such as Indore.

Keyword: Water Quality Assessment; Kahn River; Sirpur Lake; Microplastics; Land Use Land Cover (LULC)

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ACRONYMS

Acronym	Full Form
ANOVA	Analysis of Variance
APHA	American Public Health Association
ATR-FTIR	Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CETP	Common Effluent Treatment Plant
EC	Electrical Conductivity
EDCs	Endocrine Disrupting Compounds
EPs	Emerging Pollutants
EWQI	Entropy Weighted Water Quality Index
FE-SEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
HDPE	High-Density Polyethylene
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IWRM	Integrated Water Resource Management
LDPE	Low-Density Polyethylene
LULC	Land Use Land Cover
MPs	Microplastics
NbS	Nature-Based Solutions
PCA	Principal Component Analysis
PC	Polycarbonate
PE	Polyethylene
PFAS	Per- and Polyfluoroalkyl Substances
PP	Polypropylene
PPCPs	Pharmaceuticals and Personal Care Products
QA/QC	Quality Assurance and Quality Control
TSS	Total Suspended Solids
WQI	Water Quality Index

Chapter 1

Introduction

The introduction chapter outlines the overall background and framework of the present study. It includes the problem statement associated with freshwater pollution in urban rivers and wetlands, followed by the need, motivation, and scope of the Study. The chapter introduces the environmental significance of the Kahn River and Sirpur Wetland and discusses the major concerns related to physicochemical pollution, heavy metals, emerging contaminants, and urbanization-driven degradation. In addition, the chapter presents the research objectives, the study's significance, and the thesis's overall organization.

1.1 Overview

Freshwater ecosystems are increasingly threatened by rapid urbanization, industrialization, population growth, and improper waste management practices, resulting in severe deterioration of river and wetland water quality worldwide (Mekonnen et al., 2015). Urban rivers and wetlands often receive untreated sewage, industrial discharge, stormwater runoff, and solid waste, which significantly alter their physicochemical and ecological characteristics (Feng et al., 2024). In India, several freshwater systems are under continuous anthropogenic stress due to increasing urban expansion and inadequate wastewater treatment infrastructure. The situation is particularly critical in rapidly growing urban centers such as Indore, where the Kahn River and Sirpur Wetland are continually affected by untreated wastewater discharges, urban runoff, and land-use changes. These systems, therefore, represent important freshwater ecosystems for understanding the interactions among urbanization, conventional pollutants, and emerging contaminants.

This study focuses on the integrated assessment of physicochemical pollution, heavy metal contamination, and microplastic contamination in the Kahn River and the Sirpur Wetland in Indore. The study was conducted through systematic field investigations, laboratory analyses, statistical evaluation, and geospatial assessment to examine the spatial distribution and environmental behavior of pollutants within the river wetland system. Standard physicochemical parameters, nutrients, and heavy metals were analyzed using APHA-based methods, while microplastics were characterized using stereomicroscopy, FESEM, and ATR-FTIR techniques. Statistical tools, including correlation analysis, PCA, and ANOVA, were employed to identify relationships among pollutants and possible contamination sources. In

addition, an Entropy Weighted Water Quality Index (EWQI) was developed to evaluate the suitability of water for different uses.

To better understand the influence of surrounding landscapes on pollution dynamics, Land Use Land Cover (LULC) analysis and landscape metrics were incorporated using GIS-based approaches. Buffer analysis and fragmentation indices were used to evaluate how settlement expansion, urban runoff, vegetation loss, and land-use heterogeneity influence water quality and microplastic distribution within the study area. The findings indicate significant deterioration of water quality in urban stretches of the Kahn River, while Sirpur Wetland exhibited localized pollution stress associated with surrounding anthropogenic activities. Microplastic analysis revealed the dominance of fibers and fragments, suggesting a strong influence of domestic sewage and urban runoff. Overall, the study provides an integrated understanding of pollution dynamics in urban freshwater ecosystems and highlights the importance of combining conventional water quality assessment with emerging pollutant analysis and landscape-scale evaluation for sustainable freshwater management.

1.2 Background of the Problem

Freshwater ecosystems are increasingly facing severe environmental stress due to rapid urbanization, industrialization, population growth, and unplanned land-use transformation. Rivers and wetlands located near urban settlements continuously receive untreated sewage, industrial effluents, stormwater runoff, and municipal solid waste, resulting in significant deterioration of water quality and ecological health. In addition to conventional pollutants such as nutrients, suspended solids, and heavy metals, emerging contaminants, including microplastics, are now being widely detected in freshwater environments (Feng et al., 2024). These contaminants persist within aquatic systems, interact with other pollutants, and pose potential ecological and human health risks. Urban tributaries and wetlands are particularly vulnerable because they serve as pathways for pollutant transport and accumulation zones under increasing anthropogenic pressure.

In India, inadequate wastewater treatment infrastructure and rapid urban expansion have intensified pollution in several freshwater systems. The situation is especially critical in rapidly developing urban centers such as Indore, where the Kahn River and Sirpur Wetland are continuously affected by untreated wastewater discharge, urban runoff, and surrounding land-use changes. Despite growing concerns regarding freshwater degradation, integrated studies combining physicochemical pollution, heavy metals, microplastics, and landscape-level influences remain limited, particularly for urban river–wetland systems in central India.

Therefore, understanding the interactions between urbanization, land-use dynamics, conventional pollutants, and emerging contaminants is essential for developing sustainable freshwater management and restoration strategies.

1.3 Motivation of the Study

Rapid urbanization and increasing anthropogenic activities have significantly degraded the quality of freshwater ecosystems, particularly urban rivers and wetlands that continuously receive untreated sewage, stormwater runoff, industrial discharge, and solid waste. In rapidly growing cities such as Indore, the Kahn River and Sirpur Wetland are increasingly exposed to pollution stress due to expanding settlements, changing land-use patterns, and inadequate wastewater management infrastructure (Figure 1.1). Along with conventional pollutants such as nutrients, suspended solids, and heavy metals, emerging contaminants, including microplastics, are now a major environmental concern due to their persistence, transport behavior, and potential ecological impacts.



Figure 1.1 Field observations of the Kahn River highlight untreated sewage inflow, plastic waste accumulation, eutrophic stagnant zones, and foam formation due to elevated organic pollution. (Source: Self)

Although several studies have independently investigated water quality deterioration and microplastic contamination, integrated assessments linking physicochemical pollution, emerging contaminants, and surrounding land-use dynamics remain limited, particularly for

urban river–wetland systems in central India. In addition, the influence of landscape fragmentation, urban runoff, and tributary discharge on pollutant distribution is still poorly understood. Therefore, the present study was motivated by the need to comprehensively evaluate the interactions between urbanization, land-use change, conventional pollutants, and microplastic contamination in the Kahn River and Sirpur Wetland, with the aim of supporting sustainable freshwater management and ecological restoration strategies.

1.4 Objectives of the Study

- (a). To perform the initial spatial characterization of the river and the wetland in Indore and to analyze the possible sources through multivariate statistical analysis
- (b). To develop and evaluate Water Quality Index (WQI) models for categorizing monitoring locations and assessing the water-quality status of the studied water bodies.
- (c). To investigate the occurrence, distribution, and characteristics of emerging microplastic contaminants in the selected aquatic systems.
- (d). To evaluate the influence of LULC composition and spatial distribution on physicochemical characteristics and microplastic contamination using geospatial and landscape-metric approaches.

1.5 Need for the Study

Freshwater ecosystems are increasingly deteriorating due to rapid urbanization, industrialization, population growth, and unregulated pollution discharge into rivers and wetlands. Urban freshwater systems are continuously exposed to untreated sewage, industrial effluents, stormwater runoff, agricultural discharge, and solid waste accumulation, resulting in significant degradation of water quality and ecological health. In recent years, emerging contaminants such as microplastics have become an additional environmental concern due to their persistence, transport behavior, and interactions with other pollutants, including heavy metals and organic contaminants. Despite growing research on freshwater pollution, most studies have focused either on conventional physicochemical parameters or microplastic contamination independently, while integrated investigations linking both aspects remain limited.

In India, particularly in rapidly urbanizing cities such as Indore, freshwater ecosystems are under severe anthropogenic pressure from expanding settlements, inadequate wastewater treatment infrastructure, and changing land-use patterns. The Kahn River and Sirpur Wetland represent highly vulnerable urban freshwater systems that receive continuous pollutant inputs

from sewage discharge, urban runoff, and surrounding human activities. However, limited studies have comprehensively evaluated the combined influence of physicochemical pollution, heavy metals, microplastics, and landscape-level changes on these ecosystems. Furthermore, the relationships among land use, urban fragmentation, runoff pathways, and pollutant distribution remain insufficiently understood in central Indian freshwater systems.

Therefore, there is a need for an integrated assessment combining water quality analysis, microplastic characterization, statistical evaluation, and LULC-based landscape analysis to better understand pollution dynamics in the Kahn River and Sirpur Wetland. Such studies are essential for identifying pollution sources, evaluating ecological risks, supporting sustainable freshwater management, and developing effective restoration and conservation strategies for urban river-wetland ecosystems.

1.6 Scope of the Study

The research assesses the extent of freshwater pollution in Indore, Madhya Pradesh, with a focus on the Kahn River and Sirpur Wetland. These two distinct aquatic ecosystems supported a rich natural flora and fauna at that time. The Research integrates the analysis of Microplastics (MPs) as emerging contaminants to provide a holistic understanding of water quality degradation across upstream, midstream, and downstream stretches of the river and inflow-outflow zones of the wetland with traditional physicochemical parameters (pH, DO, BOD, COD, nutrients, heavy metals) and biological indicators (*E. coli* and coliform counts). The research will focus on seasonal variations, examining differences between the pre-monsoon, monsoon, and post-monsoon periods. The advanced analytical tools consist of microscopy, FTIR, and FESEM. By considering both local and global data on emerging pollutants, the research aims to identify areas with the highest pollution levels, compare river and wetland contamination, and investigate the relationship between microplastics and conventional parameters.

1.7 Thesis Organization

The thesis is organized into five chapters that assess physicochemical pollution, heavy metal contamination, microplastic contamination, and landscape-level influences in the Kahn River and Sirpur Wetland, Indore.

- Chapter 1 presents the introduction to the study, including the background of the problem, need, and motivation of the study, scope of the research, pollution scenario of urban freshwater ecosystems, and the significance of investigating physicochemical

pollution and emerging contaminants in the Kahn River and Sirpur Wetland. The chapter also outlines the objectives and overall framework of the study.

- Chapter 2 provides a detailed literature review on surface water pollution in rivers and wetlands, focusing on global and Indian freshwater pollution scenarios, urbanization impacts, sewage discharge, and land-use change. The chapter further discusses microplastics as emerging pollutants, including their sources, transport pathways, ecological impacts, and interactions with conventional pollutants. In addition, the influence of LULC dynamics, urban runoff, and landscape fragmentation on water quality deterioration is reviewed, followed by the identification of the research gaps addressed in the present study.
- Chapter 3 describes the materials and methodologies adopted in the study, including reconnaissance surveys, sampling strategy, physicochemical and heavy metal analysis, microplastic extraction and characterization, and statistical evaluation methods. The chapter also explains the analytical instruments used, including ICP-OES, AAS, FESEM, ATR-FTIR, and stereomicroscopy. Furthermore, GIS-based LULC analysis, buffer analysis, and landscape metric assessment methodologies are presented.
- Chapter 4 presents the results and discussion of the study, including physicochemical characterization, heavy metal contamination, EWQI assessment, and statistical analysis of the Kahn River and Sirpur Wetland. The chapter further discusses the abundance, morphology, polymer characterization, and spatial distribution of microplastics. In addition, the influence of urbanization, LULC dynamics, and landscape fragmentation on water quality and microplastic contamination is evaluated using correlation analysis, PCA, ANOVA, and landscape metrics.
- Chapter 5 summarizes the major findings of the study and presents the overall conclusions and recommendations for sustainable freshwater management, pollution mitigation, and restoration strategies for urban river–wetland ecosystems.

Chapter 2

Literature Review

The literature review chapter presents a comprehensive overview of surface water pollution in rivers and wetlands, beginning with a global perspective, narrowing to the Indian context, then to central India, and finally to the Kahn River and Sirpur Wetland in Indore. The chapter discusses the major sources and impacts of freshwater pollution, including urbanization, industrial discharges, sewage inflows, stormwater runoff, and land-use changes. It further reviews the occurrence, sources, transport pathways, ecological impacts, and pollutant-carrying behavior of microplastics in freshwater ecosystems. In addition, the chapter examines the influence of urban growth, LULC dynamics, buffer characteristics, and landscape fragmentation on water quality deterioration and pollutant distribution. Finally, the chapter identifies the existing research gaps and establishes the scientific basis and significance of the present study.

2.1 Surface Water Quality in Rivers and Wetlands

2.1.1 Global Scenario of Surface Water Pollution

Surface water pollution has emerged as one of the most critical environmental challenges globally, severely affecting freshwater availability, ecological stability, and human health. Rapid urbanization, industrialization, population growth, and poor waste management practices have significantly degraded the quality of rivers, lakes, and wetlands worldwide. According to the United Nations Environment Program (UNEP) and the World Health Organization (WHO), a substantial proportion of wastewater generated globally is discharged untreated into freshwater ecosystems, resulting in nutrient enrichment, eutrophication, oxygen depletion, biodiversity loss, and ecological degradation (Mekonnen et al., 2015). The increasing contamination of surface waters is associated with a broad range of pollutants, including nutrients, pathogens, heavy metals, pharmaceuticals, endocrine-disrupting compounds, plastics, and emerging contaminants such as PFAS (Feng et al., 2024; Zandaryaa et al., 2025). Several global freshwater systems, including the Ganges, Yamuna, and Citarum rivers, as well as ecologically sensitive ecosystems such as Lake Victoria and the Everglades, have become major pollution hotspots due to untreated municipal sewage, industrial discharges, agricultural runoff, and stormwater inflows (Hofstra et al., 2016).

Excessive nutrient and organic pollutant inputs have accelerated eutrophication in many freshwater ecosystems worldwide. Nitrogen and phosphorus loads from domestic wastewater, agricultural activities, and industrial discharges frequently exceed the assimilative capacity of rivers and wetlands, leading to algal blooms, hypoxia, fish mortality, and the collapse of aquatic habitats (Mekonnen et al., 2015). Waterborne pathogens, including protozoa such as *Cryptosporidium*, pose serious public health concerns in regions lacking proper sanitation infrastructure (G4). In addition, heavy metals such as lead, cadmium, mercury, and arsenic, derived from mining and industrial activities, accumulate in sediments and aquatic organisms, causing long-term ecological and toxicological impacts (Zhou et al., 2020). Organic pollutants, pharmaceuticals, endocrine disruptors, plastics, and microplastics are also increasingly being detected in freshwater systems even at trace concentrations, highlighting the growing complexity of surface water pollution worldwide (Kroeze et al., 2016; Feng et al., 2024).

2.1.2 Major Sources of Surface Water Pollution

Surface water ecosystems are exposed to both point and non-point sources of pollution, with domestic sewage, industrial effluents, agricultural runoff, stormwater discharge, and solid waste disposal acting as major contributors. Untreated domestic sewage remains one of the primary causes of water quality deterioration in urban rivers and wetlands, introducing pathogens, nutrients, suspended solids, and organic matter that stimulate eutrophication and oxygen depletion. A study conducted in the Baiyangdian Wetland, China, reported significant increases in $\text{NH}_3\text{-N}$ (+48%), TN (+27%), and TP (+47%) during the rainy season, directly linking sewage discharge and runoff to nutrient enrichment (Li et al., 2011).

Industrial activities further contribute chronic pollutants such as heavy metals, hydrocarbons, dyes, and persistent organic compounds into freshwater systems. In the Yellow River Delta wetlands, enrichment factors greater than 5 for arsenic and cadmium indicated severe contamination associated with industrial discharge (Monib et al., 2024). Similarly, industrial and mining activities in the Huelva estuary, Spain, contributed approximately 7,900 t of Fe, 3,500 t of Zn, and 1,700 t of Cu annually into adjacent aquatic ecosystems (Barba-Brioso et al., 2010). Agricultural runoff also significantly degrades freshwater quality, particularly in wetlands near agricultural areas. Studies in the Qixing River wetland, China, reported elevated COD, $\text{NH}_3\text{-N}$, and TP concentrations associated with fertilizer application and agricultural activities (Cui et al., 2020). In Xianghai Lake, agricultural and cattle runoff contributed nearly 31.65% of total water quality impairment (Gao et al., 2023).

Urban stormwater runoff intensifies pollution by transporting oils, grease, nutrients, heavy metals, plastics, and microplastics from impervious urban surfaces into rivers and wetlands

(Liu et al., 2023; Wan & Wang, 2021). Improper solid waste management further transforms rivers and wetlands into sinks for macroplastics and microplastics, increasing ecological risks and pollutant accumulation (Liu et al., 2023). Emerging pollutants, such as pharmaceuticals, antibiotics, and antibiotic resistance genes, originating from hospital waste and urban sewage are increasingly detected in freshwater ecosystems, posing additional ecological and public health concerns (Ibekwe et al., 2016).

2.1.3 Pollution in Natural Wetlands

Natural wetlands, including marshes, lakes, ponds, and floodplains, are transitional ecosystems that connect terrestrial and aquatic environments and occupy nearly 6% of Earth's land area (Cai et al., 2021). Wetlands provide essential ecosystem services, including sediment trapping, nutrient retention, groundwater recharge, flood mitigation, climate regulation, and biodiversity conservation (Zhao et al., 2001; Yimin et al., 2010). However, despite their ecological importance, wetlands are increasingly threatened by urbanization, agricultural expansion, industrial discharge, and hydrological alterations. More than half of the world's wetlands have disappeared since the beginning of the twentieth century due to anthropogenic disturbances and land-use transformation (Cai et al., 2021). In China alone, approximately 33,963 km² of wetland area was lost between 2003 and 2013 due to increased agricultural activities, urban development, and changes in water management (Zhao et al., 2001).

Wetlands generally function as pollutant sinks because of their low flow velocity, high sediment retention, and extended residence time. However, excessive pollutant accumulation may alter ecological stability and transform wetlands from pollution sinks into secondary pollution sources. Under anoxic conditions, nutrients and heavy metals retained within sediments may be remobilized into the water column, intensifying ecological risks. Agricultural expansion surrounding wetlands further accelerates nutrient enrichment and ecological degradation. For instance, agriculture contributed approximately 49.2% of total wetland loss in the Tumen River Basin between 1986 and 2016 (Liu et al., 2021). Such degradation weakens the ecological resilience and hydrological functions of wetlands, thereby reducing their ability to regulate pollutants and maintain ecosystem stability.

2.1.4 Pollution in Urban Rivers

Urban rivers are among the most vulnerable freshwater ecosystems because they continuously receive pollutants from densely populated settlements, industrial zones, drainage networks, and urban runoff. Urbanization significantly alters river hydrology through channelization, floodplain encroachment, impervious-surface development, and reduced natural infiltration capacity (Everard & Moggridge, 2012). These modifications generate rapid

runoff surges and flashy hydrographs, increasing sediment erosion and pollutant transport during rainfall events (Richardson & Soloviev, 2021). Untreated sewage discharge, industrial wastewater, and direct dumping of municipal waste significantly degrade river water quality, leading to elevated BOD, COD, nutrient, and suspended solids concentrations.

Several urban rivers worldwide exhibit characteristics of the “Urban Stream Syndrome,” which is associated with poor water quality, altered hydrology, habitat degradation, and declining biodiversity (Francis, 2014). Rivers such as the Yamuna in Delhi and the Kahn River in Indore have reported severe physicochemical deterioration due to sewage inflows and urban pollution (Haufe, 2013). Sediments within urban rivers frequently accumulate heavy metals, hydrocarbons, pathogens, and microplastics, thereby creating long-term ecological and public health risks (Shen et al., 2022). Although rivers possess a natural self-purification capacity, continuous pollutant inflows often overwhelm these processes, transforming urban rivers into highly degraded ecosystems. Restoration strategies such as riparian buffers, constructed wetlands, ecohydrological interventions, and nature-based solutions are therefore increasingly recommended for improving river health and ecological sustainability (Everard & Moggridge, 2012).

2.1.5 Surface Water Pollution Scenario in India

India is currently experiencing severe deterioration in surface water quality due to rapid urbanization, industrial growth, population expansion, and inadequate wastewater treatment infrastructure. Major river systems such as the Ganga, Yamuna, Sabarmati, and Hooghly rivers receive untreated domestic sewage, industrial discharge, agricultural runoff, and municipal solid waste, resulting in extensive ecological degradation. Elevated concentrations of BOD, COD, nutrients, heavy metals, microbial contaminants, and suspended solids have been widely reported in Indian freshwater systems (Haufe, 2013). Urban tributaries connected to densely populated settlements increasingly function as major pollution pathways transporting contaminants into larger rivers and connected wetlands.

Indian wetlands and lakes are similarly threatened by anthropogenic pressure and land-use transformation. Wetlands such as Vembanad Lake and Red Hills Lake have reported severe contamination from sewage inflows, industrial activities, and plastic waste accumulation (Gopinath et al., 2020). Slow hydrodynamics and high sediment retention further increase pollutant accumulation within these ecosystems, making Ramsar wetlands particularly vulnerable to ecological degradation. Inadequate waste management and uncontrolled urban expansion, therefore, continue to intensify the pollution burden within Indian freshwater ecosystems.

2.1.6 Surface Water Pollution in Central India

Compared with other regions of India, relatively few studies have investigated pollution dynamics and emerging contaminants within freshwater ecosystems of central India. However, rapid urbanization, increasing sewage generation, industrial activities, and poor wastewater management practices are intensifying pollution within rivers, tributaries, and wetlands in this region. Indore, one of the fastest-growing urban centers in central India, has experienced substantial expansion of settlements, urban infrastructure, and industrial activities, thereby increasing anthropogenic pressure on surrounding freshwater ecosystems.

The Kahn River, an urban tributary flowing through Indore city, receives untreated sewage, stormwater runoff, industrial discharge, and municipal waste from multiple urban drains and densely populated settlements. Continuous pollutant inflow has significantly deteriorated the river's physicochemical conditions, with elevated organic loads and nutrient concentrations frequently reported (Haufe, 2013). Similarly, the Sirpur Wetland, a Ramsar-recognized wetland ecosystem, is increasingly threatened by urban runoff, agricultural activities, and land-use changes (Zandaryaa et al., 2025). These urban tributaries and associated wetlands therefore represent highly vulnerable ecosystems where rapid urbanization and increasing anthropogenic disturbances are accelerating ecological degradation and surface water quality deterioration.

2.2 Microplastics in Freshwater Systems

2.2.1 Introduction to Microplastics

Microplastics (MPs), generally defined as plastic particles smaller than 5 mm, have emerged as one of the most persistent and widespread contaminants in freshwater ecosystems. Due to their small size, persistence, and resistance to degradation, MPs are now frequently detected in rivers, lakes, wetlands, sediments, and even drinking water systems. MPs are commonly classified into primary and secondary microplastics. Primary microplastics are intentionally manufactured in microscopic sizes for industrial and domestic applications such as cosmetic products, cleaning agents, and industrial abrasives, whereas secondary microplastics originate from the fragmentation of larger plastic debris through physical, chemical, and biological degradation processes (Singh & Jain, 2026). Increasing plastic production, rapid urbanization, improper waste disposal, and ineffective wastewater treatment systems have significantly accelerated the accumulation of MPs in freshwater environments worldwide.

Freshwater systems are increasingly recognized as major transport pathways for microplastics originating from terrestrial sources before their eventual transfer into marine

ecosystems. Urban rivers and wetlands are particularly vulnerable because they continuously receive sewage discharge, stormwater runoff, industrial effluents, and plastic waste from densely populated settlements (Xu et al., 2021). The persistence of MPs in aquatic environments raises serious environmental concerns because they can remain suspended in water, accumulate within sediments, or become ingested by aquatic organisms, thereby entering aquatic food chains and causing ecological disturbances (McCormick et al., 2016).

2.2.2 Sources of Microplastics in Freshwater Ecosystems

Microplastics in freshwater systems originate from a variety of anthropogenic activities, with domestic sewage, textile industries, urban runoff, agricultural activities, industrial discharge, and improper solid waste management acting as the major contributors. Domestic wastewater is considered one of the primary pathways of MPs into rivers because synthetic textile fibers released during laundering are poorly retained within conventional wastewater treatment plants (Ramasamy et al., 2022). Urban stormwater runoff transports fragmented plastics, tire-wear particles, packaging materials, and road dust into nearby freshwater systems during rainfall events (Liu et al., 2023), as shown in Figure 2.1.

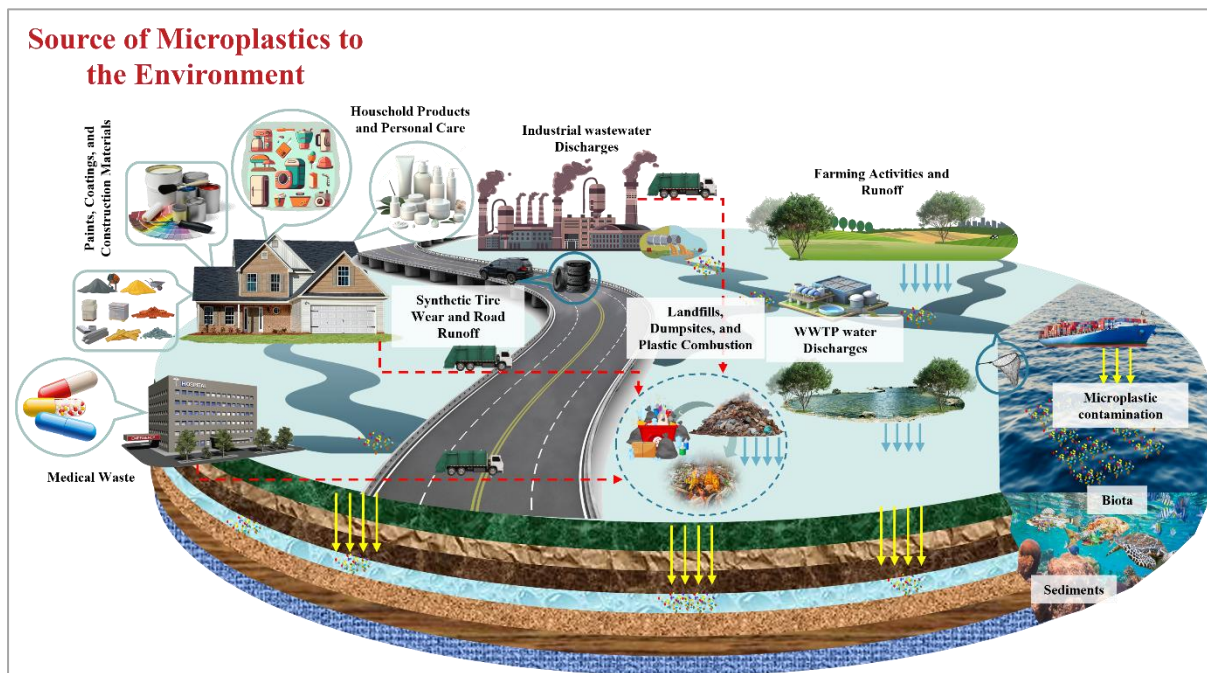


Figure 2.1 Sources and environmental pathways of MP pollution from land to aquatic ecosystems. (Source: Self)

Industrial activities also contribute substantially to MP contamination by releasing plastic pellets, industrial abrasives, packaging waste, and polymer residues. Agricultural activities further introduce MPs into freshwater environments through sewage sludge application, plastic mulching, irrigation using contaminated water, and runoff from agricultural fields (Singh &

Jain, 2026). In urban regions, open dumping of municipal solid waste along riverbanks and wetland margins accelerates the fragmentation of larger plastics into smaller particles through ultraviolet radiation, mechanical abrasion, and weathering. Consequently, urban tributaries and wetlands increasingly function as accumulation zones for microplastic contamination.

2.2.3 Fate and Transport of Microplastics in Rivers and Wetlands

The transport, distribution, and accumulation of microplastics within freshwater ecosystems are strongly influenced by hydrodynamic conditions, particle characteristics, land use, and seasonal variations. Rivers primarily function as transport pathways that convey MPs from terrestrial environments toward downstream aquatic systems, whereas wetlands frequently act as depositional sinks due to lower flow velocity and greater sediment retention capacity (Xu et al., 2021). The fate of MPs depends on particle density, shape, size, and surface characteristics, which determine whether particles remain suspended in the water column or settle to the sediment (Figure 2.2).

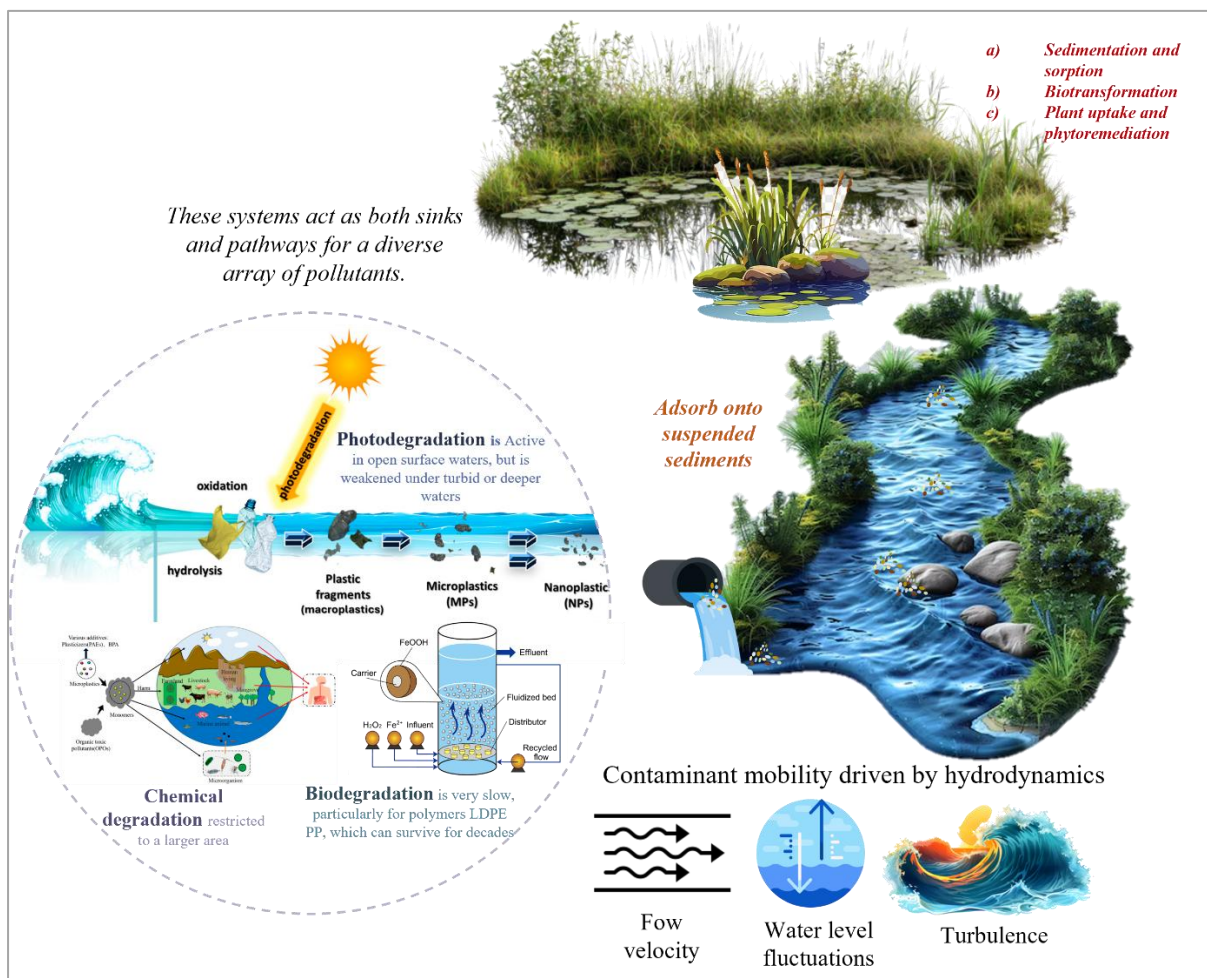


Figure 2.2 Fate and Transport of Microplastics in the River and Wetland (Source: Self)

Seasonal variations, particularly monsoon-driven runoff, significantly influence MP transport and redistribution within freshwater systems. Heavy rainfall events increase surface runoff, sediment erosion, sewage overflow, and stormwater discharge, thereby enhancing the mobilization and downstream transport of MPs (Liu et al., 2023). Conversely, low-flow conditions may favor sedimentation and accumulation of MPs within depositional zones of wetlands and slow-moving river stretches. Biofouling, aggregation with suspended solids, and adsorption of organic matter further alter the density and settling behavior of MPs in aquatic systems (Singh & Jain, 2026).

Environmental weathering processes, such as ultraviolet radiation, oxidation, mechanical abrasion, and hydrodynamic shear, gradually fragment larger plastic debris into smaller secondary MPs with rough, irregular surfaces. These weathered particles exhibit greater surface area and adsorption capacity, thereby increasing their interaction with surrounding contaminants and microorganisms. Sediment–water interactions and repeated resuspension processes during high-flow conditions further complicate the transport behavior and environmental persistence of MPs within freshwater ecosystems.

2.2.4 Occurrence of Microplastics in Rivers and Wetlands

Microplastic contamination has been widely reported in rivers, lakes, wetlands, and reservoirs worldwide. Urban rivers are increasingly recognized as major MP hotspots because they continuously receive sewage discharge, industrial effluents, and urban runoff from surrounding settlements. Studies conducted in Chinese urban rivers reported MP concentrations ranging from 0.3 to 4.0 items/L, with fibers identified as the dominant morphology and polypropylene as the dominant polymer type (Xu et al., 2021). Similarly, rivers in the United States reported average daily emissions of approximately 1.3 million MP particles downstream of sewage disposal plants (McCormick et al., 2016).

In India, several freshwater systems, including the Ganga River, Vembanad Lake, Red Hills Lake, and Netravathi River, have reported significant MP contamination associated with sewage inflow, urban runoff, textile waste, and plastic littering (Amrutha & Warriar, 2020; Gopinath et al., 2020). Fibers and fragments are generally reported as the dominant morphologies because of their widespread release from textile wastewater and degradation of larger plastic debris. Wetlands and lakes often exhibit higher MP accumulation because of lower hydrodynamic conditions and enhanced sediment deposition (Figure 2.3).

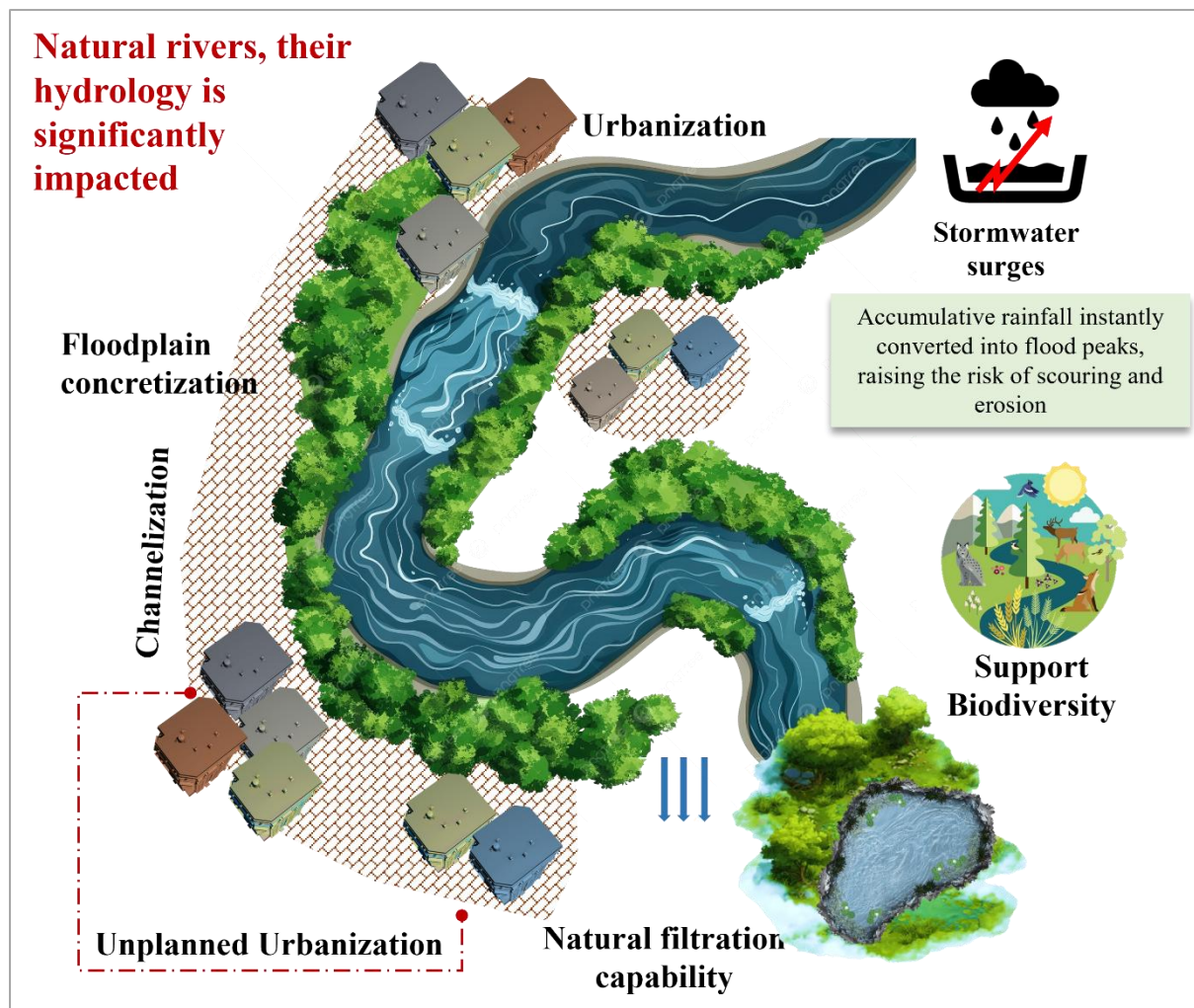


Figure 2.3 Influence of urbanization and land-use transformation on river hydrology, runoff generation, erosion processes, and ecological degradation in urban freshwater ecosystems.

(Source: Self)

2.2.5 Relationship Between Microplastics and Water Quality

Several studies have demonstrated strong relationships between MP abundance and conventional water quality parameters, indicating common anthropogenic sources and transport pathways. Elevated concentrations of MPs are frequently associated with high COD, BOD, TSS, nutrient concentrations, and urban settlement density, reflecting the influence of untreated sewage discharge and urban runoff (Singh & Jain, 2026). Wastewater-dominated rivers generally exhibit greater MP abundance because sewage discharge continuously introduces synthetic fibers, plastic fragments, and other polymeric materials into freshwater systems. Suspended solids and organic matter also influence MP transport behavior through aggregation and adsorption processes. MPs may interact with dissolved organic matter, nutrients, and sediments, altering their transport and settling characteristics within rivers and

wetlands. Several studies further suggest that increasing urbanization, impervious surfaces, and land-use transformation significantly intensify MP contamination in freshwater systems by enhancing runoff generation and improper waste disposal practices.

Microplastics are increasingly recognized as vectors for the transport of heavy metals, organic pollutants, and pathogenic microorganisms within aquatic environments. Due to their hydrophobic surfaces, large surface-area-to-volume ratio, and weathered morphology, MPs can adsorb contaminants such as lead, cadmium, chromium, copper, zinc, pesticides, hydrocarbons, and pharmaceutical residues from surrounding water (Singh & Jain, 2026). The adsorption behavior of MPs is influenced by polymer type, particle size, environmental conditions, and degree of weathering. Weathered MPs with rough, cracked surfaces exhibit greater adsorption capacity than smoother particles due to increased active surface sites. Once adsorbed, these contaminants may be transported over long distances through river systems and subsequently released under changing environmental conditions. The interaction between MPs and co-contaminants therefore increases ecological risks and may enhance pollutant bioavailability within aquatic food chains.

2.2.6 Ecological and Human Health Impacts of Microplastics

The widespread occurrence of MPs in freshwater ecosystems poses serious ecological and public health concerns. Aquatic organisms may ingest MPs directly from the water column or indirectly through contaminated food sources, leading to physical blockage, oxidative stress, inflammation, reduced feeding efficiency, and impaired reproduction (Singh & Jain, 2026). Smaller MPs may also translocate across biological membranes and accumulate within tissues, thereby increasing ecological toxicity.

Microplastics additionally influence ecosystem functioning by altering sediment characteristics, nutrient cycling, and microbial community structure within freshwater environments. Since rivers and wetlands support drinking water supply, irrigation, fisheries, and biodiversity, the continuous accumulation of MPs threatens both ecosystem sustainability and human well-being. Increasing evidence of MPs in freshwater systems therefore highlights the urgent need for integrated pollution management, improved wastewater treatment, sustainable waste disposal practices, and continuous monitoring of emerging pollutants in urban freshwater ecosystems.

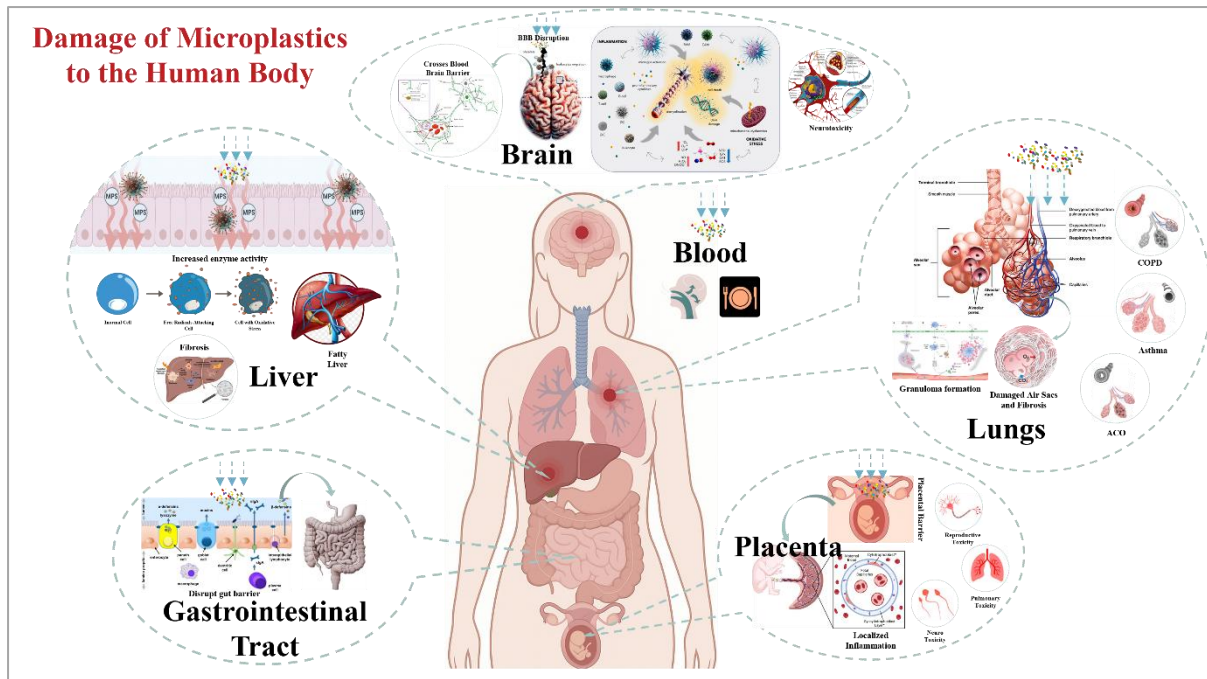


Figure 2.4 Toxicological Impacts of MPs on Human Organs and Tissues (Source: Self)

2.3 Land Use Change and Urbanization-Driven Freshwater Degradation

2.3.1 Land Use Transformation as a Driver of Water Pollution

Land use and land cover (LULC) change has been widely recognized as one of the major drivers of freshwater ecosystem degradation because anthropogenic alterations directly influence hydrological processes, runoff generation, sediment transport, nutrient loading, and pollutant mobility within watersheds. Expansion of urban settlements, agricultural intensification, industrial development, and deforestation significantly modify natural drainage systems and increase the transfer of contaminants into rivers, lakes, and wetlands (Mello et al., 2020). Anthropogenic landscapes alter evapotranspiration, infiltration, and streamflow characteristics, thereby affecting the physical, chemical, and ecological quality of freshwater systems. Studies have consistently reported that agricultural and urban land uses are major contributors to water quality deterioration through excessive nutrient enrichment, organic pollution, suspended solids, and heavy metal contamination.

Rapid urbanization further intensifies freshwater degradation by increasing built-up areas and impervious surfaces, accelerating stormwater runoff and pollutant transport. Urban runoff commonly carries nutrients, hydrocarbons, heavy metals, sewage contaminants, and suspended solids directly into adjacent aquatic ecosystems. Rimba et al. (2021) reported that population density and built-up land exhibited strong positive relationships with BOD, TSS, heavy metals, and other indicators of water quality deterioration, whereas dissolved oxygen showed a

negative relationship with urban expansion. The study emphasized that increasing anthropogenic pressure and tourism-driven urban growth significantly altered watershed hydrology and river water quality by intensifying land-use transformation and increasing pollutant loading.

Similarly, Gani et al. (2023) observed that built-up and agricultural land significantly influenced river water quality, while vegetated landscapes contributed positively to maintaining ecological stability. Their study revealed that agricultural land showed a positive association with indicators of water quality degradation, whereas built-up areas exerted strong negative impacts on river health. Forested and vegetated areas function as ecological buffers by reducing runoff velocity, promoting infiltration, and retaining sediments and contaminants before they enter aquatic systems.

2.3.2 Urban Runoff and Hydrological Alteration

Urbanization significantly alters natural hydrological behavior by converting permeable surfaces into impervious infrastructure such as roads, buildings, and pavements. This transformation reduces infiltration capacity and rapidly converts rainfall into surface runoff, thereby increasing flood peaks, erosion, sediment transport, and the flushing of pollutants into rivers and wetlands. Rather and Dar (2020) reported that increasing urban expansion and impervious surfaces within the Dal Lake catchment accelerated nutrient enrichment, sediment loading, and eutrophication processes. The study further showed that reductions in forest cover and the expansion of built-up land were associated with elevated nitrate, phosphorus, and COD concentrations in the lake ecosystem. Altered runoff pathways also increase sediment and contaminant transport during rainfall events. Mello et al. (2020) highlighted that anthropogenic LULC changes substantially modify watershed hydrology and intensify sediment, nutrient, and pollutant loading within freshwater systems. The authors emphasized that the degree of water quality deterioration depends not only on land-use type but also on watershed configuration, land-use intensity, and seasonal hydrological conditions.

2.3.3 Landscape Fragmentation and Buffer Degradation

Landscape fragmentation weakens the ecological protection capacity of natural vegetation and riparian ecosystems. Fragmented landscapes reduce vegetation continuity, disturb ecological connectivity, and increase direct hydrological linkage between pollution sources and aquatic systems. Consequently, rivers and wetlands located within fragmented urban landscapes become increasingly vulnerable to pollutant accumulation and ecological degradation. Mello et al. (2020) emphasized that changes in landscape structure and vegetation

cover significantly affect runoff dynamics, nutrient transport, and sediment retention within catchments.

Wetlands and riparian buffers naturally function as ecological sinks, retaining sediments, nutrients, and contaminants through biological and biogeochemical processes. However, urban expansion and agricultural conversion substantially reduce their purification capacity. Uwimana et al. (2017) demonstrated that agricultural intensification and wetland conversion within the Migina catchment increased nutrient and sediment transport into downstream water bodies, especially during high-flow periods. Their findings further indicated that reaches dominated by rice cultivation and vegetable farming exhibited consistently higher suspended solids and nutrient concentrations compared to vegetated and forested landscapes.

2.3.4 Spatial Scale and Buffer-Based Assessment of Water Quality

The influence of LULC on water quality is highly scale-dependent because pollutant transport and runoff processes vary across different spatial extents and landscape configurations. Buffer-zone analysis has therefore become an important approach for understanding how the surrounding land directly influences river and wetland ecosystems. Localized buffers surrounding rivers commonly represent the most active interaction zones between terrestrial anthropogenic activities and aquatic systems. Vegetated buffers improve infiltration, reduce runoff velocity, and enhance sediment and nutrient retention, whereas urban and agricultural buffers are frequently associated with elevated pollutant concentrations and ecological stress.

Several multiscale studies have further shown that different buffer distances exert varying levels of influence on water quality parameters depending on watershed characteristics and seasonal conditions. Gani et al. (2023) highlighted that spatial analysis integrating GIS, WQI, and remote sensing techniques provides effective understanding of the relationship between LULC and freshwater quality deterioration. These findings collectively support the framework of the present study, which integrates multiscale buffer analysis and landscape metrics with physicochemical and microplastic assessments to evaluate the influence of urbanization and land-use dynamics on the Kahn River and Sirpur Wetland ecosystems.

2.4 Research Gaps

Although surface water pollution has been widely reported in India, integrated studies that combine conventional water quality, heavy metals, microplastics, and land-use influences within a single framework remain limited, especially for urban river–wetland systems in central India. Existing research on microplastics has largely focused on their occurrence and sources,

while their relationships with physicochemical parameters, seasonal variability, sediment interaction, and hydrological transport remain insufficiently quantified. In particular, the processes controlling microplastic fate in river systems, including runoff-driven transport, resuspension, deposition, and interactions with dissolved pollutants and heavy metals, remain poorly understood. Similarly, the adsorption and desorption behavior of microplastics carrying metals such as Cu, Pb, Zn, and Cd under varying environmental conditions remains poorly resolved, creating uncertainty in ecological interpretation. Although advanced analytical and modeling approaches are increasingly used, many studies still do not consistently account for aging, biofouling, fragmentation, and pollutant sorption. In Indian freshwater systems, especially in monsoon-dominated catchments, data on pre-monsoon, monsoon, and post-monsoon pollution dynamics remain sparse, and the linkages between urbanization, tributary pollution, and wetland degradation have not been adequately established.

In the context of Indore, the Kahn River and Sirpur Wetland are highly vulnerable aquatic systems under strong urban pressure, yet systematic evidence linking physicochemical deterioration, heavy metal loading, microplastic contamination, and surrounding land-use change remains lacking. Although the thesis already shows that the river and wetland are affected by untreated sewage, urban discharge, and landscape transformation, the literature does not yet provide a consolidated assessment of how these stressors interact across spatial scales and across different hydrological settings. The present study, therefore, addresses this gap by integrating basin-scale and urban-stretch water quality assessment, EWQI, microplastic characterization, statistical analysis, and LULC-based landscape evaluation to explain pollution behavior in a river–wetland continuum.

2.5 Inference from the Literature Review

The literature review indicates that freshwater ecosystems, particularly urban rivers and wetlands, are increasingly deteriorating due to rapid urbanization, industrial discharges, untreated sewage inflows, stormwater runoff, and land-use changes. Existing studies demonstrate that conventional pollutants such as nutrients, suspended solids, and heavy metals significantly degrade water quality and ecological health, especially in densely populated urban regions. In recent years, microplastics have emerged as an additional environmental concern due to their persistence, transport behavior, and interactions with other contaminants in aquatic systems. The review further reveals that rivers and wetlands near urban settlements frequently serve as pathways for pollutant transport and accumulation zones, thereby increasing ecological vulnerability.

The reviewed literature also highlights that land-use change, settlement expansion, and landscape fragmentation strongly influence pollutant distribution, runoff generation, and hydrological alteration within freshwater ecosystems. Several studies have established relationships between LULC patterns and water quality deterioration; however, integrated investigations combining physicochemical pollution, microplastics, statistical analysis, and landscape-level assessment remain limited, particularly in Indian urban river–wetland systems. Moreover, studies focusing on central India and the Kahn River Basin are comparatively scarce, despite increasing urban pressure and environmental degradation in the region. Therefore, the literature suggests the need for a comprehensive, integrated assessment approach that combines water quality analysis, microplastic characterization, multivariate statistical tools, and GIS-based landscape analysis to better understand pollution dynamics and support the sustainable management of urban freshwater ecosystems.

Chapter 3

Materials and Methods

This chapter presents the various experimental approaches and analytical methodologies to achieve the study's objectives. It includes systematic field investigations, sample collection, laboratory analysis, microplastic characterization, statistical evaluation, and land-use analysis to provide a comprehensive assessment of pollution in the selected water bodies of Indore.

3.1 Experimental Design

The study was carried out through a systematic, objective-based approach, beginning with a reconnaissance survey followed by sample collection and preliminary characterization of the Kahn River and Sirpur Wetland. Further analyses, including water quality assessment, microplastic analysis, source identification, statistical analysis, and LULC evaluation, were performed to understand pollution distribution, sources, and the influence of urbanization on the selected water bodies.

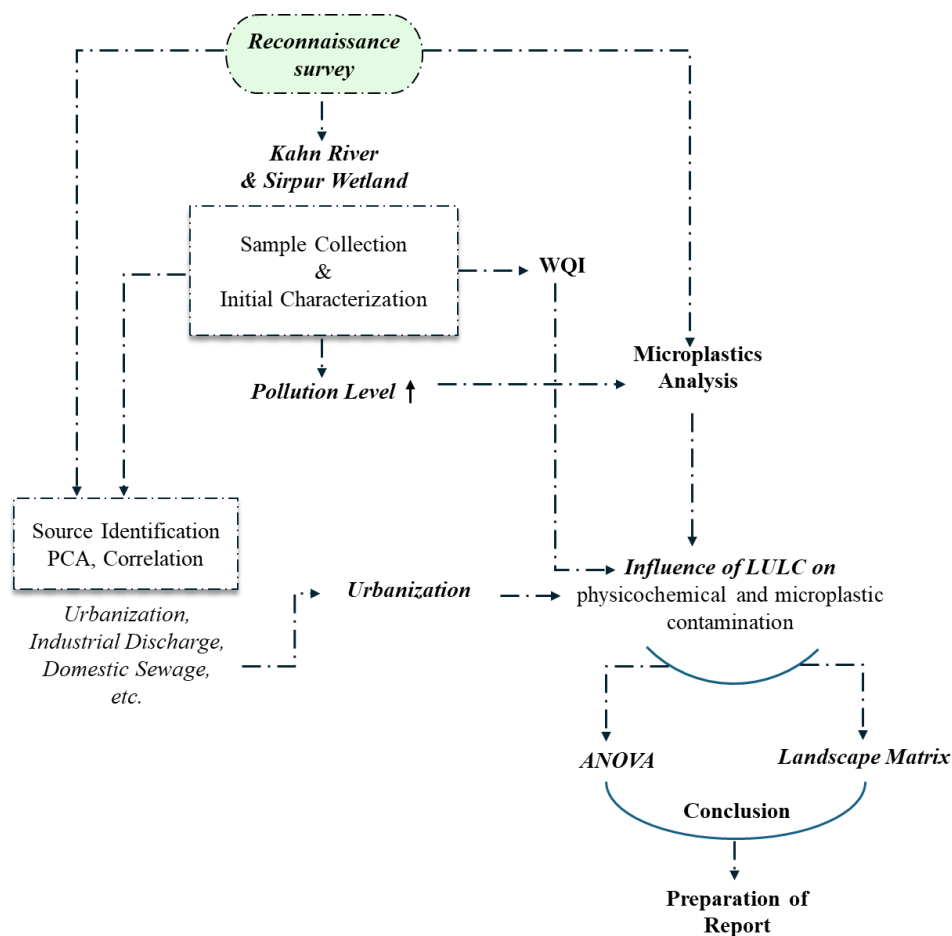


Figure 3.1 Experimental Flow Chart

3.2 Study Area Description

3.2.1 Kahn River Basin

The Kahn River is an important urban river that flows through Indore, Madhya Pradesh, India. The river originates near Limbodi village (22.6656°N, 75.8902°E) and flows through densely populated and industrially developed areas of Indore before joining the Kshipra River near Ujjain (23.1294°N, 75.7926°E), approximately 70-72 km downstream. The Kahn River forms part of the larger Ganga River basin system, as shown in Figure 3.2.

Traditionally, the river was used for drinking water, irrigation, and cultural activities (MPPCB's 2018 Khan River Rejuvenation Report). Over the past few decades, rapid urban growth, population increase, and industrial development have changed the river's hydrological and ecological characteristics. Many municipal drains and sewer pipes discharge directly into the river, and construction is taking place near the riverbanks. Sewage treatment plants (STPs) and common effluent treatment plants (CETPs) are located within Indore's city boundary, with a capacity of 260 MLD (Indore Municipal Corporation Sewerage). While the city receives a daily sewage discharge of approximately 367.8 MLD (Shrivastava et al., 2020).

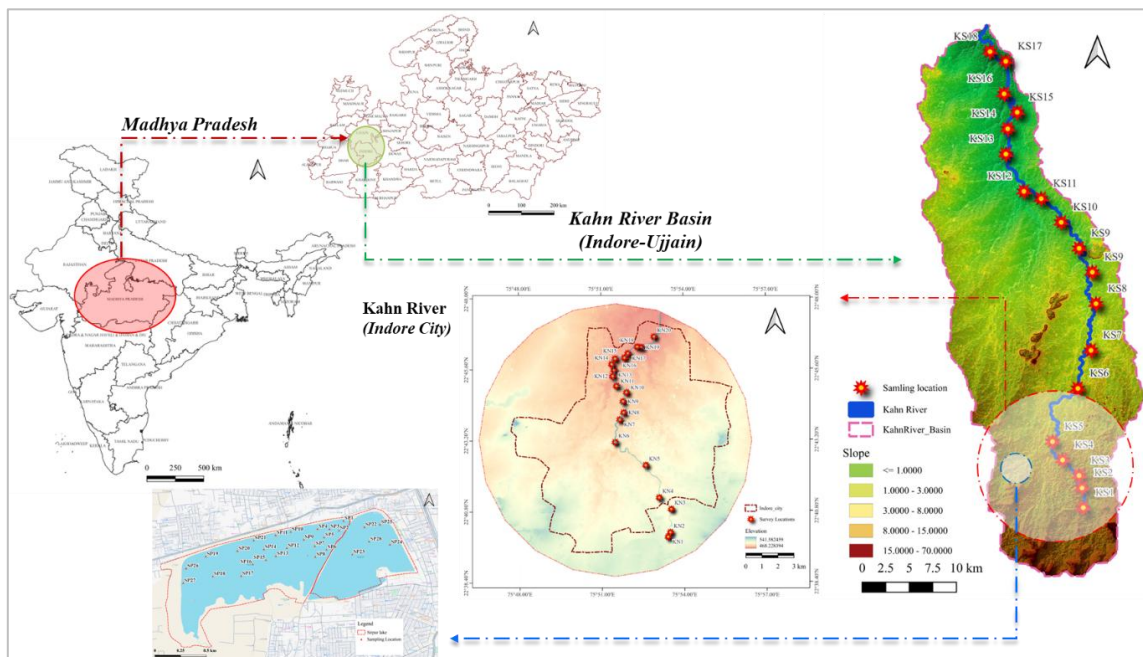


Figure 3.2 Study area map of the Kahn River and Sirpur Wetland.

3.2.2 Kahn River within the city boundary

Based on findings from the Kahn River Basin, the Kahn River within the city boundary area represents the highest level of anthropogenic stress. It is exposed to the drainage system,

proximity to the river, and human interaction. Further detailed analysis has been done on this river stretch.

3.2.3 Sirpur Lake

Sirpur Lake is a Ramsar-designated wetland located within Indore city. This man-made historical water tank, constructed around 100 years ago as one of the water storage structures used during the Holkar period, has now become an important urban wetland ecosystem. Its surface area is approximately 670-800 acres, and it retains a diverse range of aquatic plants and provides habitat for over 130 species of resident and migratory birds. Urban development along the lake's shoreline and wastewater discharge have greatly influenced its water quality over the years. Surface runoff during the monsoon season and localized waste-disposal activities contribute to the inflow of pollutants into the wetland.

3.3 Methodology

To accomplish the objectives, the study was carried out on the following bases, as summarized below (Figure 3.3). shows the experimental design of the thesis work.

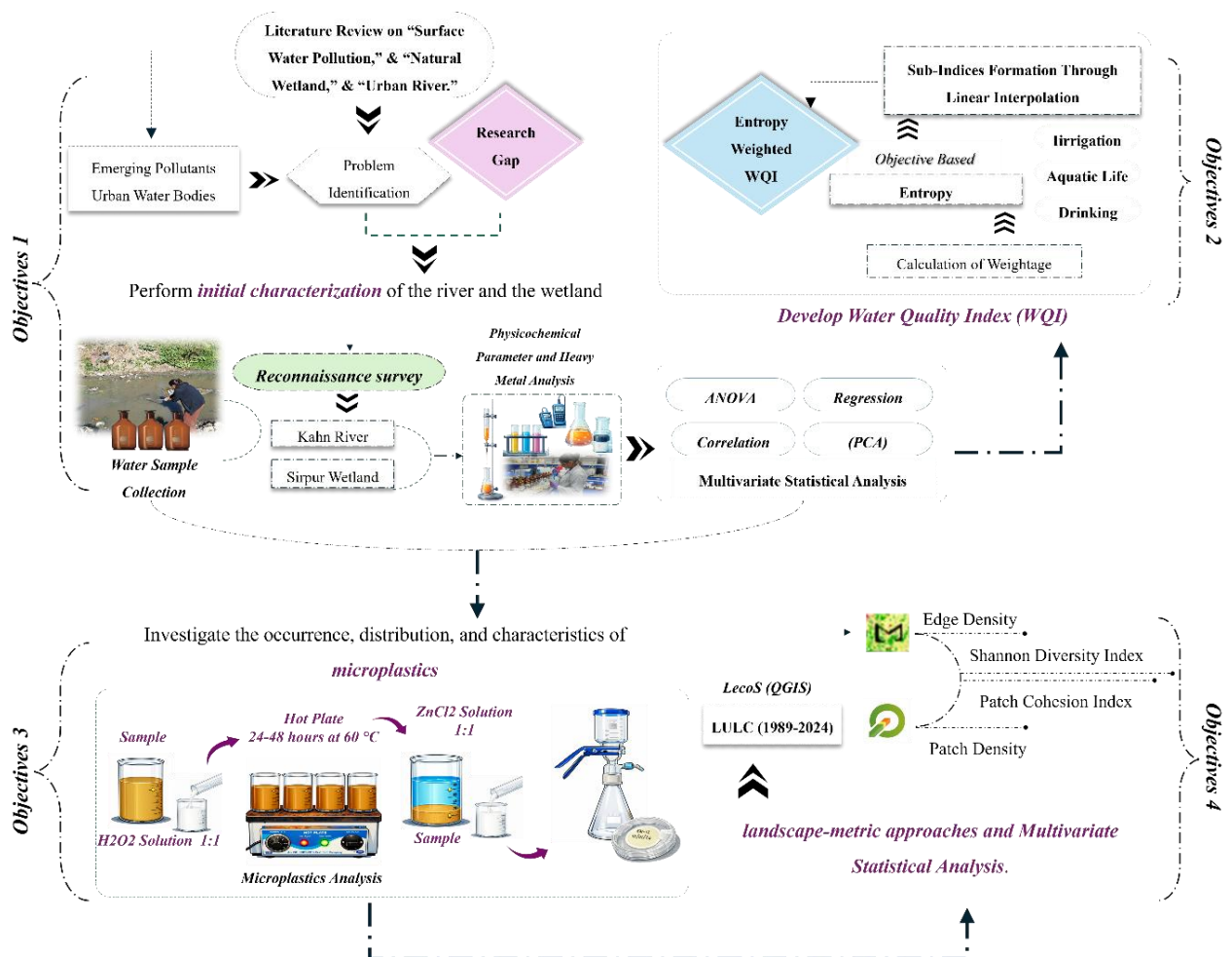


Figure 3.3 Methodological Framework

3.3.1 Reconnaissance survey

During the monsoon, a reconnaissance survey was conducted along the Kahn River and Sirpur Wetland to assess the on-the-ground condition of the riverbank. Identify the suitable sampling points, ensuring that all locations are accessible and feasible for sample collection. During the survey, some critical points were identified, including direct discharge of household wastewater into the river, anthropogenic activities, Encroachment, blocked or Choked Flow at Several Points, Solid Waste Dumping Along the Riverbank, etc. Those critical points were taken into consideration for further analysis of water samples, as shown in Figure 3.2.



Figure 3.4 Field observation of the Kahn River captured during sampling, showing untreated wastewater discharge, industrial effluents across key locations (Source: Self).

Kahn River Basin Sampling (September 2025)

The sampling began at the river's origin, in Limbodi village, to the discharge points of prominent nallas (Shakkarkhedi Nalla, Bhamori Nalla, Palasiya Nalla, Azad Nagar Nalla, Piliakhal Nalla) into the river, Industrial Areas, high-density urban habitations, and areas of intense direct human river interaction, midstream locations near slum clusters and peri-urban settlements; and downstream stretches including confluence points of the Kahn and Saraswati rivers, cremation sites, and agricultural tracts on the way to Ujjain.

Based on the reconnaissance survey, 18 samples (KS1-KS18) were collected to study the influence of anthropogenic activities, including waste-dumping areas, cremation sites, existing nalla confluences, and areas that have been encroached upon or developed for peri-urban

agricultural uses. The geographic coordinates of the Kahn River Basin are provided in the Table 3.1.

Table 3.1 Geographic coordinates of sampling locations along the Kahn River Basin

Sampling Location	Latitude	Longitude
KS1	22.6656°N	75.8901°E
KS2	22.6846°N	75.8889°E
KS3	22.6965°N	75.8860°E
KS4	22.7115°N	75.8690°E
KS5	22.7293°N	75.8587°E
KS6	22.7801°N	75.8852°E
KS7	22.8166°N	75.8990°E
KS8	22.8614°N	75.9045°E
KS9	22.9147°N	75.8874°E
KS10	22.8917°N	75.9009°E
KS11	22.9398°N	75.8690°E
KS12	22.9625°N	75.8484°E
KS13	22.9696°N	75.8306°E
KS14	23.0055°N	75.8121°E
KS15	23.0298°N	75.8142°E
KS16	23.0456°N	75.8241°E
KS17	23.0634°N	75.8106°E
KS18	23.0946°N	75.8125°E

Kahn River Within city boundary Sampling (December 2025)

Post-monsoon analysis of the urban stretch, additional sample sites will be located within the municipal limits of Indore to provide higher spatial-resolution data from the most affected reach of the river. Twenty sampling points (KN1-KN20) were systematically selected to capture spatial heterogeneity in water quality. The sampling started from the origin of the river Limbodi village, discharge points of prominent nallas into the river, urbanized areas, midstream locations near slum clusters, and downstream stretches, including confluence points of the Kahn and Saraswati rivers, etc. For the preprocessing and analysis of the sample, a detailed methodology was adopted as shown in Figure 3.3.

Table 3.2 Geographic coordinates of sampling locations along the Kahn River within the city boundary

Sampling Location	Latitude	Longitude
KN1	22.6656°N	75.8902°E
KN2	22.6681°N	75.8914°E
KN3	22.6811°N	75.896°E
KN4	22.6876°N	75.8848°E
KN5	22.7060°N	75.8767°E
KN6	22.7189°N	75.8582°E
KN7	22.7317°N	75.8611°E
KN8	22.7357°N	75.8635°E
KN9	22.7419°N	75.8631°E
KN10	22.7469°N	75.8652°E
KN11	22.7505°N	75.8592°E
KN12	22.7561°N	75.857°E
KN13	22.7596°N	75.8577°E
KN14	22.7628°N	75.8564°E
KN15	22.7661°N	75.8584°E
KN16	22.7665°N	75.8642°E
KN17	22.7684°N	75.8661°E
KN18	22.7723°N	75.8742°E
KN19	22.7725°N	75.8732°E
KN20	22.7783°N	75.882°E

Sirpur Wetland Sampling (November 2025)

Similarly, for Sirpur Lake, a post-monsoon reconnaissance survey was conducted to identify the most vulnerable and densely populated areas that discharge domestic waste into the lake. 28 samples (SP1-SP28) were collected at the discharge location and the middle of the wetland to represent the spatial heterogeneity. The geographic coordinates of the Sirpur Wetland are provided in Table 3.3.

Table 3.3 Geographic coordinates of sampling locations of Sirpur Lake

Sampling Location	Latitude	Longitude
-------------------	----------	-----------

SP1	22.7040°E	75.8176°N
SP2	22.7031°E	75.8171°N
SP3	22.7032°E	75.8162°N
SP4	22.7032°E	75.8151°N
SP5	22.7025°E	75.8157°N
SP6	22.7013°E	75.8160°N
SP7	22.7016°E	75.8148°N
SP8	22.7006°E	75.8149°N
SP9	22.7022°E	75.8138°N
SP10	22.7030°E	75.8126°N
SP11	22.7027°E	75.8111°N
SP12	22.7014°E	75.8122°N
SP13	22.7007°E	75.8112°N
SP14	22.7013°E	75.8100°N
SP15	22.7003°E	75.8102°N
SP16	22.6999°E	75.8090°N
SP17	22.6988°E	75.8079°N
SP18	22.6987°E	75.8052°N
SP19	22.7006°E	75.8045°N
SP20	22.7012°E	75.8075°N
SP21	22.7022°E	75.8090°N
SP22	22.7034°E	75.8195°N
SP23	22.7008°E	75.8184°N
SP24	22.7018°E	75.8220°N
SP25	22.7037°E	75.8210°N
SP26	22.6995°E	75.8026°N
SP27	22.6981°E	75.8024°N
SP28	22.7020°E	75.8200°N

3.3.2 Sample Collection and Analysis

Grab sampling was performed at each site, with triplicate samples to reduce variability and improve reproducibility (Sinha et al., 2025), as detailed in the methodology shown in Figure 4. At each sampling site, pre-cleaned stainless-steel buckets and a water sampler were used to collect all samples. Samples from each location were obtained at a depth of 30 cm below the

surface from the middle of the river. The samples were then transferred to two separate amber bottles and stored in insulated iceboxes at 4°C to prevent any alteration of biological or chemical properties. Each bottle was pre-rinsed three times with the corresponding site water to remove any possible cross-contamination. One sample bottle was set aside for physicochemical and heavy-metal analysis, and the other for microplastic analysis.

A significant aliquot of each water sample was filtered on Whatman No. 42 filter paper. For heavy metal analysis, the filtered sample was acidified with ultrapure concentrated nitric acid (HNO₃) to lower the pH to <2. A total of 22 physicochemical and heavy metal parameters were measured in threefold. The elaborate procedure and equipment used in the water quality analysis are depicted in Table 2. All procedures for water sample collection, preservation, transportation, and analysis were followed meticulously in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, 23rd Edition, 2017).

3.3.3 Quality Assurance and Quality Control (QA/QC)

To achieve dependable, accurate, and reproducible data, strict controls (Quality Assurance/Quality Control) were in place for all data collection and analysis throughout the project. All samples were collected and tested three times to minimize random error and increase confidence in the statistical outcome. Three measurements for each parameter were taken, and the reported values represent the arithmetic mean along with the corresponding standard deviation. This minimized variances between locations and phases, therefore providing consistent analytical measurements across all sampling locations and phases.

All instruments in the lab were calibrated before any analysis and standardized using certified standards. Multipoint calibration curves were created for spectrometric measurements based on the correct concentration ranges. Calibrated curves must have a coefficient of determination (R²) greater than 0.99 to confirm linearity and accuracy within the working range. All standards and reagents used for each analysis batch were freshly prepared to eliminate any possible error due to deterioration. Method blank samples were processed for analysis and used to determine whether contamination was introduced during sample handling, reagent preparation, or instrument measurement during physicochemical or heavy metal analysis. Any blank value detected will be considered when interpreting results.

For microplastic analysis, both procedural air blank samples were included for airborne fiber contamination and to counter background laboratory interference. Selected parameters have been tested for recovery by spiking an analyte calibration standard into the matrix of interest for method validation. The results of these recovery studies indicate that the methods are reliable and achieved acceptable recovery percentages, as measured against the method's

analytical limits. In addition, the detection limits for all instrumental methods used in this study were determined from standard calibration and blank data and were quantifiable at concentrations above the minimum quantifiable level. All glassware and sample containers were cleaned and rinsed prior to use to minimize contamination. All sample preservation procedures, such as acidification of metal samples and refrigeration at approximately 4°C, were followed to ensure the sample composition would not change prior to analysis. These QA/QC measures ensured that the analytical data generated in this study were accurate, reproducible, and suitable for subsequent statistical evaluation and interpretation.

3.4 Analysis

3.4.1 Experimental Analysis

Physicochemical and Heavy Metal Analysis

All collected water samples were transported to the Environmental Engineering Laboratory, IIT Indore, under 4 °C to maintain their original properties for subsequent laboratory analysis. The analyses were performed as per the standard procedures recommended by the American Public Health Association (APHA, 2017). All physicochemical and heavy metal parameters were determined under controlled laboratory conditions. Standard solutions and reagent blanks were prepared before each batch of tests to calibrate equipment and ensure accuracy. To ensure analytical precision and reproducibility, all tests were performed in triplicate. The water quality parameters, analytical methods, and instruments used are detailed in Table 3.4, ensuring standardized, accurate measurements in accordance with APHA guidelines.

Microplastics Analysis

The water samples for microplastics analysis were processed in a fume hood to prevent contamination. The Organic matter in the samples was digested with 30% hydrogen peroxide (H₂O₂) by adding about 20% of the sample volume, then diluted with distilled water in a 1:1 ratio (Mandal et al., 2025; Singh & Jain, 2026). The samples were kept at 60 °C for 12-24 hours under controlled conditions until the organic matter was completely digested and no visible residues were left. For samples with undigested matter, the process was further continued for an additional 12 hours. The fully digested samples were then subjected to density separation by adding an equal volume (1:1) of zinc chloride solution (ZnCl₂), prepared with about 0.75 kg ZnCl₂ per 500 mL, to separate low-density microplastic particles from mineral for 24 hours (Singh & Jain, 2026). After settling or centrifugation, the supernatant liquid was carefully removed and vacuum-filtered using glass fiber filter paper (Whatman, 47mm diameter). The filtered particles were then dried and stored in a petri dish in a closed environment.

The filter papers were first examined directly under an optical stereomicroscope to distinguish microplastic particles by shape, color, and size. MPs Particles were selected from the filter paper using stainless-steel pointed forceps. MPs particles were selected from the filter paper using stainless-steel pointed forceps and placed in clean petri dishes for further analysis. To analyze the surface morphology, field-emission scanning electron microscopy (FE-SEM; GeminiSEM 360, ZEISS) was used. The particles were then analyzed using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy (Bruker ALPHA II) to identify the polymer (Sinha et al., 2025).

Irrigation water quality parameters

The suitability of water for irrigation was evaluated using standard irrigation water quality indices that reflect the potential hazards posed by sodium and magnesium enrichment. The SAR (Eq. 1) quantifies the relative concentration of sodium to calcium and magnesium, indicating the degree of sodium hazard that may impair soil structure (Todd, 1980). KR (Eq. 2) expresses sodium levels as a fraction of divalent cations; values greater than 1 typically indicate unsuitability for irrigation (Kelley, 1963). The SSP (Eq. 3) examines the proportions of sodium and potassium relative to the total cationic load, providing insight into the risk of reduced soil permeability when sodium dominates (Ghalib, 2017). Additionally, the MAR (Eq. 4) evaluates the contribution of magnesium to potential soil alkalinity issues, as excessive magnesium disrupts soil aggregation and reduces crop productivity (Raghunath, 1987).

$$\text{SAR} = \frac{[\text{Na}^+]}{\sqrt{\frac{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]}{2}}} \quad (1)$$

$$\text{KR} = \frac{[\text{Na}^+]}{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]} \quad (2)$$

$$\text{SSP} = \frac{[\text{Na}^+] + [\text{K}^+]}{[\text{Na}^+] + [\text{K}^+] + [\text{Ca}^{2+}] + [\text{Mg}^{2+}]} \times 100 \quad (3)$$

$$\text{MAR} = \frac{[\text{Mg}^{2+}]}{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]} \times 100 \quad (4)$$

3.4.2 Statistical Analysis

Principal component analysis (PCA)

According to Sinha and Jain (2025), PCA is a crucial multivariate statistical tool for reducing the dimensionality of a dataset while retaining as much data variability as possible. Singh et al. (2019) note that PCA produces principal components (PCs), which serve as new independent variables obtained by linear combinations of the original parameters. The eigenvalues of each principal component indicate how much of the data's variability it explains. The selection of components for PCA can be based on cumulative variance or on cutoff eigenvalues (Sinha et al., 2025). OriginPro 2026 was used to conduct PCA in this study to derive PCs and apply orthogonal rotation to enhance the transparency of the factor structure. The Varimax rotation method was employed to improve the interpretability of the component loadings.

Correlation Analysis and Linear Regression

The Correlation Matrix is an essential multivariate statistical tool used to evaluate the different parameters associated with water quality, how they interact, and how they respond to variation within the dataset (Callies, 2005; Noori et al., 2010). In this study, the matrix was developed using 144 variables in OriginPro 2026, employing Pearson's correlation method, which quantifies relationships between variables through correlation coefficients and their corresponding p-values. The coefficient 146 ranges from -1 to 1 , with values between 0 and 1 indicating positive associations and those 147 between -1 and 0 indicating negative associations. The p-value reflects the significance level. Additionally, linear regression analysis was performed to quantify the relationship between microplastic abundance and the selected physicochemical parameters, which shows a significant relationship with land use.

Entropy-weighted water quality index:

The theory of information entropy was first proposed by Shannon (1948) as a fundamental concept in information theory. It was theorized that entropy is a measure of quantified uncertainty or information content of a system. Entropy has an inverse relationship with the probability of an event; the lower the probability, the greater the entropy. Over the past few years, the theory of entropy has found growing application in various fields of hydrology and water quality evaluation (Adimalla, 2021; Ozkul et al., 2000; K. R. Singh et al., 2019) and has proven to be an effective tool for water quality evaluation. To calculate the Entropy-Based Water Quality Index (EWQI), a set of systematic procedures was followed. The first step is to allocate an entropy weight to each water quality parameter. To this end, when there are m water

samples ($i = 1, 2, \dots, m$) and each is analyzed for n quality parameters ($j = 1, 2, \dots, n$), an eigenvalue matrix X (Eq. 10) is formed based on the data observed.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdot & x_{1n} \\ x_{21} & x_{22} & \cdot & x_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ x_{m1} & x_{m2} & \cdot & x_{mn} \end{bmatrix} \quad (10)$$

This matrix serves as a basis for calculating the entropy weights for each parameter. Pre-treatment of the data was performed to remove the effects of varying units and scales across water quality parameters. This was done by making use of two normalization functions (Eq. 11 & 12)

For the efficiency type,

$$y_{ij} = \frac{x_{ij} - (x_{ij})_{\min}}{(x_{ij})_{\max} - (x_{ij})_{\min}} \quad (11)$$

For the cost type,

$$y_{ij} = \frac{(x_{ij})_{\max} - x_{ij}}{(x_{ij})_{\max} - (x_{ij})_{\min}} \quad (12)$$

The standardized matrix Y (Eq. 13) was obtained after undergoing this transformation.

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdot & y_{1n} \\ y_{21} & y_{22} & \cdot & y_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ y_{m1} & y_{m2} & \cdot & y_{mn} \end{bmatrix} \quad (13)$$

Next, the proportionate value of the j -th index in the i -th sample was computed using the following (Eq. 14).

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^m y_{ij}} \quad (14)$$

The information entropy is calculated using the formula below (Eq. 15)

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m P_{ij} \ln P_{ij} \quad (15)$$

Using these entropy values, the entropy-based weight for each parameter was calculated through the corresponding formula (Eq. 16)

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (16)$$

In the second step of the EWQI calculation, a quality rating (q_j) was assigned to each water quality parameter. This rating was determined using Eq. 17, which reflects the parameter's concentration relative to the acceptable standards.

$$q_j = \left(C_j / S_j \right) \times 100 \quad (17)$$

C_j = the concentration of each water quality parameter in each water sample in mg/l,

S_j = the limit for drinking water of each parameter in mg/l according to quality standards for drinking water of BIS, CPCB, and WHO.

The EWQI can be calculated in the third step using the following (Eq. 18),

$$EWQI = \sum_{j=1}^n \omega_j q_j \quad (18)$$

According to EWQI, groundwater is classified into five ranks, ranging from "excellent water" to "extremely poor water". The water quality classification scale of EWQI, as suggested by (Jianhua et al., 2011; K. R. Singh et al., 2019). It is classified into five ranks, ranging from 'excellent' to 'extremely poor'. The classification for Drinking and Irrigation and Aquatic Life ranks is listed in Tables 3.4 and 3.5.

Table 3.4 Drinking water, EWQI Scale

DWQI	Water Quality Status
<50	Excellent
50-100	Good
100-150	Moderate
150-200	Bad
>200	Very Bad

Table 3.5 Irrigation and Aquatic Life, EWQI Scale bar

IWQI & AWQI range	Water Quality Status
0-25	Very Good
25-50	Good
50-75	Average
Above 75	Poor

3.4.3 Remote Sensing Analysis

Image Preprocessing, LULC Classification, and Change Detection Analysis

Landsat 5 and Landsat 8/9 satellite images (1989-2024) were obtained from the USGS Earth Explorer and pre-processed using ArcGIS 10.0 for mosaicking and extraction of the Area of Interest (AOI). Natural color composites were generated using band combinations (3-2-1 for Landsat 5 and 4-3-2 for Landsat 8/9). Supervised classification was performed using the Maximum Likelihood method with region-based training samples, resulting in classification of the study area into agriculture, built-up areas, water bodies, and open land. LULC change detection was performed using a post-classification comparison approach, in which classified maps from different time periods were compared pixel-wise. The ArcGIS Combine tool was used to identify “from-to” transitions, and cross-tabulation was performed to quantify land-use changes. The magnitude (K) and percentage change (A) were calculated as:

$$K = F - I, A = \frac{F - I}{I} \times 100$$

where F and I represent final and initial land-use values, respectively.

Accuracy assessment was conducted using QGIS (Semi-Automatic Classification Plugin) through confusion matrix analysis, from which overall accuracy, user’s accuracy, producer’s accuracy, and Kappa coefficient were derived:

$$K = \frac{P(A) - P(E)}{1 - P(E)}$$

where P(A) is observed agreement and P(E) is expected agreement by chance. The classification accuracy exceeded 85%, indicating reliable performance for further analysis. The LULC classification was also used to establish spatial relationships between land-use patterns and water-quality parameters.

ANOVA for LULC Impact Assessment

To evaluate the influence of surrounding land use, a 500 m buffer was delineated around each sampling site. It effectively captures localized anthropogenic influences within an approximate walking range and allows assessment of scale-dependent effects on water quality (Haldar et al., 2020; Zhang et al., 2021). The LULC composition within each buffer was quantified. Each site was assigned a dominant land-use class based on maximum area coverage. Water quality parameters were grouped by dominant LULC classes, and one-way ANOVA was performed to identify statistically significant differences among groups (Hua, 2017; Zhang et al., 2019). Assumptions of normality and homogeneity of variance were tested prior to analysis, with a significance level of $p < 0.05$.

Landscape Matrix Analysis

Landscape matrix analysis was performed using the LecoS (Landscape Ecology Statistics) plugin in QGIS to evaluate the spatial characteristics of LULC around each sampling location. Buffer analyses at 500 m and 1000 m were conducted for all sampling points, followed by the extraction of land-use diversity and the percentage distribution of individual LULC classes within each buffer zone. Further, landscape metrics such as Edge Density (ED), Patch Density (PD), Shannon's Diversity Index (SHDI), and Patch Cohesion Index (PCI) were calculated to better understand the spatial behavior, fragmentation, and heterogeneity of land use patterns influencing water quality and microplastic contamination.

3.4.4 Instrumental Analysis

Table 3.6 shows the Various Instruments used to perform the analysis in this research work.

Table 3.6 List of monitored water quality parameters along with their units, abbreviations, and analysis techniques

Table Parameter	Unit	Abbreviation	Analytical Method	Instrument/Device	Make & model
pH	—	pH	Electrometric method	Research-grade benchtop pH meter	Hanna Instruments HI5522
Electrical Conductivity	μS/cm	EC	Conductometric method	Conductivity meter	Hanna Instruments HI98311
Total Dissolved Solids	mg/L	TDS	TDS meter method	Portable TDS meter	Hanna Instruments HI98130
Total Suspended Solids	mg/L	TSS	Gravimetric method (APHA)	Hot air oven and analytical balance	Thermo Scientific / Shimadzu
Turbidity	NTU	Tur	Nephelometric method	Turbidity meter	Hanna Instruments HI83414
Dissolved Oxygen	mg/L	DO	Membrane electrode method	DO meter	Lutron DO-5509
Biochemical Oxygen Demand (5-day)	mg/L	BOD	5-day incubation method	BOD incubator	REMI / Thermolab

Chemical	mg/L	COD	Closed reflux	COD reactor and	Hanna
Oxygen Demand			colorimetric method	photometer	Instruments
Sodium	mg/L	Na ⁺	Flame photometry	Flame photometer	HI839800
Potassium	mg/L	K ⁺	Flame photometry	Flame photometer	YA-SAN (India)
Calcium	mg/L	Ca ²⁺	EDTA titrimetric method	Digital burette setup	YA-SAN (India)
Fluoride	mg/L	F ⁻	Photometric method	HR Fluoride Portable Photometer	Borosil
Chloride	mg/L	Cl ⁻	Argentometric titration	Titration assembly	Hanna Instruments
Total Alkalinity	mg/L	TA	Acid titration method	Digital titration setup	HI97739
Total Hardness	mg/L	TH	EDTA titrimetric method	Digital titration setup	Borosil
Magnesium	mg/L	Mg ²⁺	ICP-OES	Inductively Coupled Plasma-Optical Emission Spectrometer	Borosil
Iron	mg/L	Fe	ICP-OES / AAS	ICP-OES / Atomic Absorption Spectrophotometer	Agilent 5800 ICP-OES
Manganese	mg/L	Mn	ICP-OES / AAS	ICP-OES / Atomic Absorption Spectrophotometer	Agilent 5800 ICP-OES / PerkinElmer AAnalyst 400
Zinc	mg/L	Zn	ICP-OES / AAS	ICP-OES / Atomic Absorption Spectrophotometer	Agilent 5800 ICP-OES / PerkinElmer AAnalyst 400
Phosphate	mg/L	PO ₄ ³⁻	Photometric method	Phosphate Photometer	Hanna Instruments
Nitrite	mg/L	NO ₂ ⁻	Photometric method	Nitrite Photometer	HI97713
					Hanna Instruments
					HI97728

Nitrate	mg/L	NO ₃ ⁻	Photometric method	Nitrate Photometer	Hanna Instruments HI97728
Microplastic Identification	—	MPs	Visual characterization and counting	Stereo microscope	Leica EZ4 / Olympus SZ61
Microplastic Morphology	—	—	Field Emission Scanning Electron Microscopy (FESEM)	FESEM	ZEISS GeminiSEM 300 / JEOL JSM-7610F
Polymer Identification	—	—	ATR–FTIR spectroscopy	ATR–FTIR Spectrometer	PerkinElmer Spectrum Two / Bruker Alpha II
Surface Imaging	—	—	Optical microscopy	Compound microscope	Olympus CX23 / Magnus MLX

Chapter 4

Results and Discussion

This chapter presents the results of the experimental work and discusses the spatial variation, distribution, and interrelationships of conventional and emerging pollutants in the Kahn River in Indore. The findings from physicochemical analysis, heavy metal assessment, microplastic characterization, statistical evaluation, and land-use analysis are systematically discussed in line with the objective to understand the influence of anthropogenic activities and urbanization on the overall water quality and ecological condition of the Kahn River and Sirpur Wetland.

4.1 Physicochemical and Heavy Metal Analysis

4.1.1 Kahn Rive Basin-Scale Assessment (September 2025)

The spatial variation in water quality along the Kahn River was evaluated by dividing the 18 sampling locations into three functional zones: upstream stretch, urban midstream stretch, and downstream.

The upstream stretch (KS1-KS5), starting at Limbodi village, represents the least disturbed portion of the river before major urban influence. In this section, pH values remained within a neutral to slightly alkaline range, indicating stable baseline conditions. However, even at the upstream sites, certain parameters, such as hardness and chloride, showed moderate values, suggesting early anthropogenic inputs or geological contributions. DO levels at the initial site were moderate but declined noticeably at subsequent upstream points. Turbidity increased sharply at certain upstream sites, likely due to monsoon-driven runoff and sediment mobilization. EC and TDS were lower at the initial site but increased gradually, reflecting an increasing ionic load along the flow path.

The midstream stretch (KS5-KS12), which flows through densely populated, highly urbanized areas of Indore, exhibited significant deterioration in water quality. This zone receives discharge from municipal drains and prominent nallas (Shakkarkhedi Nalla, Bhamori Nalla, Palasiya Nalla, Azad Nagar Nalla, Piliakhil Nalla), and this impact is clearly reflected in multiple parameters. Dissolved oxygen levels remained consistently low in several midstream sites, indicating high organic pollution and oxygen demand. In contrast, BOD and COD values were elevated, confirming a substantial organic load, both biodegradable and non-biodegradable. EC and TDS values showed a marked increase in this zone, especially near

major discharge points. This indicates higher dissolved ionic content resulting from domestic wastewater, sewage discharge, and possibly industrial inputs. Hardness and alkalinity also remained elevated, suggesting a cumulative contribution of dissolved salts. Turbidity exhibited localized peaks, particularly near sites influenced by solid waste dumping and stormwater inflow. This increase can be attributed to suspended solids and runoff carrying particulate matter during the monsoon. Nitrate concentrations were higher in the urban stretch than in the upstream zone, indicating nutrient enrichment likely from domestic sewage and surface runoff. Such nutrient loading may contribute to eutrophication risks downstream.

In the downstream stretch (KS13–KS18), after the river passes through the core urban region, mixed influences from agricultural runoff and diluted urban discharge were observed. Some parameters showed partial stabilization, while others remained elevated. DO exhibited slight improvement at certain downstream sites compared to the severely depleted midstream locations, possibly due to dilution and atmospheric re-aeration. EC and TDS remained relatively high, reflecting cumulative upstream loading. Hardness and major cations, such as calcium and sodium, also remained elevated, suggesting that dissolved salts are transported downstream without significant attenuation. Turbidity decreased in some downstream locations compared to peak midstream values, likely due to settling of suspended particles. However, localized increases were observed near areas influenced by agricultural activities and confluence points.

To compare the parameters with the standard guidelines for Drinking (WHO, BIS, CPCB, IS10500 -2012), Irrigation (IS 11624- 2019), and Aquatic Life (CPCB, WHO-2017 and USEPA), most of the parameters (Table 4.1) exceed the acceptable and permissible limits, as shown in Figure 4.1, Figure 4.2, and Figure 4.3.

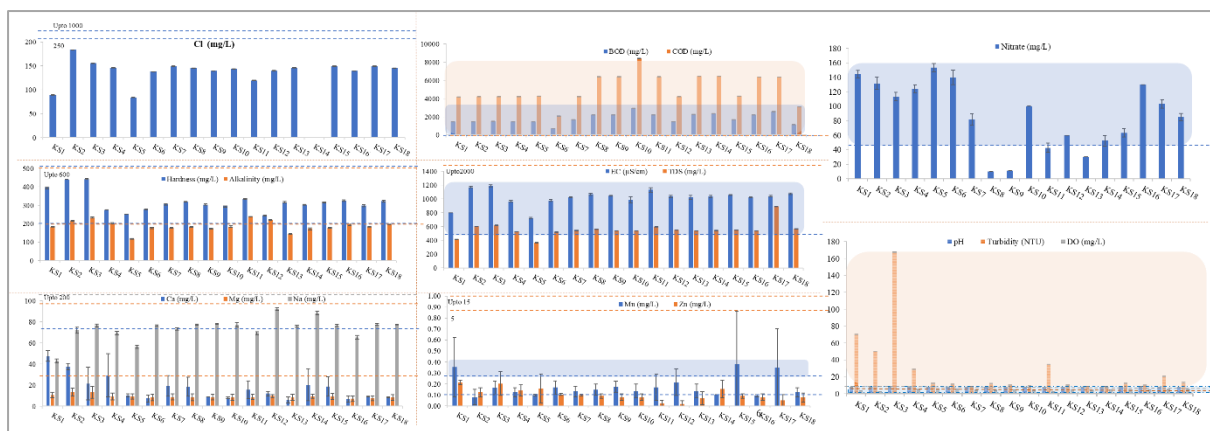


Figure 4.1 Physicochemical water quality parameters in the Kahn River Basin for Drinking Water quality.

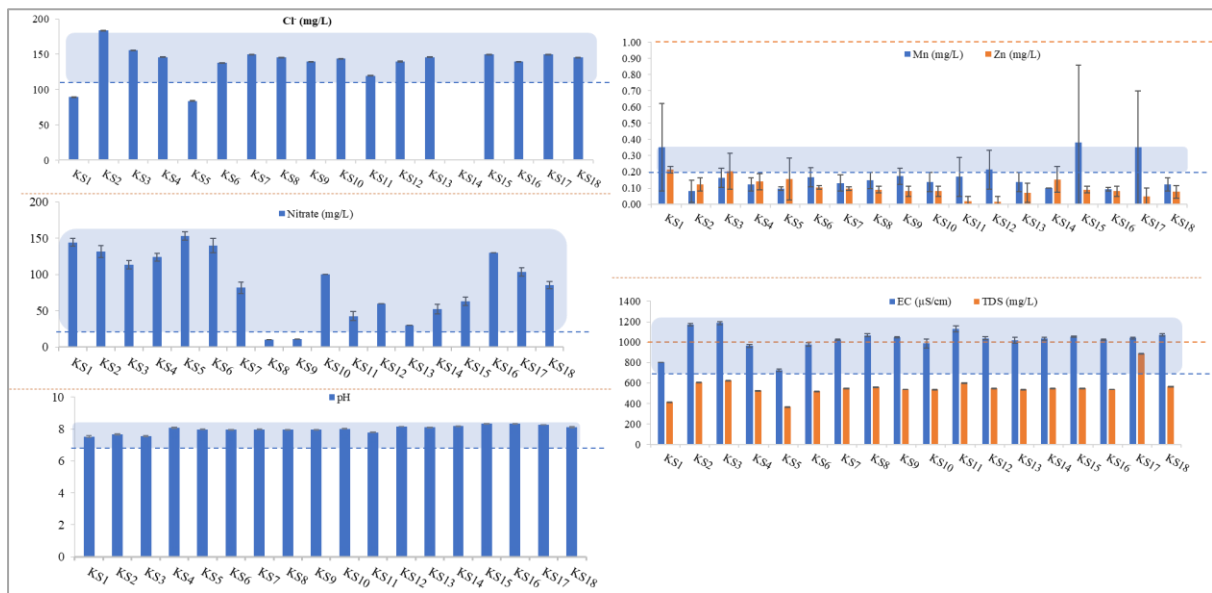


Figure 4.2 Physicochemical water quality parameters in the Kahn River Basin for Irrigation Water quality.

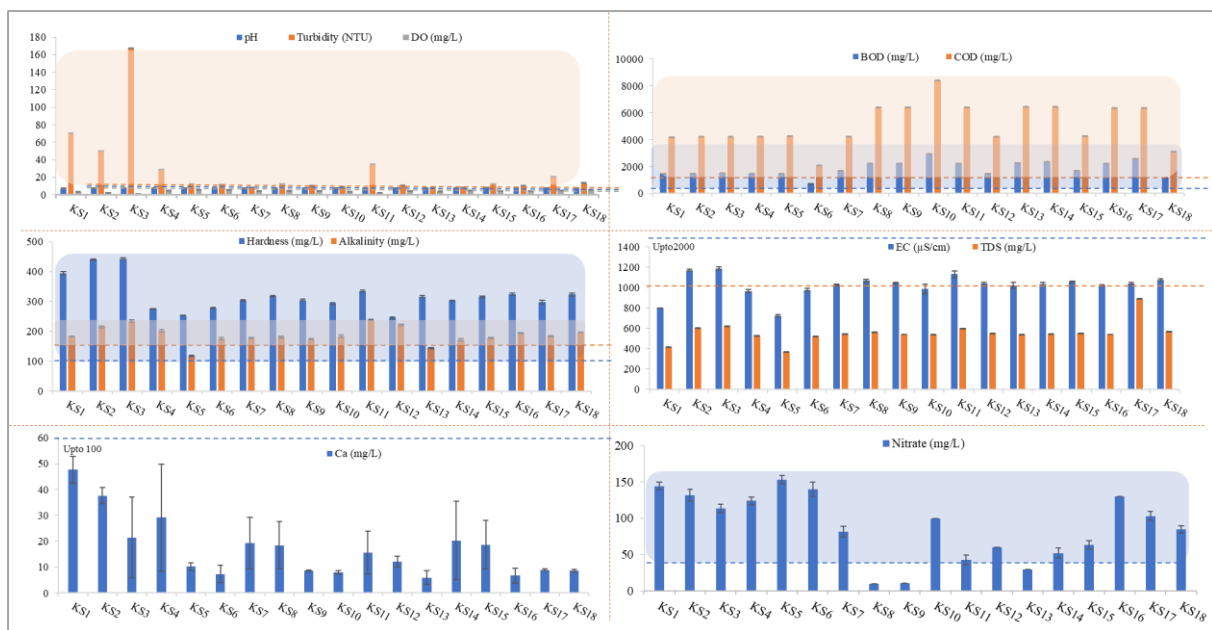


Figure 4.3 Physicochemical water quality parameters in the Kahn River Basin for Aquatic Life.

Table 4.1 Physicochemical characteristics and heavy metal concentrations of water samples, Kahn basin (KS1-KS18).

Samp le ID	pH	TH	Cl ⁻	TA	Tur	DO	BOD	COD	EC	TDS	NO ³⁻	Ca ²⁺	Mg ²⁺	Mn	Na	Zn
KS1	7.53±0.07	394.67±5.51	89.93±0.05	183.00±1.00	70.47±0.21	3.43±0.21	1477.11±0.76	4221.56±0.85	800.00±0.00	416.67±0.01	144.33±5.13	47.70±5.19	10.63±2.67	0.35±0.27	43.13±1.63	0.21±0.02
KS2	7.67±0.03	440.67±2.08	183.84±0.14	215.33±3.06	50.03±0.40	2.53±0.06	1490.56±0.50	4181.22±1.00	1170.00±1.00	606.67±0.02	131.67±8.50	37.63±3.11	13.33±3.70	0.08±0.07	72.07±2.90	0.12±0.04
KS3	7.56±0.03	442.67±2.52	155.81±0.23	233.33±3.79	167.53±0.40	0.83±0.06	1510.96±1.012	4301.56±0.50	1186.67±1.528	623.33±0.02	113.33±5.77	21.40±15.59	13.09±5.44	0.16±0.06	76.63±1.19	0.20±0.11
KS4	8.08±0.03	275.00±1.00	145.70±0.40	202.00±3.46	29.07±0.35	5.20±0.10	1478.98±2.16	4174.00±0.72	963.33±15.28	526.67±0.02	124.00±5.29	29.17±20.67	9.15±3.29	0.12±0.04	69.50±1.65	0.14±0.05
KS5	7.97±0.02	252.00±1.00	83.81±0.27	118.00±2.00	12.23±0.50	5.43±0.25	1498.31±7.21	3246.67±1.36	723.33±11.55	366.67±0.01	153.33±5.77	10.23±1.53	9.23±2.38	0.10±0.01	56.40±1.67	0.16±0.13
KS6	7.96±0.01	278.00±1.73	137.84±0.15	176.33±3.51	11.27±0.49	5.43±0.21	737.52±0.50	4086.67±0.58	976.67±15.28	520.00±0.01	140.00±10.00	7.37±3.31	8.23±2.93	0.17±0.06	76.53±0.81	0.10±0.01
KS7	7.97±0.02	304.33±2.52	149.66±0.47	178.00±2.65	8.37±0.32	4.17±0.21	1688.47±0.94	4198.67±1.04	1026.67±5.77	546.67±0.02	81.67±7.64	19.23±9.90	8.77±2.98	0.13±0.05	73.37±1.10	0.10±0.01
KS8	7.95±0.02	318.33±1.53	145.93±0.03	181.33±2.52	11.97±0.42	4.20±0.17	2231.89±2.072	4080.27±0.55	1066.67±1.528	563.33±0.01	10.00±0.00	18.37±9.13	8.44±3.14	0.15±0.05	77.52±0.57	0.09±0.02
KS9	7.96±0.01	304.00±3.00	139.71±0.37	173.67±2.08	10.50±0.36	4.47±0.23	2245.22±0.10	3313.33±1.10	1046.67±5.77	540.00±0.00	11.00±0.00	8.70±0.20	8.68±2.59	0.17±0.05	78.20±0.70	0.08±0.03
KS10	8.02±0.02	293.33±2.52	143.67±0.47	184.00±3.46	8.77±0.62	3.60±0.44	2945.29±1.21	3920.00±1.62	986.67±45.09	536.67±0.01	100.00±0.00	7.90±0.70	8.38±2.86	0.14±0.06	77.20±2.08	0.08±0.03
KS11	7.80±0.01	334.67±2.31	119.66±0.49	238.67±1.53	34.77±0.45	2.37±0.12	2258.21±8.15	2366.67±2.52	1130.00±3.00	600.00±0.01	42.67±6.43	15.60±8.32	8.70±2.54	0.17±0.12	69.39±1.25	0.02±0.03
KS12	8.17±0.00	245.00±3.61	139.62±0.55	221.00±3.00	10.57±0.50	4.53±0.21	1496.89±1.089	3170.00±1.08	1036.67±1.528	550.00±0.01	60.00±0.00	12.07±2.12	9.68±1.45	0.21±0.12	92.35±1.16	0.02±0.03
KS13	8.11±0.01	316.00±3.61	145.70±0.43	144.00±2.00	8.89±0.29	3.97±0.06	2290.36±5.24	4013.33±0.58	1020.00±3.00	540.00±0.01	30.00±0.00	5.93±2.66	8.33±2.83	0.14±0.06	75.80±1.08	0.07±0.06

KS14	8.18±0.	303.00±1	0.00±0.0	172.00±4	8.67±0.0	4.57±0.	2364.07±6.	3873.33±1	1033.33±1	546.67±0	52.33±6.8	20.30±15	9.39±1.8	0.10±0.	88.55±1.	0.15±0.
	01	.73	0	.58	3	32	68	.53	5.28	.01	1	.13	8	00	66	08
KS15	8.34±0.	315.33±3	149.61±0	177.67±2	12.43±0.	4.77±0.	1687.51±1	3922.67±2	1053.33±5.	550.00±0	63.33±5.7	18.70±9.	9.10±2.9	0.38±0.	76.52±0.	0.09±0.
	01	.06	.56	.52	32	06	0.76	.20	77	.01	7	40	4	48	99	02
KS16	8.33±0.	324.67±4	139.58±0	194.00±2	10.17±0.	4.53±0.	2233.09±1	4376.67±1	1023.33±5.	540.00±0	130.00±0.	6.70±2.9	7.17±2.6	0.09±0.	65.22±2.	0.08±0.
	01	.04	.42	.65	25	06	0.60	.65	77	.00	00	9	2	01	06	03
KS17	8.25±0.	298.00±5	149.57±0	184.67±2	20.72±0.	4.90±0.	2581.87±3	3396.67±1	1040.00±1	890.00±0	103.33±5.	9.00±0.2	7.51±2.4	0.35±0.	77.63±0.	0.05±0.
	00	.57	.38	.08	45	17	3.43	.01	0.00	.29	77	6	4	35	77	05
KS18	8.11±0.	323.00±5	145.72±0	196.33±0	13.10±0.	4.93±0.	1171.00±9.	2320.00±2	1073.33±1	566.67±0	85.00±5.0	8.60±0.6	8.33±2.7	0.12±0.	77.53±0.	0.08±0.
	03	.00	.35	.58	70	06	60	.73	1.55	.02	0	2	5	04	21	04

mean ± standard deviation from triplicates

4.1.2 Kahn River within city boundary (December 2025)

The physicochemical characteristics of water samples collected from various sites along the Kahn River indicate highly polluted, heterogeneous water quality, resulting from intense anthropogenic influence and the constant discharge of untreated domestic wastewater. The pH values of river water at all sampling points ranged from 6.08 to 6.55, indicating slightly acidic to near-neutral conditions. The result is similar to the pH values of the Bagmati River in Nepal and the Tame River in the UK, as reported by Karki et al. (2024) and Rivett et al. (2011). Total alkalinity (TA) ranged from 1068.55 to 1807.67 mg/L, while total hardness (TH) ranged from 360.67 to 843.88 mg/L. Both values exceeded the permissible limit for drinking purposes as per IS 10500 (2012). The results show trends comparable to those reported by Stets et al. (2014) for polluted rivers in the conterminous US for TA & TH. Organic pollution levels were extremely high throughout the river stretch. BOD values ranged from 76.67 to 786.37 mg/L. The extremely high BOD values ($>600 \text{ mg L}^{-1}$) were observed at specific sampling locations (KN6, KN11, KN15, KN17) associated with major drain outfalls and represent localized peak conditions, whereas other locations exhibited comparatively lower values. Such elevated BOD levels have also been reported in urban rivers such as the Sabarmati River. (Hussain & Husain, 2013) and the Bagmati River in the Kathmandu valley (Baniya et al., 2019), where untreated sewage enters the river system. Similarly, COD values ranged from 106.67 to 1386.67 mg/L, which corroborates the COD values reported for the Bagmati River, Nepal, by Baniya et al. (2019) and Karki et al. (2024). These values indicate the presence of both biodegradable and non-biodegradable organic matter, reflecting combined domestic, urban, and possible industrial inputs. The wide variation in BOD and COD values reflects strong spatial heterogeneity driven by localized point-source discharges, hydrodynamic conditions, and in-stream processes (Joshi et al., 2022; Wang et al., 2023). Elevated COD values indicate the presence of both biodegradable and non-biodegradable organic matter, likely originating from a combination of domestic wastewater, detergent residues, and possible industrial inputs in urban stretches (Arzhanghi & Partani, 2025; Fadillatur Ro & Aini Dahalan, 2024). In contrast, relatively lower BOD and COD values at other locations may be attributed to dilution effects, mixing within the river channel, and partial biodegradation of organic matter along the flow path. Additionally, reduced flow velocity and localized stagnation zones in certain stretches promote the accumulation of organic pollutants and enhance oxygen depletion. The intermittent

discharge from multiple nallas and urban runoff further contributes to fluctuations in both BOD and COD levels, resulting in pronounced spatial variability along the river continuum.

DO levels ranged from 0.11 to 1.46 mg/L, reflecting intense microbial oxygen consumption under high organic loading, similar to the results reported by Sharma et al. (2025) for the Yamuna River (Delhi stretch). The chord diagrams (Fig. 4.4) provide a clear visualization of the relationships between sampling locations and water quality parameters, highlighting distinct spatial patterns of pollution along the river. Strong linkages were observed between midstream locations (e.g., KN5, KN10, KN11, KN15-KN17) and organic pollution indicators, indicating intense wastewater discharge in these zones.

TDS ranged from 386.67 to 706.67 mg/L, and Comparable trends have been reported in a study conducted in the Goynuk canyon area (Turkey) by Kareem and Leventeli (2024). TSS ranged from 14.1 to 270.3 mg/L; a similar range was reported by Karki et al. (2024). EC of 730 to 1330 $\mu\text{S}/\text{cm}$ was recorded in water samples from the Kahn River, indicating high dissolved ion concentrations due to domestic wastewater, detergent residues, and urban runoff. Similar results have been reported for EC values of water samples from the Buriganga River in Dhaka by Mustari et al. (2021). The values showed significant spatial variation in chloride concentration (25.26-270.88 mg/L), as observed in other polluted river basins in the city's urban area receiving sewage and industrial effluents (Sulaiman et al., 2014). The suspended matter and turbidity (15.67-300.33 NTU) are also signs of the pollution stress in the river system. Similar values were reported by Lu et al. (2023) in the rivers of the Lai Chi Wo catchment in China, which showed high sediment and particulate matter loads at some points, possibly due to urban runoff, drain discharges, and channel disturbance. High concentrations of suspended solids reduce light transmission and cause sedimentation, thereby degrading habitat quality in aquatic ecosystems. The nutrient concentration also reflects the effect of domestic wastewater. Nitrate concentrations were inconsistent, and some stations showed high levels (0.83-7.13 mg/L). The result again validates the Nitrate concentration values recorded by Enyoh (2020) for the Njaba River, Nigeria, and Liu et al. (2024) for the Luan River basin, China. The phosphate concentration ranged from 5.8 to 18.4 mg/L. Similar value was also reported by Adesuyi, Njoku, and Akinola (2015) and Isiuku & Enyoh (2020), indicating high levels of nutrient enrichment. These nutrients contribute to eutrophication and further oxygen depletion in water bodies. Trace metals such as Fe, Mn, and Zn were recorded at low to moderate levels, indicating localized pollution. The major components, such as Na^+ , K^+ , Ca^{2+} , and Mg^{2+} , were also recorded at high levels. Sharma et al. (2025) also reported similar results and further supported the cause of mixed pollution from domestic and industrial sources. As

shown in Figure 4.4, EC, TDS, Na^+ , and Cl^- showed strong associations with urban-dominated stretches, reflecting the influence of domestic sewage, detergent residues, and dissolved salts. Nutrient parameters (NO_3^- , PO_4^{3-}) were also strongly linked to these locations, suggesting significant nutrient enrichment from wastewater inflows. In contrast, upstream locations exhibited weaker connections with most pollution parameters, indicating relatively lower contamination levels.

These relationships are further supported by the Pearson correlation analysis (Figure 4.9), confirming strong positive associations among organic and ionic parameters. The measured parameter ranges are comparable to or worse than those reported for heavily polluted urban rivers, clearly demonstrating that Kahn River water is in deplorable condition and is unsuitable for drinking, irrigation, and supporting Aquatic Life. These findings strongly indicate direct or poorly treated industrial and municipal discharges entering the river, confirming intense anthropogenic pressure on the river stretch.

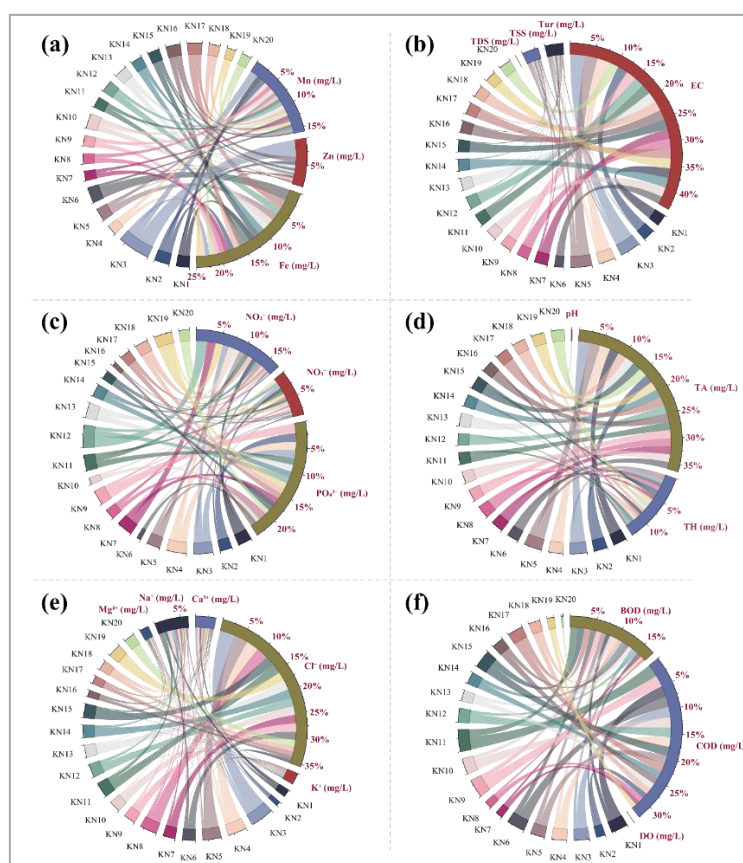


Figure 4.4 Chord diagrams illustrating relationships between sampling locations (KN1–KN20) and water quality parameters: (a) trace metals (Fe, Zn, Mn), (b) EC, TDS, TSS, and turbidity, (c) major ions (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^-), (d) nutrients (NO_2^- , NO_3^- , PO_4^{3-}), (e) pH, total alkalinity (TA), and total hardness (TH), and (f) organic pollution indicators (BOD, COD, DO).

Table 4.2 Physicochemical characteristics and heavy metal concentrations of water samples kahn River within the city boundary (KN1-KN18)

Sa mp le ID	TA	TH	Cl ⁻	BOD	COD	DO	F ⁻	pH	TDS	TSS	EC	Ca ²⁺	K ⁺	Na ⁺	PO ₄ ³⁻	NO ₂ ⁻	NO ₃ ⁻	Tur	Fe	Mg ²⁺	Mn	Zn
Uni t	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		(mg/L)	(mg/L)	(μS/cm)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
KN 1	1441.3 3±5.51	475.0 0±2.8 9	25.26 ±0.60	469.2± 0.02	1173.3 3±0.00	0.19 ±0.0 1	0.33 ±0.0 6	6.08 ±0.0 8	480.0 0±0.0 0	1.88± 0.73	906.67 ±5.77	34.16 ±26.6 2	6.82± 0.13	40.96 ±23.5 5	9.20± 0.00	8.00± 0.00	5.97 ±0.1 2	40.33 ±0.58	0.09 ±0.0 1	7.75± 3.85	0.08 ±0.0 0	0.02 ±0.0 1
KN 2	1358.6 6±5.23	568.0 0±2.3 1	32.23 ±1.31	275.44 ±0.05	604.44 ±0.00	0.22 ±0.0 2	5.20 ±0.0 0	6.42 ±0.0 2	500.0 0±0.0 2	7.39± 0.47	943.33 ±20.82	6.91± 3.98	5.52± 0.06	16.19 ±0.54	16.00 ±0.00	3.00± 0.00	1.50 ±0.1 0	40.00 ±0.00	0.08 ±0.0 1	9.45± 2.30	0.08 ±0.0 3	0.06 ±0.0 3
KN 3	1807.6 7±2.52	615.6 7±5.6 5	270.8 8±2.7 7	407.79 ±6.32	1102.2 2±12.3 2	0.23 ±0.0 2	3.43 ±0.1 2	5.85 ±0.0 4	706.6 7±0.0 1	11.64 ±1.10	1330.0 0±10.0 0	39.72 ±18.2 5	9.32± 0.14	30.16 ±13.4 0	15.13 ±0.06	11.00 ±0.00	6.30 ±0.0 0	209.3 3±0.5 8	0.07 ±0.0 1	10.37 ±0.52	0.13 ±0.0 4	0.27 ±0.0 3
KN 4	1627.6 7±2.52	427.7 6±1.3 0	205.0 6±0.8 1	467.7± 3.32	1031.1 1±12.3 2	0.21 ±0.0 2	0.00 ±0.0 0	6.24 ±0.0 0	576.6 7±0.0 1	7.31± 0.70	1076.6 7±23.0 9	36.96 ±24.0 2	8.86± 0.20	30.44 ±17.6 7	15.40 ±0.00	11.00 ±0.00	7.13 ±0.0 6	159.0 0±1.0 0	0.07 ±0.0 0	10.36 ±0.40	0.07 ±0.0 3	0.01 ±0.0 0
KN 5	1699.6 7±3.10	843.8 8±1.2 4	226.7 0±1.8 2	532.3± 6.32	888.89 ±12.32	0.36 ±0.0 1	0.00 ±0.0 0	6.55 ±0.0 6	643.3 3±0.0 1	2.85± 0.33	1216.6 7±11.5 5	15.83 ±13.2 7	21.30 ±0.60	17.16 ±9.53	8.00± 0.00	9.70± 0.00	4.87 ±0.2 1	300.3 3±0.5 8	0.11 ±0.0 1	6.43± 3.32	0.06 ±0.0 2	0.02 ±0.0 1
KN 6	1068.5 5±3.51	615.3 3±3.4 6	129.8 6±3.1 5	623.4± 0.06	1173.3 3±0.00	1.46 ±0.0 2	0.00 ±0.0 0	6.40 ±0.0 6	386.6 7±0.0 1	12.87 ±0.35	730.00 ±0.00	5.73± 3.40	5.48± 0.08	55.53 ±1.11	6.27± 0.06	0.00± 0.00	0.87 ±0.0 6	15.67 ±0.58	0.18 ±0.0 1	5.58± 0.23	0.04 ±0.0 0	0.01 ±0.0 1
KN 7	1263.1 1±1.43	532.8 9±0.7 7	142.2 2±0.8 9	268.08 9±3.32	462.22 ±12.32	0.28 ±0.0 1	3.93 ±0.1 2	6.25 ±0.0 1	490.0 0±0.0 0	3.29± 0.83	913.33 ±5.77	6.44± 3.75	9.53± 0.13	24.18 ±8.17	10.20 ±0.00	16.00 ±0.00	0.83 ±0.0 6	109.6 7±0.5 8	0.08 ±0.0 0	5.42± 2.73	0.05 ±0.0 1	0.01 ±0.0 0

KN	1282.3	601.6	201.7	243.33	533.33	0.36	3.87	6.39	486.6	0.07±	910.00	23.05	9.45±	20.44	8.20±	6.00±	3.60	36.33	0.08	6.85±	0.07	0.00
8	3±1.64	7±2.8	4±1.4	±0.02	±0.00	±0.0	±0.0	±0.0	7±0.0	0.02	±10.00	±21.0	±14.3	8	0.00	0.00	±0.0	±6.35	±0.0	0.34	±0.0	±0.0
		9	0			1	6	3	1			6	0.11	8			0		1	0.34	2	0
KN	1312.6	442.0	141.0	568.43	1244.4	1.18	0.00	6.28	500.0	9.13±	936.67	4.31±	9.38±	23.69	18.40	4.00±	3.13	25.00	0.08	6.69±	0.06	0.02
9	7±5.93	0±3.4	6±1.0	±12.59	4±32.5	±0.0	±0.0	±0.0	0±0.0	0.06	±5.77	0.18	0.04	±10.2	±0.00	0.00	±0.0	±1.00	±0.0	0.19	±0.0	±0.0
		6	0		9	1	0	2	1					3			6		0	0.19	2	1
KN	1211.4	521.0	144.4	468.22	1102.2	0.17	0.00	6.40	473.3	7.73±	886.67	9.52±	8.08±	12.50	6.80±	3.00±	2.00	44.33	0.10	6.21±	0.07	0.05
10	4±2.04	0±1.7	6±1.5	±3.32	2±12.3	±0.0	±0.0	±0.0	3±0.0	0.60	±20.82	0.14	0.11	±7.31	0.10	0.00	±0.0	±1.15	±0.0	0.11	±0.0	±0.0
		3	0		2	2	0	4	1								0		1	0.11	2	0
KN	1326.6	409.3	164.4	786.37	1386.6	0.21	0.00	6.34	496.6	7.37±	926.67	6.16±	9.05±	50.00	12.23	9.00±	5.67	63.67	0.09	8.33±	0.06	0.01
11	7±2.78	3±4.6	2±2.3	±0.07	7±0.00	±0.0	±0.0	±0.0	7±0.0	0.12	±11.55	3.83	0.13	±8.68	±0.06	0.00	±0.1	±1.53	±0.0	2.48	±0.0	±0.0
		2	0			2	0	4	1								2		1	2.48	2	1
KN	1352.0	367.3	146.2	356.67	1046.6	0.88	0.00	6.30	493.3	1.06±	930.00	20.53	9.03±	27.19	11.30	20.00	7.00	76.33	0.12	6.50±	0.06	0.00
12	0±2.52	3±1.1	9±1.0	±16.44	7±11.2	±0.0	±0.0	±0.0	3±0.0	0.03	±0.00	±9.25	0.21	±13.9	±0.10	±0.00	±0.0	±1.53	±0.0	0.36	±0.0	±0.0
		5	7		2	0	0	1	1					9			0		1	0.36	3	0
KN	1391.3	490.3	155.6	421.2±	675.56	0.44	0.00	6.36	490.0	0.74±	926.67	3.72±	8.45±	17.90	12.17	10.00	3.60	59.00	0.10	6.15±	0.06	0.03
13	3±2.41	3±6.3	2±1.0	3.59	±32.59	±0.0	±0.0	±0.0	0±0.0	0.02	±15.28	0.01	0.12	±0.65	±0.06	±0.00	±0.0	±1.00	±0.0	0.27	±0.0	±0.0
		5	2			1	0	3	1								0		0	0.27	2	0
KN	1354.6	400.6	151.2	456.17	746.67	0.34	0.00	6.40	483.3	7.64±	906.67	3.72±	8.84±	26.36	11.87	7.00±	2.70	55.00	0.10	7.86±	0.04	0.03
14	7±4.58	7±1.1	5±0.3	±0.20	±0.00	±0.0	±0.0	±0.0	3±0.0	0.31	±5.77	0.14	0.17	±13.5	±0.06	0.00	±0.0	±1.00	±0.0	2.16	±0.0	±0.0
		5	8			1	0	7	1					8			0		1	2.16	1	1
KN	1372.6	541.6	172.2	765.21	1031.1	0.11	0.00	6.43	490.0	0.49±	916.67	7.87±	8.34±	21.48	8.30±	2.00±	4.80	54.33	0.10	7.53±	0.03	0.04
15	7±2.34	7±2.8	5±0.8	±14.63	1±24.6	±0.0	±0.0	±0.0	0±0.0	0.24	±5.77	3.48	0.27	±5.00	0.10	0.00	±0.1	±0.58	±0.0	2.09	±0.0	±0.0
		9	0		3	2	0	1	0								0		1	2.09	0	1
KN	1344.0	360.6	57.93	446.27	746.67	0.35	0.00	6.32	490.0	0.79±	920.00	13.90	8.76±	18.98	5.83±	0.00±	1.90	48.67	0.09	6.44±	0.05	0.07
16	0±3.24	7±1.1	±1.63	±0.00	±0.00	±0.0	±0.0	±0.0	0±0.0	0.11	±0.00	±12.5	0.25	±0.34	0.06	0.00	±0.0	±1.15	±0.0	0.30	±0.0	±0.0
		5				1	0	8	0			6					0		1	0.30	0	3
KN	1354.0	473.3	77.03	658.89	888.89	0.36	0.00	6.30	480.0	0.34±	910.00	19.29	8.27±	13.79	10.27	5.00±	2.87	54.67	0.14	7.42±	0.04	0.03
17	0±1.02	3±0.0	±1.29	±16.63	±24.63	±0.0	±0.0	±0.0	0±0.0	0.08	±10.00	±8.94	0.09	±8.10	±0.06	0.00	±0.0	±0.58	±0.0	2.51	±0.0	±0.0
		0				2	0	6	0								6		1	2.51	0	0

KN	1407.3	477.9	83.89	456.56	675.56	0.42	0.00	6.35	483.3	1.27±	923.33	26.15	9.19±	33.52	10.33	8.67±	3.83	59.33	0.09	6.70±	0.06	0.01
18	3±2.34	2±1.1	±1.26	±7.32	±12.32	±0.0	±0.0	±0.0	3±0.0	0.06	±15.28	±16.7	0.28	±12.8	±0.12	0.58	±0.0	±1.15	±0.0	0.20	±0.0	±0.0
		4				2	0	3	1			5		3			6		1	0.20	2	1
KN	1356.0	521.3	156.4	262.22	462.22	0.17	5.17	6.35	486.6	1.37±	910.00	17.30	9.03±	19.37	11.17	14.00	5.53	32.67	0.07	6.57±	0.05	0.01
19	0±1.53	3±1.5	5±1.0	±8.32	±12.32	±0.0	±0.0	±0.0	7±0.0	0.17	±10.00	±22.9	0.10	±1.08	±0.06	±0.00	±0.0	±0.58	±0.0	0.17	±0.0	±0.0
		3	9			1	6	5	1			8					6		0	0.17	2	0
KN	1369.3	507.6	109.4	76.67±	106.67	0.86	4.20	6.30	513.3	0.55±	970.00	19.92	8.55±	22.22	8.30±	5.33±	3.77	31.33	0.08	6.65±	0.06	0.00
20	3±0.77	7±3.2	9±1.9	0.00	±0.00	±0.0	±0.1	±0.0	3±0.0	0.12	±0.00	±8.70	0.15	±17.8	0.00	0.58	±0.1	±0.58	±0.0	0.14	±0.0	±0.0
		1	9			1	0	9	1					4			2		1	0.14	2	0

mean ± standard deviation from triplicates

4.1.3 Sirpur Wetland (October 2025)

Sirpur Wetland samples (SP1-SP28) analysis indicate that it is a moderately nutrient-enriched freshwater ecosystem with considerable spatial heterogeneity, influenced by natural wetland processes, biological activities, and anthropogenic influences. To complement this understanding, the irrigation-related indices (SAR, KR, SSP, and MAR) further highlight variations in ionic composition across the wetland. These indices exhibit distinct spatial patterns, reflecting differences in sodium and magnesium dominance at various sites and reinforcing the non-uniform character of the system, as shown in Figures 4.5, 4.6, and 4.7, which visually illustrate site-specific comparisons, highlighting hotspots of potential contamination and enabling more accurate assessments of the water quality in the wetland. pH values exhibited a range of values from moderately neutral to alkaline (6.78–7.78) and therefore indicate the potential for high buffering capacity because of the carbonate and bicarbonate content derived from the presence of carbonate-rich sediments and the decomposition of submerged plant material. Alkalinity levels had a broad range (135–364 mg/L), indicating that the water has a significant bicarbonate load, similar to the values reported for the Nalban Ramsar Wetland (Mohan et al., 2019). Hardness values ranged from 169 mg/L to 397 mg/L; therefore, the wetland has been classified as hard to very hard, which corresponds to high Ca and Mg concentrations resulting from ion concentration through natural evaporation during periods of drought. According to Figure 4.5, available chloride levels were consistently low (between 0.28 and 20.77 mg/L), except for a localized spike at site SP13 with a chloride concentration of 28.57 mg/L. This spike indicates intermittent input of household wastewater into the study area. The chloride concentration also confirms that there has been no significant saline intrusion, consistent with trends previously documented for the Ropar Ramsar Wetland (Akhter et al., 2020).

Organic load indicators, BOD concentrations (ranging from 3.97–20.42 mg/L) and COD concentrations (ranging from 20.08–89.3 mg/L), indicated the active decomposition of biodegradable and semi-refractory organic material, originating from macrophyte decomposition, bird droppings, and human usage of the wetland edges. These similar patterns can be seen in Borsola Beel under NWMP (2022) and Rudrasagar 205 Wetland (Abir et al., 2014). Dissolved oxygen (DO) levels exhibited considerable spatial variability (2.30–8.00 mg/L), with higher DO concentrations at SP22–SP25 sites corresponding to zones of dense floating aquatic vegetation, which were dominated by daytime photosynthetic processes. The lower DO at SP4–SP6 sites resulted from organic enrichment, reduced light penetration into deeper waters due to algal surface mats, and increased microbial respiration. Field observations

revealed dense algal growth in several littoral regions, limiting sunlight penetration into the deeper water column and suppressing photosynthesis below the surface. Decomposing plant material accumulates organic matter, bird droppings, and human waste, increasing oxygen demand and reducing oxygen availability in small areas, lowering DO. Akhter et al. (2020) also found that a similar phenomenon occurs in the Ropar Ramsar Wetland due to nutrient pollution, leading to decreased suspended solids levels due to eutrophication. Fluoride concentrations reached up to 2.07 mg/L, with several sites close to exceeding the drinking-water limit. These higher concentrations are most likely due to natural geological processes, particularly the dissolution of fluoride-rich minerals. Similar results have also been reported in the Thol and Wadhvana Ramsar Wetlands in Gujarat, India (Chaudhari et al., 2025). TDS levels ranged from low to moderate (240-434 mg/L), with higher levels observed at sampling points SP22–SP25. At the same time, EC values (456-813 $\mu\text{S}/\text{cm}$) indicate ionic enrichment in areas receiving runoff from impervious surfaces and groundwater from household wastewater.

Major cations, Ca^{2+} (13.6 to 52.7 mg/L) and Mg^{2+} (11.5 to 20.1mg/L), represent baseline geological contributions; however, higher Na^{+} concentrations at SP22-SP25 (17 to 68mg/L) suggest the introduction of detergents through greywater and evaporative concentration of Na^{+} . The concentration of potassium (1.40-5.13 mg/L) is slightly higher in areas exposed to human washing, plant decomposition, and minor agricultural runoff. The pattern observed with the nutrient parameters provides clear evidence of the biological activity in the wetlands. In particular, the concentrations of nitrates (0.0-6.4 mg/L), which peak at the sampling points SP6 (6.43 mg/L) and SP7 (6.67 mg/L), correspond to those sampling points with high levels of human contact, and birds congregate, which add urea, organic nitrogen, and fecal material into the wetlands. Although the concentrations are below the limit for confirming nuisance algae growth, the presence of additional nutrients may still indicate potential nuisance algae growth. Turbidity values (2.30-24 NTU) are generally low in this wetland, except for spikes that occur at sampling points SP23 through SP25 due to increased resuspension of sediments caused by wind, the motion of waterfowl, and the accumulation of organic matter. The aluminum (0.17-0.77 mg/L), chromium (0.01-0.04 mg/L), and zinc (0.02-0.11 mg/L) exhibit lower variability than the other trace elements, indicating the influence of natural geological and biogeochemical factors. The other significant contamination is iron (0.20-5.43 mg/L), which has increased markedly at sampling points SP7 and SP23 due to interactions between sediments and water, the presence of alternate oxidized states, and the breakdown of organic matter.

To compare the parameters with the standard guidelines for Drinking (WHO, BIS, CPCB, IS10500 -2012), Irrigation (IS 11624- 2019), and Aquatic Life (CPCB, WHO-2017 and

USEPA), most of the parameters (Table 4.3) exceed the acceptable and permissible limits, as shown in Figure 4.5, Figure 4.6, and Figure 4.7.



Figure 4.5 Physicochemical water quality parameters of Sirpur Wetland for Drinking Water.



Figure 4.6 Physicochemical water quality parameters of Sirpur Wetland for Irrigation Water.



Figure 4.7 Physicochemical water quality parameters of Sirpur Wetland for Aquatic Life.

Table 4.3 Physicochemical characteristics and heavy metal concentrations of water samples Sirpur Lake (SP1-SP28).

Sample ID	TA	TH	Cl ⁻	BOD	COD	DO	F ⁻	pH	TDS	EC	Ca ²⁺	K ⁺	Na ⁺	NO ₃ ⁻	Tur	Al	Cr	Fe	Mg ²⁺	Mn	Zn
Unit	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		(mg/L)	(μS/cm)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
SP 1	364.00±2.65	196.00±1.00	0.21±0.14	12.85±0.08	64.67±5.03	2.89±0.02	1.03±0.06	6.99±0.13	250.67±0.58	472.67±6.43	48.30±2.59	4.60±0.20	26.60±1.04	0.77±0.12	2.37±0.12	0.18±0.14	0.04±0.00	0.38±0.13	0.07±0.01	0.00±0.00	0.02±0.01
SP 2	184.67±2.01	227.67±1.50	45.59±18.13	8.07±0.05	42.58±0.15	2.45±0.03	1.50±0.10	7.07±0.05	250.00±0.00	467.33±4.62	398.33±9.24	3.67±0.12	19.03±0.23	0.70±0.10	2.33±0.06	0.22±0.01	0.01±0.00	0.22±0.04	11.71±5.76	0.00±0.01	0.02±0.01
SP 3	147.33±1.02	235.67±1.84	42.16±16.93	10.67±0.28	62.67±2.31	2.98±0.02	0.00±0.00	7.06±0.12	250.33±0.58	470.00±0.00	34.73±1.89	3.73±0.21	23.10±0.85	1.43±0.06	2.70±0.17	0.20±0.06	0.01±0.01	0.41±0.06	13.67±1.53	0.05±0.08	0.04±0.01
SP 4	173.67±0.69	394.00±1.15	49.01±19.32	3.97±0.03	20.89±0.77	2.33±0.05	0.57±0.06	7.30±0.58	250.00±0.00	470.00±0.00	31.03±4.66	3.87±0.42	24.23±0.35	0.00±0.00	2.33±0.12	0.17±0.01	0.02±0.01	0.50±0.24	14.12±1.09	0.01±0.01	0.03±0.01
SP 5	170.33±1.58	187.33±2.01	42.63±16.66	14.32±0.31	74.83±5.01	2.37±0.03	1.97±0.06	7.12±0.09	253.33±5.77	476.67±5.77	41.23±8.78	4.30±0.95	25.17±3.56	1.17±0.06	4.03±0.06	0.57±0.04	0.06±0.01	3.19±0.50	13.71±1.28	0.02±0.01	0.04±0.02
SP 6	181.67±1.64	184.67±1.39	29.71±11.42	20.42±0.31	83.11±2.78	2.85±0.05	1.23±0.06	7.01±0.10	242.67±4.62	466.00±5.29	36.20±2.26	2.50±0.44	21.87±1.30	6.40±0.30	3.07±0.12	0.56±0.02	0.03±0.01	2.85±0.32	13.70±1.21	0.02±0.01	0.05±0.01
SP 7	164.67±3.01	171.00±2.52	36.39±13.91	12.12±0.07	64.00±0.00	3.24±0.03	1.63±0.12	7.20±0.10	243.33±5.77	465.00±5.00	34.33±2.90	3.23±0.61	27.63±4.26	3.67±0.15	2.53±0.40	0.77±0.04	0.04±0.02	5.43±1.22	11.52±5.45	0.03±0.01	0.06±0.02
SP 8	176.67±2.01	193.67±0.84	51.53±21.05	14.84±0.18	64.00±0.00	3.01±0.02	2.03±0.06	7.09±0.10	246.67±5.86	460.00±0.00	36.40±3.64	4.13±0.12	23.87±0.58	0.00±0.00	3.03±0.75	0.39±0.02	0.02±0.00	0.23±0.05	14.08±1.09	0.01±0.00	0.02±0.01
SP 9	182.33±0.84	191.67±2.50	22.84±9.03	15.28±0.09	83.56±3.08	2.79±0.02	0.00±0.00	7.11±0.07	256.67±5.77	482.67±6.43	46.03±4.87	3.57±0.06	18.07±0.35	1.50±0.00	3.13±0.25	0.18±0.00	0.01±0.01	0.20±0.03	15.18±0.23	0.06±0.10	0.24±0.08
SP 10	170.33±1.58	242.33±0.69	33.01±12.69	12.64±0.05	67.00±3.00	2.65±0.03	1.13±0.06	7.09±0.07	250.00±0.00	476.33±6.35	45.80±1.93	4.97±0.55	29.87±0.85	1.27±0.12	3.33±0.32	0.39±0.03	0.04±0.02	0.50±0.28	13.80±0.89	0.01±0.00	0.05±0.01
SP 11	155.33±2.01	227.00±1.73	39.46±15.31	12.60±0.15	66.00±3.46	2.70±0.03	1.17±0.12	7.05±0.04	243.33±5.77	463.00±6.08	51.03±1.31	3.67±0.12	18.60±0.62	1.27±0.06	3.27±0.06	0.39±0.03	0.02±0.00	0.70±0.41	13.94±1.96	0.01±0.00	0.03±0.01
SP 12	142.00±2.08	241.33±4.02	39.46±15.31	14.89±0.12	83.56±3.08	2.50±0.01	1.20±0.10	7.04±0.06	243.33±5.77	461.33±3.21	52.67±9.29	3.87±0.40	19.27±0.76	1.00±0.17	3.73±0.25	0.21±0.04	0.02±0.01	0.26±0.05	12.03±5.75	0.01±0.00	0.03±0.02

SP	135.00±	176.00	93.90±	12.05	64.00	2.30±	1.33±	6.94±	250.00	470.00	486.67	3.47±	17.50	1.13±	3.13±	0.31±	0.02±	0.22±	13.85	0.01±	0.02±
13	2.52	±3.00	37.84	±0.03	±0.00	0.01	0.06	0.15	±0.00	±0.00	±8.50	0.06	±0.17	0.06	0.15	0.05	0.01	0.03	±1.27	0.00	0.01
SP	179.00±	261.33	22.72±	16.73	88.20	2.36±	1.10±	7.02±	256.67	483.00	322.67	5.13±	23.93	1.63±	2.40±	0.33±	0.03±	0.41±	15.09	0.01±	0.02±
14	0.58	±2.78	9.11	±0.61	±2.80	0.02	0.00	0.09	±5.77	±6.08	±9.71	0.51	±0.25	0.06	0.10	0.01	0.01	0.08	±1.54	0.01	0.01
SP	155.33±	203.67	48.66±	11.57	64.73	2.74±	2.07±	6.89±	250.00	480.00	32.47±	4.00±	24.00	2.00±	3.57±	0.35±	0.04±	0.48±	14.33	0.01±	0.03±
15	2.01	±3.72	19.53	±0.29	±1.27	0.01	0.06	0.21	±0.00	±0.00	2.14	0.00	±0.36	0.00	0.12	0.05	0.01	0.09	±1.78	0.00	0.01
SP	172.33±	194.67	45.86±	16.67	89.28	2.36±	0.00±	7.09±	246.67	460.00	46.70±	3.90±	20.40	0.70±	3.10±	0.53±	0.03±	0.29±	13.96	0.00±	0.02±
16	1.84	±2.52	17.96	±0.34	±5.85	0.01	0.00	0.06	±5.77	±0.00	1.57	0.10	±0.69	0.17	0.20	0.03	0.01	0.06	±1.00	0.01	0.01
SP	163.67±	276.33	29.17±	11.14	62.83	2.57±	1.37±	7.29±	248.33	479.67	14.40±	1.40±	11.77	0.33±	2.33±	0.44±	0.03±	1.02±	13.98	0.01±	0.06±
17	3.72	±1.50	11.73	±0.18	±2.02	0.03	0.06	0.56	±2.89	±0.58	4.33	0.36	±1.89	0.06	0.06	0.04	0.02	0.09	±1.26	0.00	0.01
SP	165.67±	174.00	26.11±	19.56	88.04	3.24±	1.67±	7.05±	245.33	466.67	21.90±	4.23±	27.07	0.87±	2.87±	0.38±	0.03±	0.55±	14.24	0.01±	0.03±
18	1.58	±1.15	10.34	±0.43	±3.50	0.02	0.06	0.08	±5.03	±5.77	0.60	0.06	±0.95	0.65	0.21	0.02	0.02	0.32	±1.26	0.00	0.01
SP	146.00±	169.67	39.34±	8.85±	42.31	2.45±	1.60±	6.91±	256.67	482.33	46.83±	4.20±	22.10	1.23±	1.80±	0.18±	0.02±	0.75±	15.15	0.01±	0.07±
19	3.06	±0.84	15.39	0.05	±0.62	0.03	0.10	0.08	±5.77	±6.81	1.64	0.17	±0.69	0.15	0.17	0.01	0.01	0.41	±1.10	0.00	0.01
SP	215.67±	173.00	54.84±	15.62	82.98	2.31±	0.83±	6.96±	245.00	459.00	46.00±	3.93±	21.30	0.43±	2.47±	0.39±	0.02±	0.40±	14.32	0.00±	0.03±
20	1.50	±1.53	22.30	±0.06	±2.72	0.03	0.06	0.05	±5.00	±1.73	1.93	0.06	±0.00	0.06	0.35	0.03	0.02	0.09	±0.89	0.01	0.01
SP	190.67±	182.67	16.11±	10.72	64.40	0.66±	1.20±	6.79±	246.67	469.33	47.03±	4.73±	21.60	0.50±	4.57±	0.42±	0.02±	1.08±	14.47	0.01±	0.06±
21	1.84	±0.38	6.57	±0.16	±0.69	0.07	0.00	0.07	±5.77	±1.15	1.99	0.80	±0.79	0.00	0.21	0.02	0.00	0.63	±1.70	0.00	0.01
SP	274.00±	276.33	35.74±	15.58	82.88	8.00±	0.77±	7.62±	430.00	806.67	271.33	3.77±	67.00	0.20±	24.00	0.28±	0.03±	0.34±	14.57	0.01±	0.04±
22	6.03	±1.35	14.29	±0.08	±2.29	0.04	0.06	0.10	±0.00	±5.77	±9.71	0.84	±1.73	0.17	±1.00	0.03	0.01	0.20	±0.93	0.01	0.01
SP	285.67±	285.33	68.06±	14.26	85.22	5.96±	1.97±	7.52±	434.67	813.33	378.67	4.83±	68.67	0.30±	15.67	0.39±	0.03±	1.50±	18.79	0.01±	0.11±
23	1.64	±3.02	27.38	±0.12	±0.19	0.01	0.06	0.09	±5.03	±5.77	±9.07	0.32	±1.15	0.00	±1.15	0.01	0.01	0.27	±2.18	0.00	0.02
SP	295.33±	244.67	51.49±	13.55	68.03	7.24±	1.47±	7.70±	426.67	806.67	370.67	4.30±	63.00	0.43±	22.00	0.24±	0.01±	0.20±	18.47	0.01±	0.03±
24	3.29	±3.01	21.07	±0.24	±2.37	0.03	0.06	0.06	±5.77	±5.77	±9.61	0.00	±0.00	0.06	±1.00	0.01	0.01	0.11	±1.27	0.01	0.01
SP	277.33±	177.67	58.09±	11.93	63.33	7.44±	1.97±	7.67±	429.00	462.67	393.00	4.27±	42.67	0.27±	20.67	0.32±	0.04±	1.06±	19.31	0.01±	0.06±
25	1.07	±1.64	23.60	±0.02	±1.15	0.04	0.06	0.07	±1.73	±6.43	±7.00	0.06	±2.52	0.06	±0.58	0.06	0.02	0.21	±2.16	0.00	0.01
SP	174.33±	174.33	35.90±	16.60	84.94	3.84±	1.07±	7.10±	249.33	459.33	29.80±	1.83±	24.33	1.67±	2.47±	0.22±	0.02±	0.56±	20.11	0.00±	0.02±
26	1.58	±0.84	14.19	±0.07	±1.78	0.01	0.06	0.03	±1.15	±1.15	6.21	0.12	±0.71	0.12	0.12	0.04	0.01	0.10	±1.64	0.00	0.00
SP	157.33±	182.00	19.55±	11.86	63.33	3.33±	1.27±	6.78±	240.00	456.67	35.37±	2.83±	21.23	1.77±	8.73±	0.36±	0.03±	0.44±	14.49	0.01±	0.04±
27	1.07	±1.15	7.76	±0.10	±1.15	0.01	0.06	0.08	±0.00	±5.77	1.29	0.32	±2.71	0.12	0.61	0.05	0.01	0.08	±1.29	0.00	0.00
SP	286.33±	397.00	51.98±	18.56	80.20	7.38±	1.20±	7.78±	410.00	778.33	13.57±	1.40±	19.87	0.40±	19.00	0.54±	0.04±	0.90±	15.35	0.01±	0.04±
28	0.69	±0.58	20.78	±0.13	±2.11	0.02	0.10	0.05	±0.00	±2.89	5.80	0.10	±1.63	0.00	±1.00	0.02	0.02	0.05	±0.37	0.00	0.01

4.2 Statistical Analysis

4.2.1 Pearson's Correlation

Pearson's correlation analysis was performed to understand relationships among physicochemical parameters, nutrients, and heavy metals under three different conditions: (a) monsoon Kahn River Basin, (b) Sirpur Lake, and (c) Kahn River within the city boundary.

Kahn River Basin

Under monsoon conditions, a strong positive correlation between EC and TDS was observed, confirming that dissolved ionic content controls conductivity. Chloride and major cations also showed association with TDS, indicating transport of dissolved salts through runoff and wastewater inflow. Dissolved Oxygen (DO) showed a negative correlation with turbidity and organic load indicators (BOD/COD), suggesting oxygen depletion in zones with higher suspended solids and biodegradable matter. This reflects dilution–transport dynamics typical of high-flow conditions. Metal correlations were relatively moderate, indicating mixed sources and active transport rather than localized accumulation. Overall, the monsoon river behaves as a transport-dominated system, where runoff-driven mixing influences parameter relationships as shown in Figure 4.8.

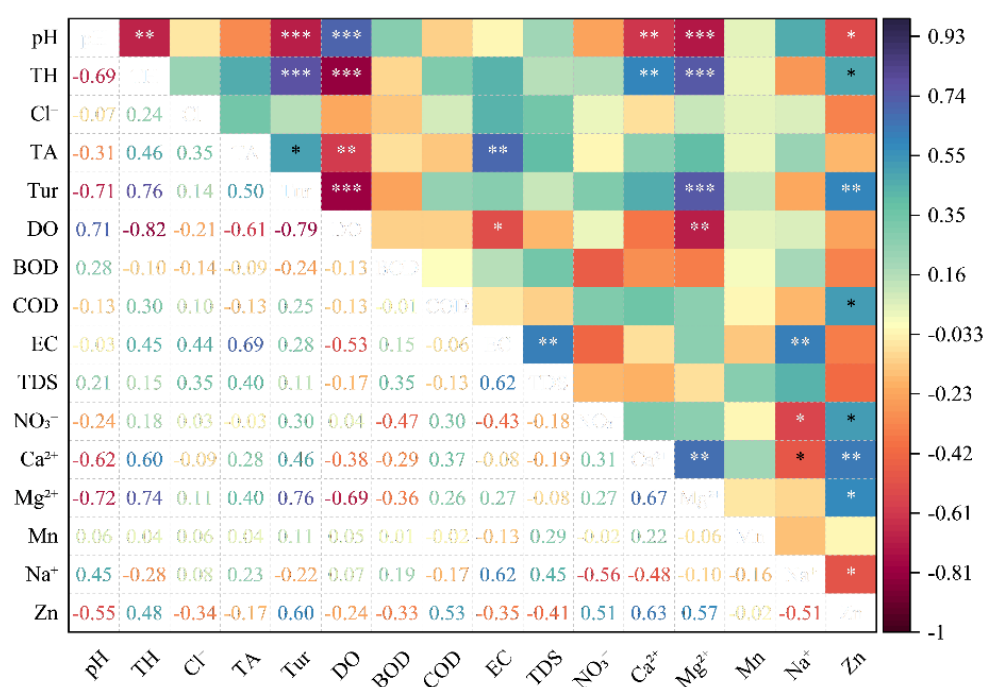


Figure 4.8 Correlation matrix of water quality parameters of the Kahn Basin Scale.

Kahn River within the city boundary

The post-monsoon urban stretch showed the strongest and most defined correlations. A clear negative correlation between DO and BOD/COD confirms severe oxygen depletion driven by high organic loading under low-flow conditions. EC, TDS, chloride, and sodium formed a strong positive cluster, indicating a common sewage-derived ionic source. Metals such as Fe and Mn showed association with turbidity and TSS, suggesting particulate-bound transport in the urban reach. Compared to monsoon conditions, relationships in this phase are sharper and more source-specific, reflecting the influence of concentrated discharge within the municipal boundary, as shown in Figure 4.9.

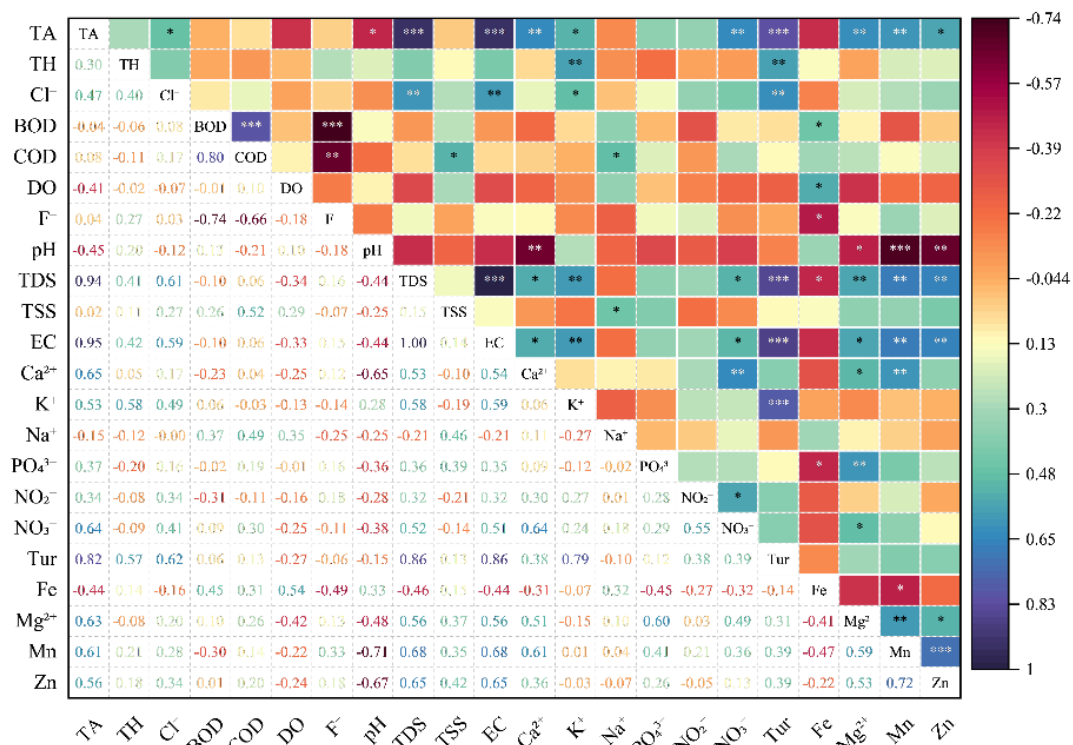


Figure 4.9 Correlation matrix of water quality parameters in the Kahn River within the city boundary.

Sirpur Wetland

At Sirpur Lake, EC and TDS again showed a strong positive correlation, whereas the relationships for other parameters were more compartmentalized. DO exhibited a weaker correlation with BOD and COD compared to the river system, indicating more stable internal biogeochemical processes. Metals such as Fe and Al showed association with turbidity and suspended solids, suggesting adsorption onto particulate matter and sediment interaction as illustrated in Figure 4.10. This pattern reflects pollutant retention rather than rapid downstream

transport. The lake matrix, therefore, represents a retention-controlled system in which accumulation and localized interactions are more important than flow-driven mixing.

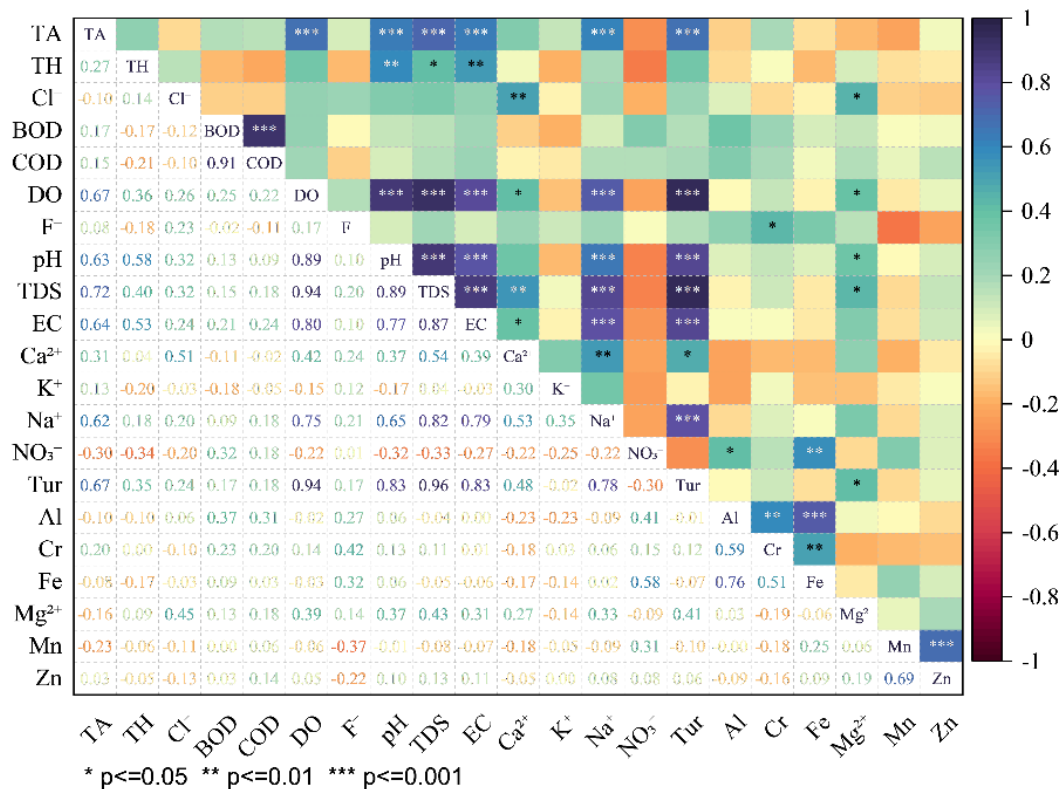


Figure 4.10 Correlation matrix of water quality parameters of Sirpur Wetland.

4.2.2 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed to reduce the dataset's dimensionality and identify the dominant factors controlling water quality variation in the Kahn River (monsoon and post-monsoon urban stretches) and Sirpur Lake. The scree plots indicate that the first few principal components account for a substantial portion of the total variance in all three datasets, suggesting that water quality variability is governed by a limited number of dominant processes.

Kahn River Basin

In the monsoon dataset (Figure 4.11), the first two principal components account for a significant proportion of total variance, as indicated by the sharp decline in eigenvalues after PC2. PC1 is primarily associated with ionic parameters such as EC, TDS, chloride, and total alkalinity, indicating that dissolved solids and runoff-driven ionic transport are the dominant controlling factors during monsoon flow. The clustering of these variables along the same loading direction confirms their common source, likely municipal discharge combined with surface runoff. PC2 shows a strong association with turbidity, hardness, magnesium, and

certain metal fractions, suggesting the influence of suspended solids and geogenic mineral contribution. Dissolved oxygen loads in the opposite direction of BOD and COD, confirming the inverse relationship between oxygen availability and organic pollution. The spatial distribution of sampling points along PC1 reflects increasing anthropogenic influence downstream.

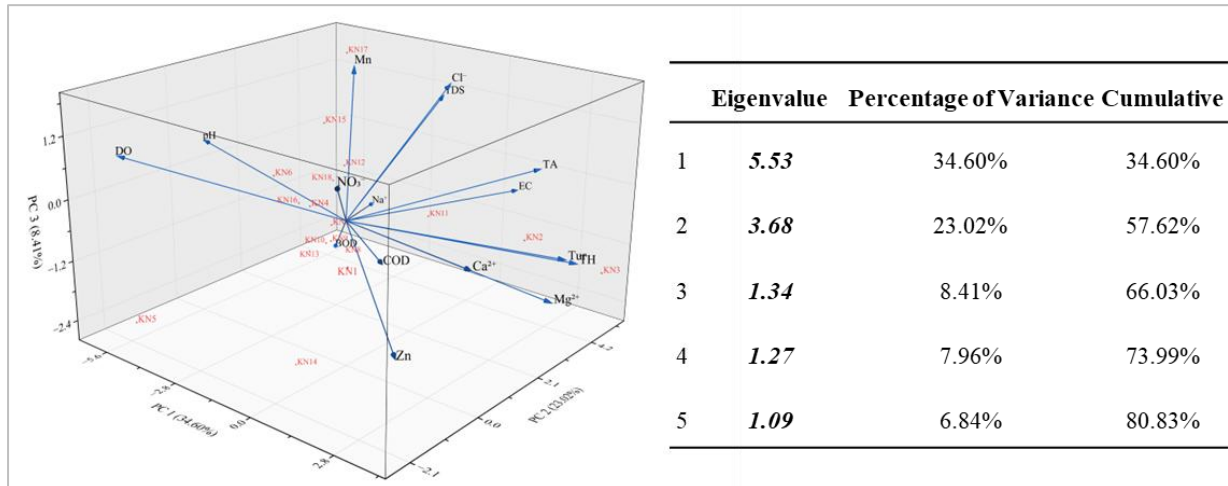


Figure 4.11 PCA biplot and variance contribution of principal components for the Kahn River Basin

Kahn River within the city boundary

In the post-monsoon urban stretch (Figure 4.12), the scree plot shows that the first two components account for a large fraction of the total variance, with PC1 having particularly high explanatory power. PC1 is dominated by BOD, COD, chloride, EC, TDS, and sodium, clearly representing anthropogenic sewage influence.

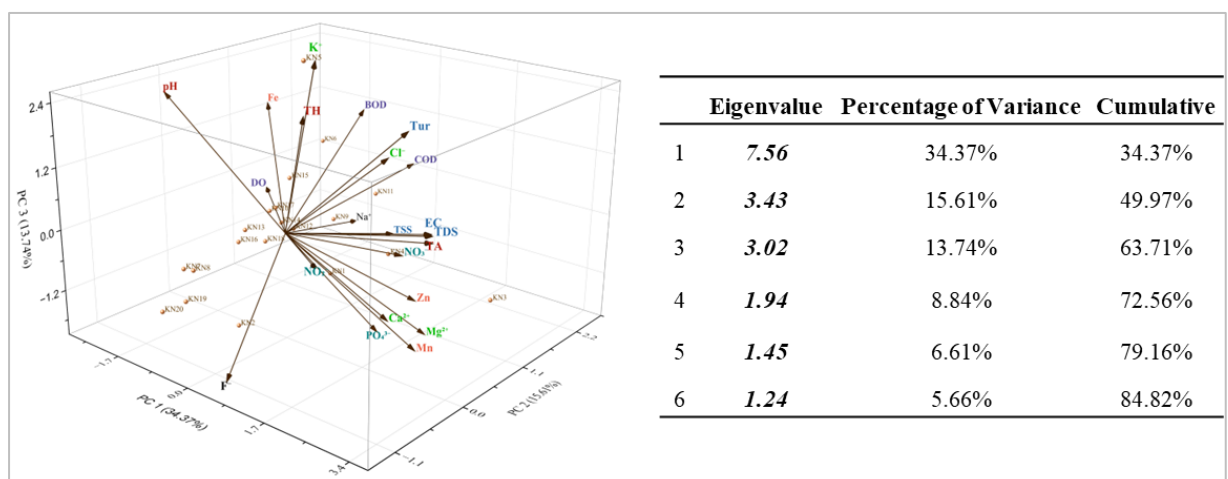


Figure 4.12 PCA biplot and variance contribution of principal components for the Kahn River within the city boundary

The strong alignment of these parameters indicates a common pollution source, most likely untreated municipal discharge. PC2 is influenced by turbidity, suspended solids, and certain metals such as Fe and Mn, indicating particulate-bound transport mechanisms. Dissolved oxygen loads in the opposite direction of BOD and COD, showing a strong negative association and confirming oxygen depletion under high organic load. Compared to monsoon conditions, the urban stretch PCA displays sharper grouping of sewage-related parameters, reflecting concentrated discharge under reduced dilution.

Sirpur Wetland

For Sirpur Lake (Figure 4.13), the scree plot indicates that the first three components explain most of the variance, reflecting slightly more complex internal interactions compared to the river. PC1 is strongly influenced by EC, TDS, sodium, and other dissolved ions, indicating ionic concentration and evaporation-related accumulation in stagnant zones. PC2 shows an association with BOD and COD, representing organic load variation within the lake. PC3 is influenced by selected metals such as Fe and Zn, suggesting sediment–metal interaction processes. Unlike the river system, DO shows little opposition to organic parameters, indicating relatively stable oxygen dynamics in the wetland environment. Sampling locations appear more clustered, reflecting lower spatial variability compared to the river.

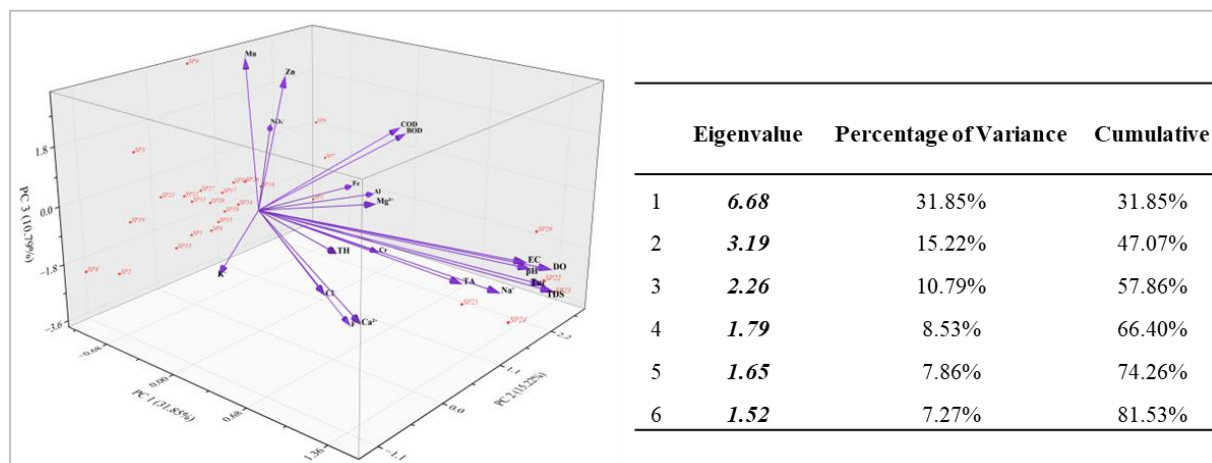


Figure 4.13 PCA biplot and variance contribution of principal components for the Sirpur Wetland

4.2.3 Concluding Remark

The physicochemical and statistical analyses revealed severe deterioration in water quality across the Kahn River system, particularly within the urban stretch influenced by sewage discharge, industrial activities, and urban runoff. Several parameters, including BOD, COD, nutrients, TSS, and heavy metals, exceeded permissible limits, while correlation analysis and

PCA indicated strong interrelationships among pollution indicators and dominant anthropogenic influence. Owing to the complex variation and multidimensional nature of the dataset, an Entropy Weighted Water Quality Index (EWQI) was further developed to provide an integrated assessment of water suitability for drinking, irrigation, and Aquatic Life.

4.3 Entropy-Based Water Quality Index (EWQI) Assessment

4.3.1 Kahn River Basin

The EWQI was computed for the basin-scale sampling locations in the Kahn River to assess overall water quality under monsoon flow conditions. The entropy method assigns objective weights to individual parameters based on their information contribution, thereby minimizing subjective bias in index formulation. The calculated EWQI values indicate considerable spatial variation along the river stretch. The spatial distribution of EWQI values shows a clear deterioration trend from upstream to midstream urban regions. Upstream locations, although relatively less impacted, still do not meet desirable quality standards, suggesting early anthropogenic influence. The highest EWQI values are observed within the urban core of Indore, where the river receives untreated municipal wastewater and drain discharge. These elevated index values correspond to high BOD, COD, and dissolved solids, and to low dissolved oxygen, as observed in the analytical results. Downstream sites exhibit cumulative effects of pollutant transport, and although slight dilution may occur, the EWQI values remain in poor-quality categories, indicating limited natural recovery as shown in Table 4.4.

Table 4.4 EWQI-based assessment of the Kahn River Basin shows that water quality across most sampling locations is unsuitable for drinking, irrigation, and Aquatic life, with particularly critical conditions observed for aquatic ecosystems.

Location	Drinking	Irrigation	Aquatic Life
KS1	165.81	120.988	1817.41
KS2	135.88	135.784	1826.09
KS3	304.73	146.71	1932.9
KS4	102.4	134.612	1781.31
KS5	174.41	142.842	1773.94
KS6	178.43	187.688	928.79
KS7	163.71	137.066	1900.38
KS8	157.78	122.77	2601.29
KS9	155.66	147.063	2607.24

KS10	165.99	173.43	3405.75
KS11	193.9	129.598	2656.43
KS12	165.65	161.747	1771.2
KS13	154.98	161.907	2642.33
KS14	149.38	118.553	2699.58
KS15	174.2	148.527	1910.82
KS16	173.01	177.926	2611.82
KS17	193.08	191.623	2859.81
KS18	172.14	168.441	1382.05

4.3.2 Kahn Within the city boundary

The EWQI results for the Kahn River within the Indore city boundary indicate severe water-quality degradation across all sampling locations. The index values for drinking and irrigation consistently exceed acceptable limits, while those for Aquatic Life are extremely high, reaching 1241 at KN5, indicating critical ecological stress. Such elevated EWQI values suggest excessive organic loading, nutrient enrichment, and the presence of contaminants due to continuous discharge of untreated sewage, industrial effluents, and urban runoff. The uniformly poor water quality across sites indicates that the river is unsuitable for drinking, irrigation, and especially for sustaining aquatic ecosystems, suggesting a highly polluted, ecologically compromised urban river, as shown in Table 4.5.

Table 4.5 EWQI-based assessment of the Kahn River within the city boundary shows that water quality across most sampling locations is unsuitable for drinking, irrigation, and Aquatic Life, with particularly critical conditions observed for aquatic ecosystems.

Location	Drinking	Irrigation	Aquatic Life
KN1	772	392	2037
KN2	977	341	1719
KN3	1166	760	2462
KN4	633	833	728
KN5	1241	506	2282
KN6	420	119	2058
KN7	1004	719	1852
KN8	594	328	1319

KN9	1057	342	2612
KN10	501	444	1775
KN11	959	479	3104
KN12	1137	790	2211
KN13	945	515	1802
KN14	901	408	2116
KN15	565	224	2645
KN16	359	134	1586
KN17	675	324	2531
KN18	1062	503	2039
KN19	998	585	1743
KN20	1085	403	1884

4.3.3 Sirpur Lake

EWQI assessment of Sirpur Lake indicates noticeable spatial variation in water quality across the monitored locations. While several sites fall within the good to moderate category for drinking and irrigation purposes, certain locations exhibit elevated index values, reflecting localized pollution stress. The results suggest that organic load, nutrient enrichment, and ionic constituents contribute significantly to overall water quality. Although the lake shows relatively better conditions than the Kahn River, the presence of moderate to poor classifications at specific points underscores the need for continuous monitoring and targeted management interventions to prevent further degradation, as shown in Table 4.6.

Table 4.6 Entropy-Based Water Quality Index (EWQI) Assessment of Sirpur Lake for Drinking, Irrigation, and Aquatic Life Suitability.

Location	Drinking	Irrigation	Aquatic Life
SP1	37.91	34.33	77.01
SP2	45.42	32.57	84.7
SP3	33.85	24.94	59.95
SP4	83.36	35.12	57.31
SP5	101.11	48.79	64.01
SP6	137.01	45.8	70.64

SP7	54.12	42.71	59.19
SP8	42.44	44.11	63.08
SP9	33.04	22.29	67.15
SP10	52.88	37.34	64.56
SP11	40.19	32.03	62.52
SP12	34.41	31.73	66.57
SP13	49.99	31.06	81.5
SP14	50.15	29.63	86.77
SP15	46.87	43.83	59.7
SP16	54.48	25.78	67.78
SP17	46.65	35.67	61.52
SP18	51.15	42.89	67.27
SP19	37.07	36.42	50.9
SP20	53.02	32.02	67.79
SP21	42.24	32.27	59.51
SP22	93.24	37.43	116.17
SP23	70.19	44.07	114.77
SP24	83.81	39.99	116.01
SP25	83.01	40.82	108.1
SP26	21.57	34.3	66.37
SP27	34.26	35.39	62.84
SP28	32.46	43.23	106.88

4.3.4 Concluding Remark

The EWQI assessment further confirmed the severe deterioration of water quality across the Kahn River system, with most sampling locations categorized as unsuitable for drinking, irrigation, and Aquatic Life. The index effectively integrated the complex physicochemical dataset into a single representative value, clearly highlighting the cumulative impact of urban sewage discharge, industrial effluents, and anthropogenic disturbances on river health. Since conventional pollutants alone could not fully explain the extent of environmental degradation observed during field investigations, the study was further extended to assess emerging pollutants, particularly microplastics, to understand their abundance, characteristics, and possible interactions with water quality deterioration in the aquatic system.

4.4 Microplastics Analysis- Kahn River

4.4.1 Abundance distribution of MPs

The abundance of microplastics in Kahn River water ranged from 4 to 87 particles/L, with an average of 23.8 ± 21 particles/L (Figure 4.14). Approximately 3 ± 1 particles/L were detected in procedural blanks, and these values have been accounted for in the reported results. Reported MP Concentration matches the research on the Ganga River and its tributaries in Varanasi, India, which reported 12–34 MPs/L (pre-monsoon) and 28–58 MPs/L (post-monsoon) in water samples (Singh et al., 2024), 1.30–14.38 items/L (water) MPs found as mentioned in the Ganga River Basin study (Chaudhary et al., 2026). The spatial distribution of MPs along the river stretch highlights a strong influence of anthropogenic activities on their abundance. The river flows through slums, urban areas, and industrial areas. Most river stretches experience intense anthropogenic activities, direct sewage discharge from households and industries, and waste discharge from religious sites.

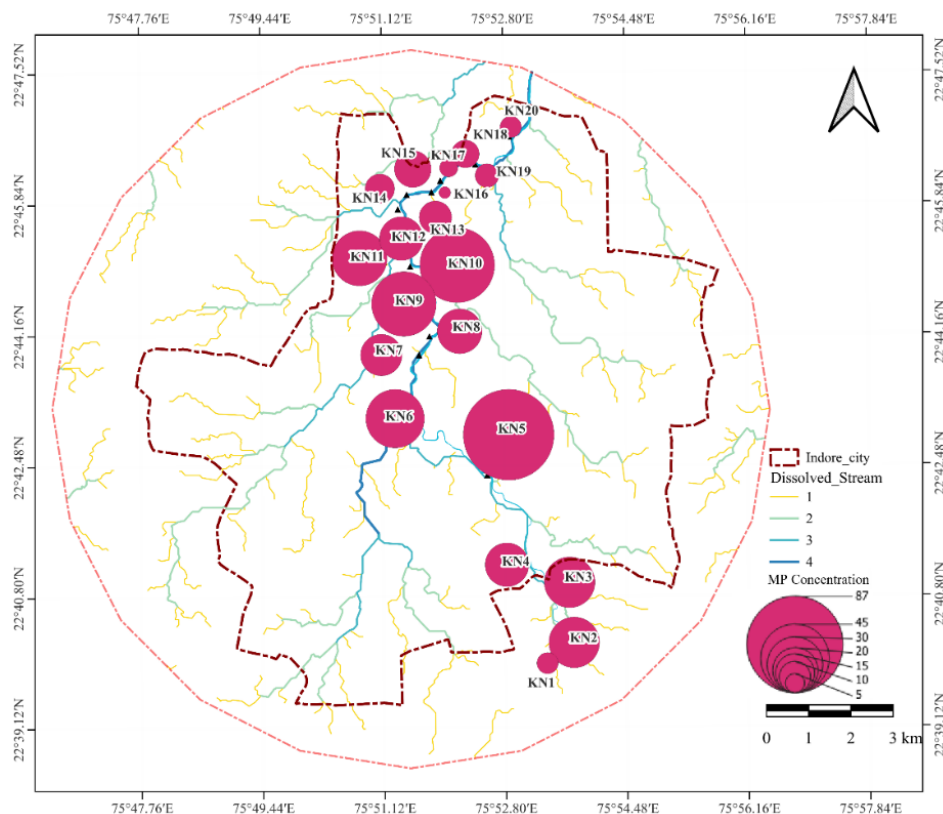


Figure 4.14 Distribution of microplastic concentrations in the Kahn River system, Indore, highlighting spatial heterogeneity across urban-influenced sampling locations. Proportional circles indicate MP abundance (particles/L).

However, the significant content of MPs found at its origin point (KN1) is dominated by rural areas, institutional, and religious places, contributing to MP contamination in the Kahn

River. A gradual increase in MP load was observed from upstream regions characterized by village clusters (KN2 & KN3), slum settlements (KN4), and emerging urban interfaces towards densely urbanized (KN5– KN10) and industrial areas, where the highest concentrations were recorded. These zones experience intense human activity, including improper waste disposal, industrial effluents, and frequent public interaction near road crossings, runoff, mixing of other pollutants, all of which contribute significantly to microplastic inputs. Visuals captured during the reconnaissance survey (Fig. 1) indicate improper waste management in rural and slum areas, and inadequate wastewater management further accelerates microplastic contamination. In contrast, comparatively lower MP abundance at certain downstream locations may be associated with reduced direct human interference and the predominance of agricultural land use.

4.4.2 Morphological Characterization of Microplastics

There were three dominant microplastic forms of fiber, fragment, and film found in the microplastic morphological analysis from all 20 sampled sites. A total of 475 microplastics ($> 200 \mu\text{m}$) were found per liter of water sample. Fibers were the most abundant, accounting for 247 particles/L (52.0%) across all sampling locations.

This dominance of fibers is clearly reflected in the Sankey diagram (Fig. 4.16), where fibers consistently constitute the dominant fraction across all river segments, indicating a continuous, system-wide input source rather than localized contributions. Such fiber predominance is widely recognized as a signature of domestic wastewater contamination, particularly from laundry effluents, where synthetic textiles (e.g., polyester, nylon, acrylic) release large quantities of microfibers during washing (Ramasamy et al., 2022; Xu et al., 2018). These fibers are poorly retained in conventional wastewater treatment systems and are directly transported into river systems through untreated or partially treated sewage discharges. The significantly higher fiber abundance observed at midstream locations, particularly at KN5 (85 ± 2 particles/L), KN6 (37 ± 5 particles/L), and KN3 (28 ± 7 particles/L), corresponds to dense urban settlements and major drain outfalls. Similar fiber-dominated profiles linked to wastewater inputs have been reported in urban river systems such as the Nanming River (Peng et al., 2023), Qing River (Wei et al., 2022), and Houjin River (Huang et al., 2023), reinforcing the role of textile-derived microplastics as tracers of sewage pollution.

In contrast, the increased proportion of fragments in urban stretches, as observed in Figure 4.16, indicates secondary microplastic formation through fragmentation of larger plastic debris, driven by mechanical abrasion, UV-induced degradation, and hydrodynamic shear (Liu et al., 2024; Mandal et al., 2025). The relatively low abundance of films suggests either limited direct

input of plastic bags or their rapid transformation into smaller particles under environmental stress (Bajt, 2021; S. Singh & Jain, 2026). The spatial trend observed in the Sankey diagram, where fiber dominance persists across all segments while fragment contribution increases in urban reaches (notably around KN5–KN10), highlights the combined influence of continuous wastewater-derived inputs and in-situ degradation processes.

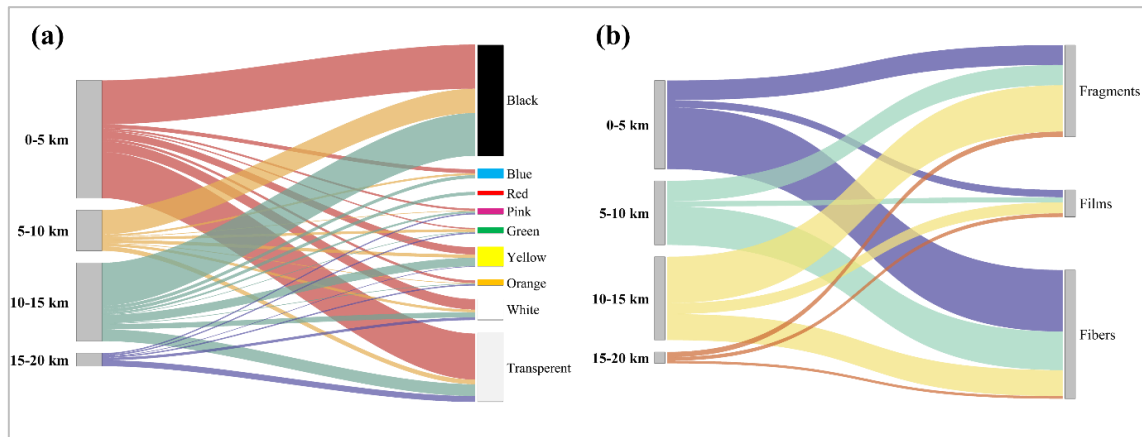


Figure 4.15 Sankey diagrams illustrating the spatial distribution of microplastics along the river stretch. (a) Distribution of microplastic particles by color (black, blue, red, pink, green, yellow, orange, white, and transparent) across different river distances

4.4.3 Morphological and Surface Characterization of Microplastics

The representative particles identified by stereomicroscopy (Figure 4.16) exhibit significant variability in color, shape, and morphology, including fibers, corner fragments, and thin films.

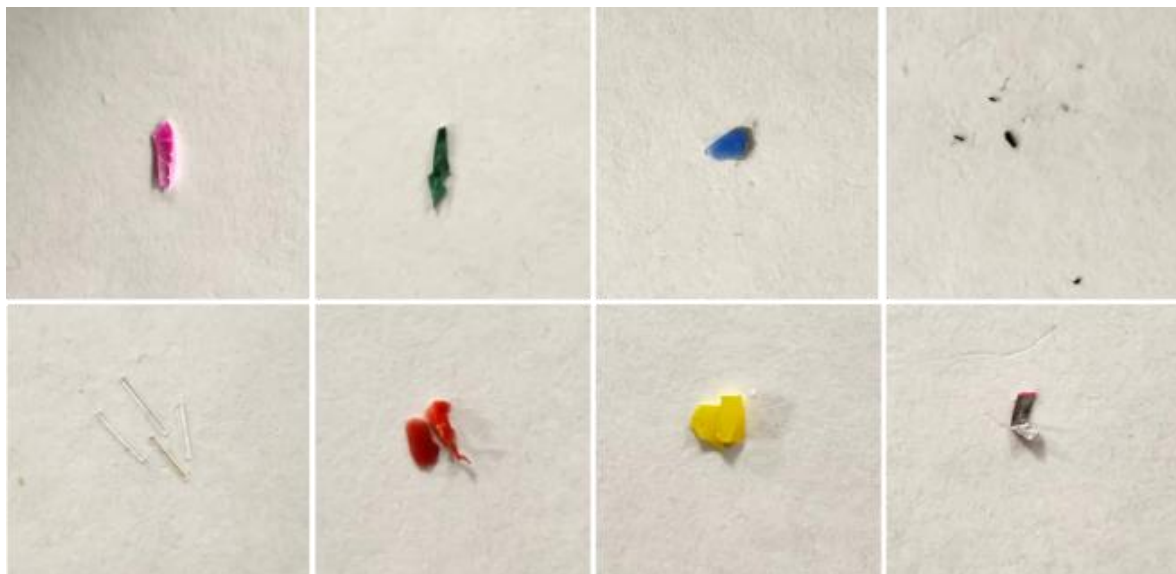


Figure 4.16 Representative microplastic particles isolated from samples showing variations in color, shape, and morphology.

While some particles have irregular shapes with sharp edges and irregular surfaces, others are clear fragments, indicating they come from different sources of plastic and have been degraded to varying extents. The large number of irregular and broken particles indicates that they are secondary microplastics.

SEM analysis of the isolated small microplastic particles (<500µm) shown in Figure 4.17 reveals irregularly shaped fragments and fine fibers with rough, uneven surfaces and fractured edges, reflecting advanced stages of environmental degradation. Many particles exhibit micro-scale cracks, peeling, and granular patterns, revealing mechanical degradation of larger plastics into smaller particles during river transport. The smaller particle size and higher surface roughness increase the likelihood of interaction with suspended contaminants and microorganisms, suggesting that these weathered microplastics can serve as efficient carriers of pollutants in the river system.

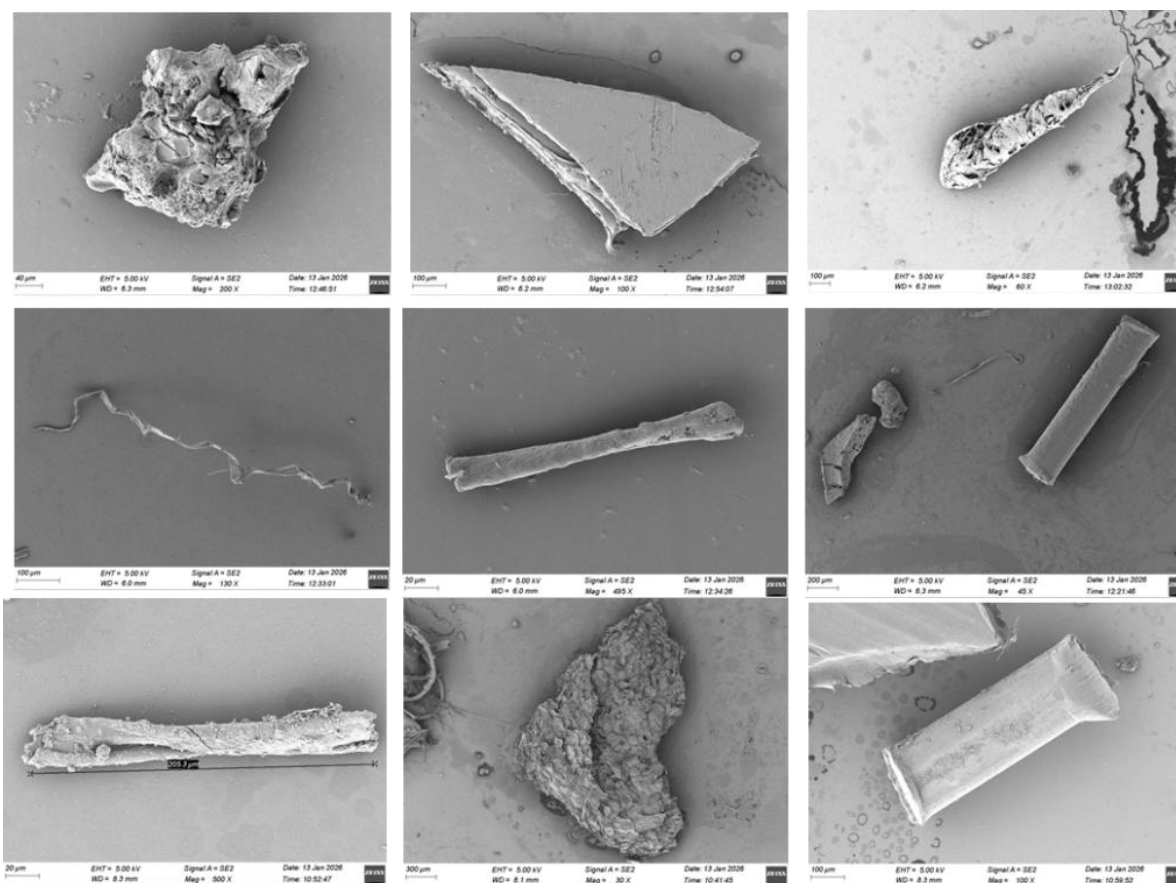


Figure 4.17 SEM images of microplastic particles showing diverse morphologies and surface textures, including fragments and fibers, at different magnifications.

4.4.4 Polymer composition of Microplastics

To identify the polymer types of recovered microplastic particles, samples were analyzed by ATR-FTIR spectroscopy, and the resulting spectra were compared with standard reference

libraries to confirm polymer identity. The spectra exhibited well-defined absorption bands corresponding to characteristic functional groups, enabling reliable identification of polymer composition.

FTIR analysis revealed a diverse range of polymers in microplastic particles collected from the Kahn River, indicating multiple anthropogenic sources within the urban catchment. Identified polymers included polypropylene (PP), Polyethylene (PE), polydimethylsiloxane (PDMS), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polycarbonate (PC), styrene-ethylene/butylene-styrene (SEBS), styrene-butadiene rubber (SBR), polyalphaolefin (PAO), and polystyrene (PS).

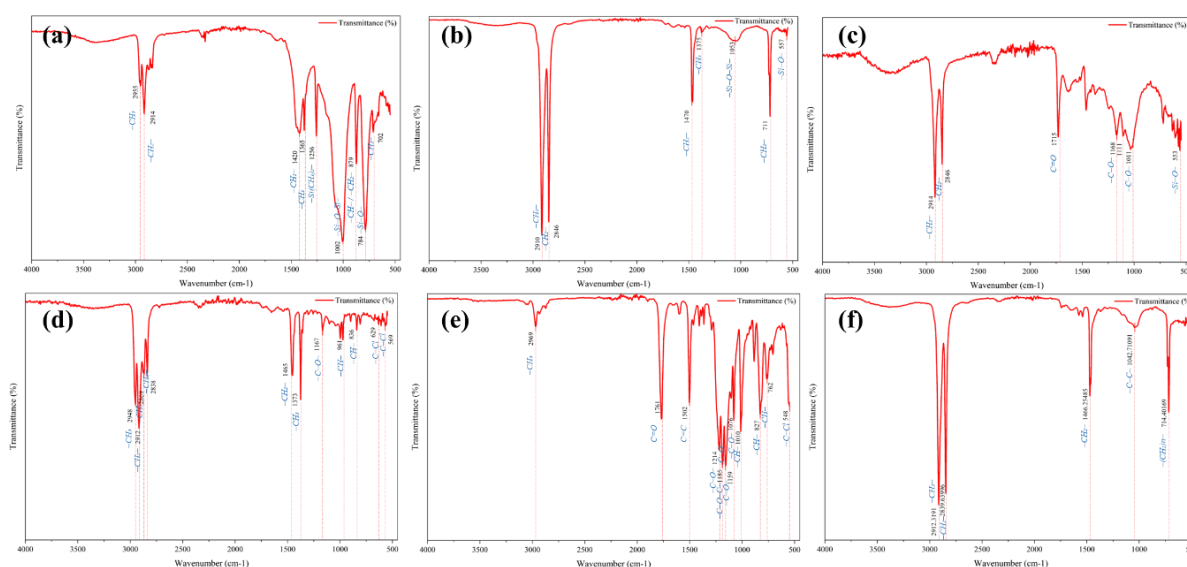


Figure 4.18 FTIR spectra of representative particles (a) Polydimethylsiloxane (PDMS), (b) Polyethylene (PE), (c) High-density polyethylene (HDPE), (d) Polypropylene (PP), (e) Polycarbonate (PC), and (f) Low-density polyethylene (LDPE).

Among the detected polymers, polypropylene (PP) was the most abundant (42.9%), followed by polyethylene (PE) and PDMS (20.4% each). LDPE accounted for 4.1%, while HDPE, PC, SEBS, SBR, PAO, and PS each accounted for about 2% of the total identified particles. The predominance of PP and PE suggests that polyolefin-based plastics are the major consumers of plastics, accounting for the majority of the microplastic load in the river system, in line with work in other urban freshwater systems. Similar types of polymers were identified in the WangYu River network in China, and the Yangtze River in China by Fan et al. 2022, 2025).

Polymer identification was supported by characteristic infrared absorption bands. Polyolefin polymers such as PP and PE showed strong C–H stretching vibrations near 2915–

2848 cm^{-1} , along with CH_2 bending vibrations around 1460–1375 cm^{-1} and characteristic rocking modes near 720 cm^{-1} , confirming the presence of polyethylene and polypropylene structures. PDMS particles displayed prominent Si–O–Si stretching bands between 1000–1100 cm^{-1} , indicative of silicone-based materials. Polycarbonate particles exhibited distinct carbonyl ($\text{C}=\text{O}$) stretching peaks near 1770 cm^{-1} , while polystyrene particles showed aromatic C–H bending features typical of styrenic polymers. These functional group signatures of particles closely matched reference spectra, confirming polymer identification as shown in Figure 4.18.

The occurrence of PP and PE can be linked to their lower densities relative to water, which enable them to suspend and float, thereby facilitating long-distance transport. These two polymers have been widely used in packaging materials, carry bags, and household items, and are usually discharged into water bodies due to inadequate waste and wastewater management. The influence of environmental, mechanical, and hydrodynamic forces further degrades these materials into secondary microplastics. The coexistence of LDPE and HDPE fragments implies the use of plastic films and rigid consumer and infrastructure products, such as containers and pipes. The application of PDMS implies PDMS-based sealant, personal care products, and construction materials. On the other hand, the use of PC, SEBS, and SBR implies the use of engineering plastics, automotive materials, road dust, and industrial materials. The employment of PAO suggests the use of synthetic lubricants, and the presence of PS fragments suggests the use of disposable packaging and foam products.

4.4.5 Concluding Remark

The microplastic analysis confirmed the widespread presence of MPs across the Kahn River, with fibers and fragments identified as the dominant forms, reflecting strong anthropogenic influence and urban pollution inputs. Polymer characterization further indicated the persistence of plastic-derived contaminants within the aquatic environment. The observed relationship between microplastic abundance and water quality parameters suggested that surrounding land-use patterns and urban landscape structure significantly influence pollutant distribution. Therefore, further analysis was carried out to evaluate the impact of LULC dynamics and landscape fragmentation on physicochemical and microplastic contamination.

4.5 LULC-Based Spatial Analysis

4.5.1 Land Use Land Cover (LULC) Dynamics

The spatio-temporal LULC analysis (1989–2024) reveals substantial landscape transformation driven by rapid urbanization. Supervised classification of Landsat imagery,

validated through accuracy assessment (overall accuracy >85%), provided a reliable basis for evaluating long-term land-use dynamics and their environmental implications.

Kahn River Basin

The LULC maps of the Kahn River Basin from 1999 to 2024 reveal significant land transformation, as shown in Figure 4.19, driven by urbanization and anthropogenic pressures. Over time, there is a noticeable increase in settlement areas (Table 4.7), particularly in the downstream and central regions, accompanied by a decline in dense vegetation and agricultural land. The expansion of urban areas and the conversion of barren land indicate intensified human activity, which likely contributes to increased surface runoff, increased pollutant loading, and ecological degradation. These spatio-temporal changes highlight the strong linkage between land-use dynamics and the deteriorating water quality in the Kahn River Basin.

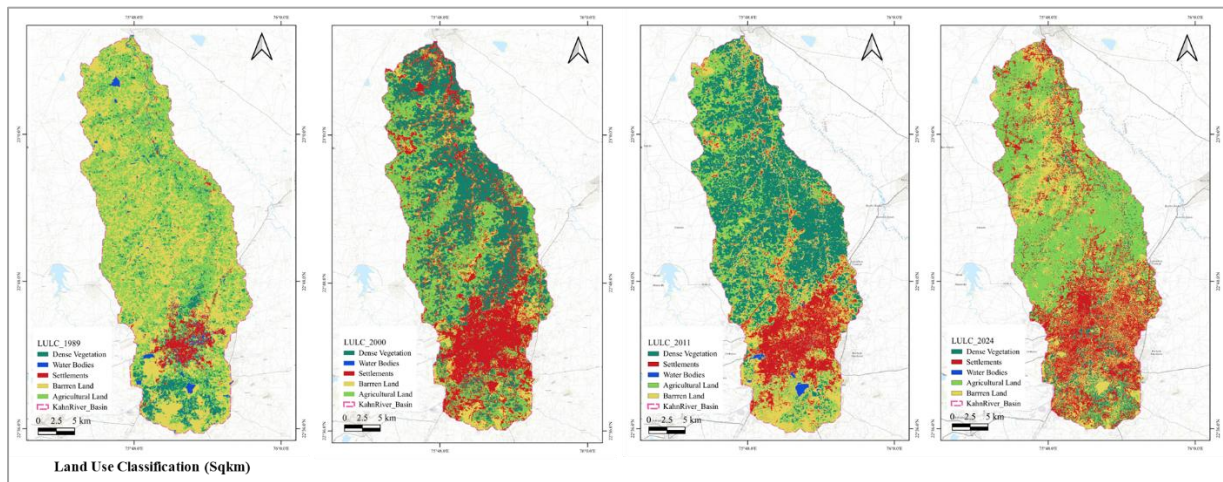


Figure 4.19 Temporal changes in land use and land cover (LULC) of the Kahn River Basin from 1999 to 2020.

Table 4.7 Percentage Distribution of LULC Classes in the Kahn River Basin

Land Use	1989	2000	2010	2024
Settlements	2.16	2.02	2.01	2.01
Dense Vegetation	7.18	24.70	37.31	7.48
Agricultural Land	45.72	28.75	21.05	36.66
Barren Land	40.72	30.34	24.20	29.62
Water Bodies	4.23	14.19	15.43	24.23

Kahn River Within the Indore city boundary

The LULC results indicate a significant expansion of settlement areas from 16.07% in 1989 to 45.01% in 2024 (Table 4.8), reflecting accelerated urban growth and spatial densification. This expansion has occurred primarily at the expense of vegetation and barren land, both of which have shown marked declines, indicating increasing landscape fragmentation and a loss of natural buffering capacity. Agricultural land exhibited moderate fluctuations, highlighting transitional dynamics in peri-urban zones, while water bodies showed a gradual decline, suggesting increasing pressure on surface water resources (Figure 4.20). The Land use transformation represents a shift from a relatively permeable, vegetated system to a highly impervious, anthropogenically dominated urban matrix. Such changes are known to alter hydrological processes by increasing surface runoff, reducing infiltration, and enhancing the connectivity between pollutant sources and river channels. The conversion pathways identified through change detection, particularly vegetation and open land transitioning into built-up areas, highlight the spatial patterns of urban sprawl and their implications for pollutant transport.

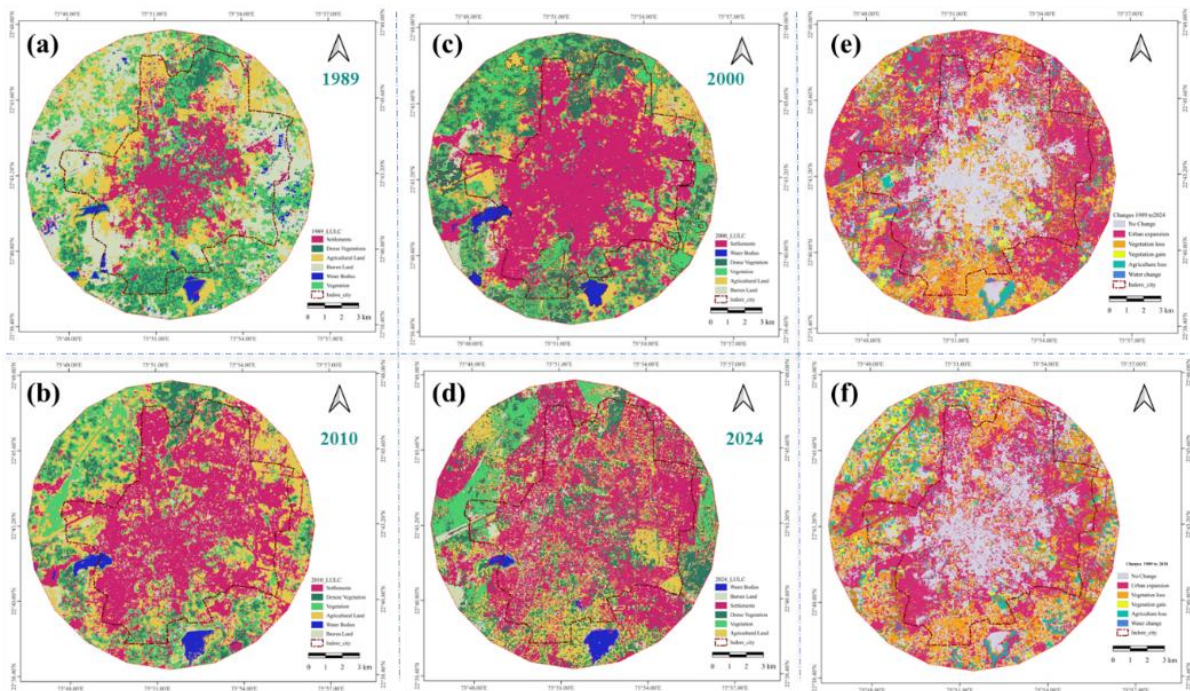


Figure 4.20 Spatio-temporal changes in land use and land cover (LULC) of the Kahn River Basin for the years (a) 1989, (b) 2010, (c) 2000, and (d) 2024, (e) Change Map 1989-2000, and (f) Change Map 2000-2024.

Table 4.8 Percentage Distribution of LULC Classes in the Kahn River within the city boundary

Land Use	1989	2000	2010	2024
Settlements	16.07	33.61	40.81	45.01
Dense Vegetation	31.99	26.32	21.6	18.6
Agricultural Land	24.12	21.32	25.84	23.73
Barren Land	25.59	17.16	10.77	11.54
Water Bodies	2.23	1.59	0.98	1.12

Sirpur Lake

The LULC maps of the Sirpur wetland from 1999 to 2024 indicate progressive land-use transformation around the lake ecosystem (Table 4.9). Over time, there is a clear increase in built-up areas and barren land, accompanied by a reduction in vegetation cover and surrounding natural land uses (Figure 4.21). The expansion of anthropogenic activities in the vicinity of the wetland suggests increasing pressure on the lake system, potentially affecting its hydrological balance and ecological integrity. These changes highlight the growing vulnerability of Sirpur Lake to urban encroachment and emphasize the need for sustainable land management practices to protect the wetland ecosystem.

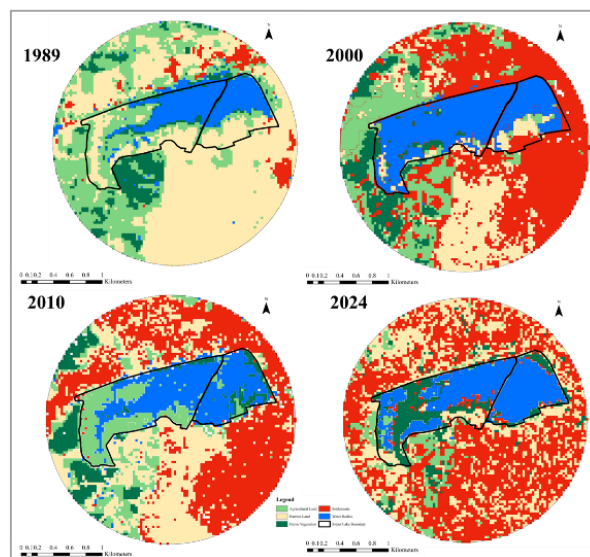


Figure 4.21 Temporal changes in land use and land cover (LULC) of the Sirpur Wetland from 1999 to 2020.

Table 4.9 Percentage Distribution of LULC Classes in the Sirpur Wetland

Land Use	1989	2000	2010	2024
Settlements	6.7	10.2	16.2	32
Dense Vegetation	26.32	23.21	15.32	8.98
Agricultural Land	17.56	18.2	19.09	12.3
Barren Land	6.22	7.23	11.2	5.4
Water Bodies	43.2	41.2	38.19	41.32

4.5.2 Impact of LULC on Water Quality (ANOVA Results)

Spatial Distribution of LULC Within the 500m Buffer Zone-Kahn River within the city boundary

Along the river, the marked sampling locations (Table 3.3) were analyzed using a 500 m buffer to assess the surrounding LULC distribution. Figure 4.22 indicates a clear dominance of settlement areas across most sites, particularly in the upstream and central stretches, reflecting strong urban influence. Agricultural land is more prevalent in downstream locations, while vegetation and dense vegetation are relatively limited and fragmented. The reduced presence of natural land cover and water bodies highlights significant landscape modification due to urban expansion.

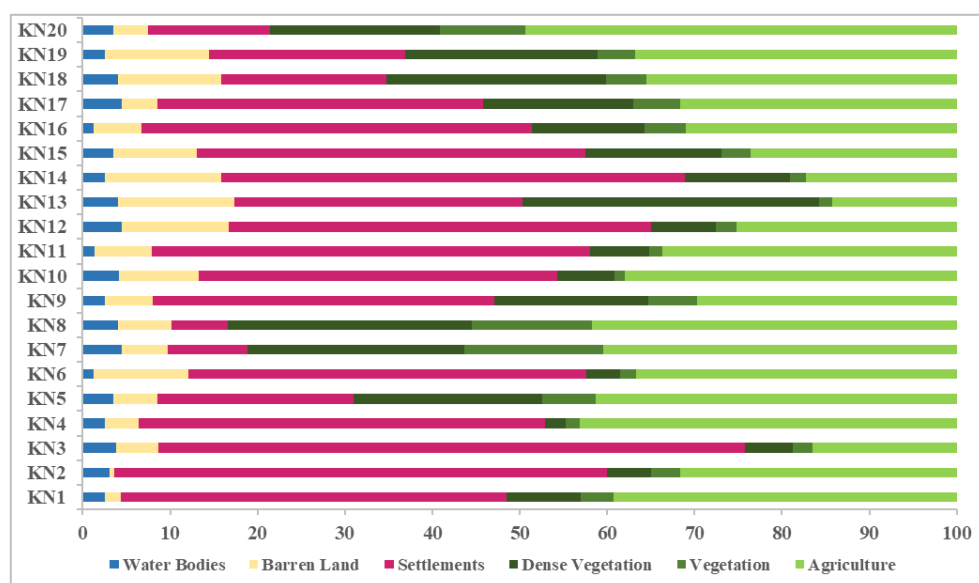


Figure 4.22 Percentage distribution of land use and land cover (LULC) classes within a 500 m buffer in Kahn River (KN1-KN20).

The one-way ANOVA was used to confirm that land use exerts a selective, statistically significant influence on specific water quality parameters (Figure 4.24), highlighting the role of surrounding landscape characteristics in governing river chemistry.

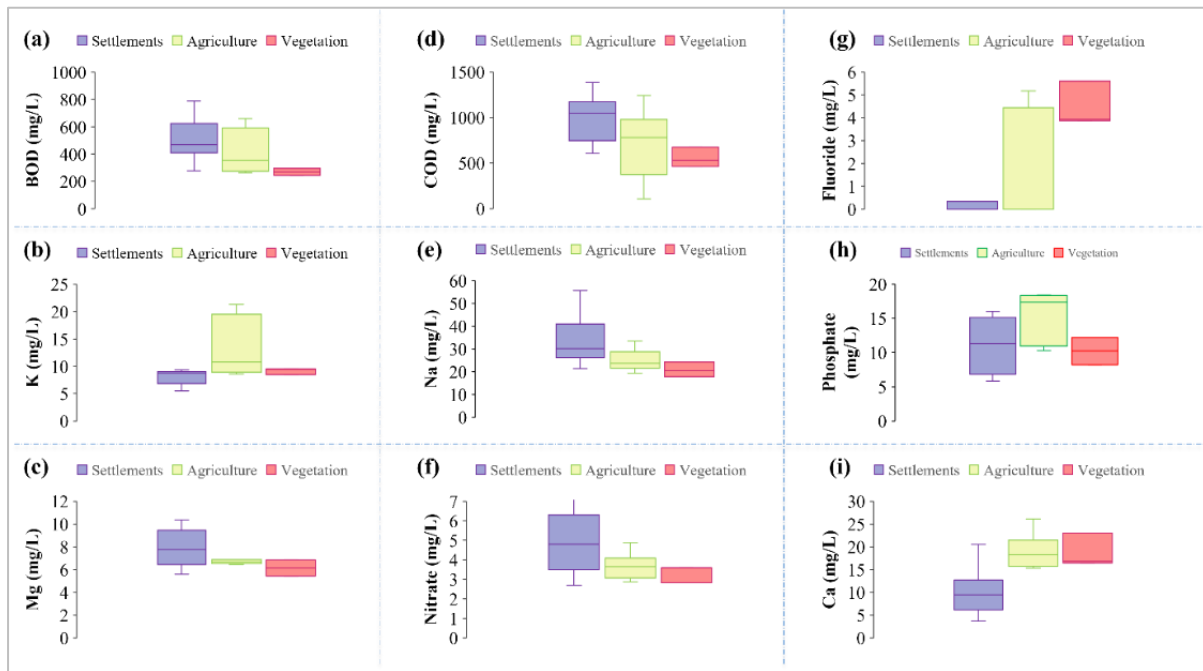


Figure 4.23 Water quality parameters across different land-use classes (settlements, agriculture, and vegetation): (a) BOD, (b) K, (c) Mg, (d) COD, (e) Na, (f) nitrate, (g) fluoride, (h) phosphate, and (i) Ca.

At a significance level of $p < 0.05$, parameters such as COD ($F = 4.29$, $p = 0.0309$), fluoride ($F = 4.22$, $p = 0.0324$), calcium ($F = 10.63$, $p = 0.0010$), potassium ($F = 5.17$, $p = 0.0176$), and phosphate ($F = 3.87$, $p = 0.0412$) showed significant variation across LULC classes as mentioned in Table 4.10. Among these, Ca exhibited the strongest dependence on land use, indicating the influence of soil composition and agricultural inputs. Elevated COD levels in settlement-dominated areas highlight the concentration of organic pollution within dense urban landscapes, where inadequate wastewater management and high impervious surface connectivity facilitate direct discharge of pollutants into the river system. In contrast, higher concentrations of potassium and phosphate in agricultural regions reflect the influence of fertilizer-driven nutrient loading, characteristic of diffuse, non-point source pollution processes. The strong dependence of calcium on land use further indicates the combined influence of soil characteristics and land management practices across different landscape types.

Table 4.10 Land-use-wise distribution of physicochemical parameters and corresponding one-way ANOVA statistics (F and p-values).

Parameters	LULC Classification			ANOVA Results	
	Settlements	Agriculture	Vegetation	F	p value
TA (mg/L)	1387.76	1416.50	1312.26	0.380698	0.689066
TH (mg/L)	482.04	544.36	541.63	0.760772	0.482569
Chloride (mg/L)	136.35	132.44	166.53	1.045422	0.377437
BOD (mg/L)	502.04	379.37	310.87	2.92695	0.080845
COD (mg/L)	1013.13	711.11	557.04	4.294782	0.030923
DO (mg/L)	0.40	0.73	0.36	1.42145	0.268641
Fluoride (mg/L)	0.81	1.56	4.47	4.223783	0.032421
pH	6.29	6.36	6.33	0.405436	0.672964
TDS (mg/L)	506.97	517.78	488.89	0.173213	0.842424
TSS (mg/L)	6.02	2.59	1.37	2.576524	0.105349
EC	952.12	977.78	916.67	0.222451	0.802848
Ca (mg/L)	9.82	18.97	18.76	10.62591	0.001015
K (mg/L)	8.01	13.21	9.14	5.174877	0.017568
Na (mg/L)	29.98	21.63	20.84	3.323598	0.060491
phosphate (mg/L)	10.76	13.82	10.19	3.869553	0.041215
Nitrite (mg/L)	6.73	7.78	11.67	0.648364	0.535355
Nitrate (mg/L)	6.73	4.00	2.68	3.070593	0.072701
Tur (NTU)	73.33	38.89	68.33	1.074883	0.363435
Fe (mg/L)	0.10	0.10	0.09	0.245252	0.785229
Mg (mg/L)	7.85	6.74	6.14	2.721218	0.094345
Mn (mg/L)	0.07	0.06	0.06	0.732956	0.495067
Zn (mg/L)	0.05	0.02	0.01	1.004048	0.387113

Spatial Distribution of LULC Within the 500m Buffer Zone-Sirpur Wetland

Along the wetland, the marked sampling locations (Table 3.4) were analyzed using a 500 m buffer to assess the surrounding LULC distribution. Figure 4.24 shows a clear dominance of settlement over vegetation. Agricultural land is more prevalent in the outskirts sampling location.

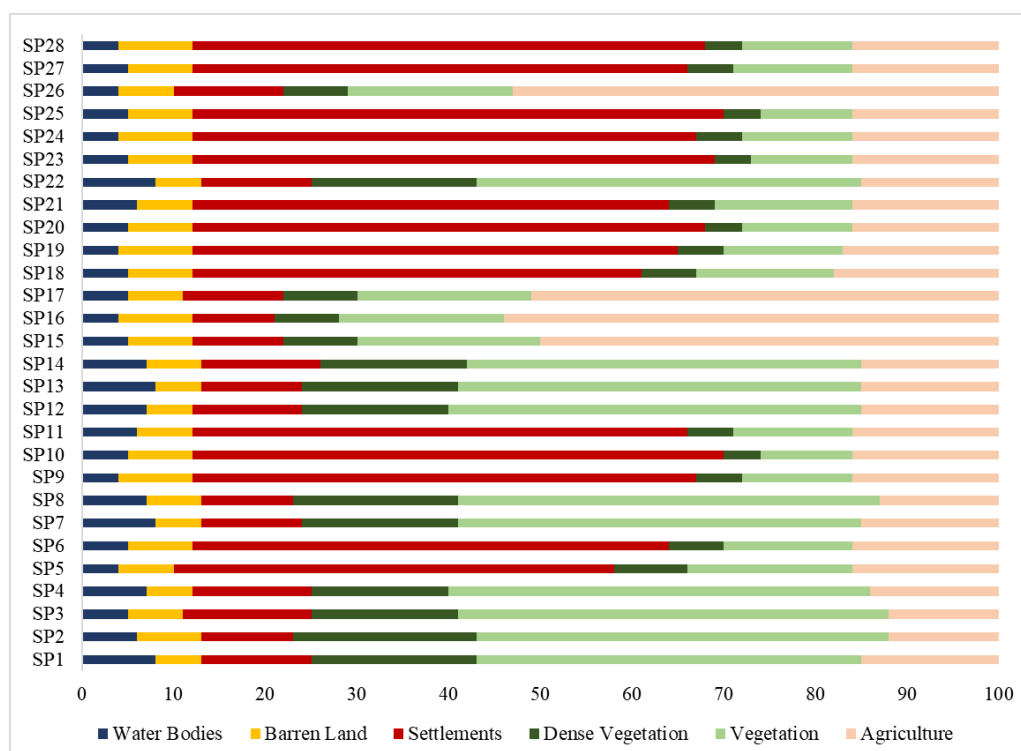


Figure 4.24 Percentage distribution of land use and land cover (LULC) classes within a 500 m buffer in Sirpur Wetland (SP1-SP28).

The boxplot analysis (Figure 4.25) illustrates the variation of key physicochemical parameters across different land-use classes in Sirpur Lake, highlighting the influence of surrounding LULC on water quality.

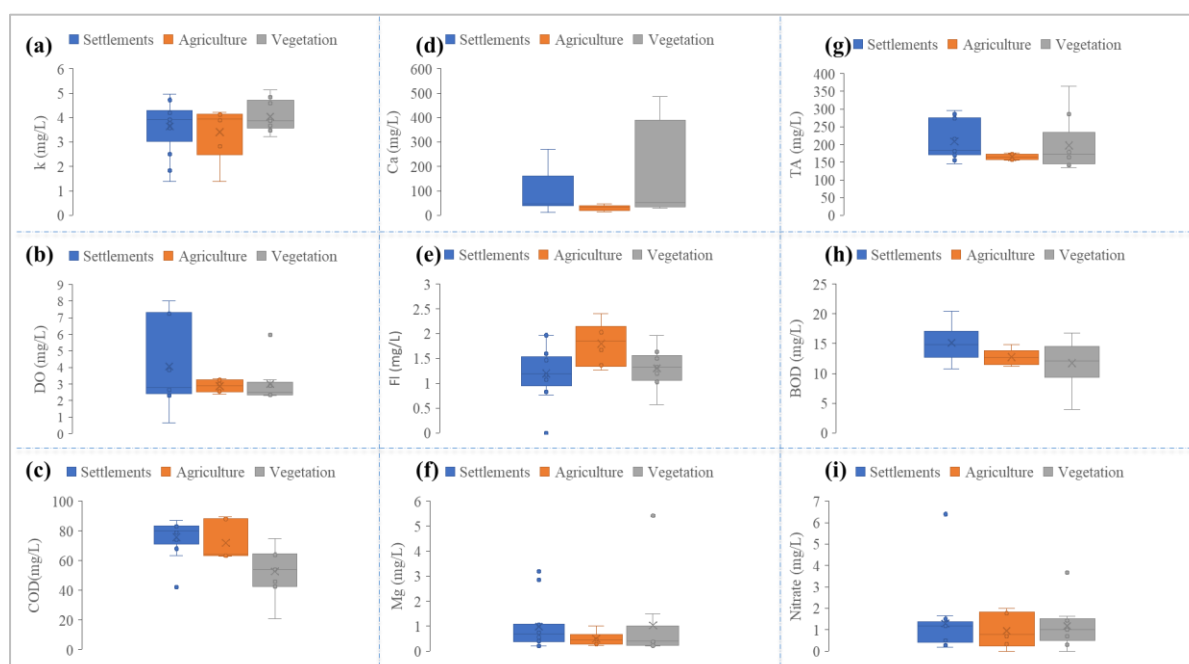


Figure 4.25 Water quality parameters across different land-use classes (settlements, agriculture, and vegetation).

Most of the parameters, such as TA, TH, chloride, pH, TDS, EC, major ions (Na, K, Mg), nitrate, turbidity, and heavy metals, show no statistically significant variation among land-use classes ($p > 0.05$) as shown in Table 4.9, indicating relatively uniform background geochemical conditions across the lake. However, selected parameters, particularly BOD ($F = 0.042$), COD ($F = 0.002$), and fluoride ($F = 0.045$), exhibit statistically significant differences, suggesting localized anthropogenic impacts. Higher BOD and COD concentrations in settlement areas (15.16 mg/L and 75.86 mg/L, respectively) indicate increased organic pollution from domestic wastewater inflows, whereas comparatively lower values in vegetation zones reflect reduced human interference and stronger ecological buffering. Fluoride levels are elevated in agricultural areas (1.80 mg/L), likely linked to fertilizer inputs and soil leaching. The boxplots further reveal greater variability in parameters such as Ca, TA, and DO in settlement-dominated regions, indicating heterogeneous pollution sources and fluctuating inputs. Despite these variations, DO levels remain moderate across all classes, suggesting a partial self-purification capacity of the wetland, as shown in Table 4.11.

Table 4.11 Land-use-wise distribution of physicochemical parameters and corresponding one-way ANOVA statistics (F and p-values), indicating significant variation ($p < 0.05$) in COD, fluoride, DO, BOD, etc. across LULC classes.

	LULC Classification			ANOVA Results	
	Settlements	Agriculture	Vegetation	F	p value
TA (mg/L)	209.20	165.17	197.33	0.315902	3.38519
TH (mg/L)	217.56	204.06	243.15	0.445452	3.38519
Chloride (mg/L)	15.64	14.73	17.56	0.742065	3.38519
BOD (mg/L)	15.16	12.73	11.73	0.042351	3.38519
COD (mg/L)	75.86	72.04	52.72	0.00229	3.38519
DO (mg/L)	4.05	2.88	3.00	0.309813	3.38519
Fluoride (mg/L)	1.20	1.80	1.30	0.045174	3.38519
pH	7.22	7.03	7.13	0.347171	3.38519
TDS (mg/L)	303.03	246.17	269.89	0.224584	3.38519
EC	545.31	467.17	508.07	0.412369	3.38519
Ca (mg/L)	110.66	31.21	198.60	0.102859	3.38519
K (mg/L)	3.65	3.42	4.04	0.449942	3.38519
Na (mg/L)	30.42	21.39	27.77	0.473691	3.38519
Nitrate (mg/L)	1.29	0.95	1.18	0.87167	3.38519

Tur (NTU)	8.75	3.94	4.13	0.20129	3.38519
Al (mg/L)	0.06	0.06	0.09	0.349626	3.38519
Cr (mg/L)	0.36	0.41	0.31	0.439837	3.38519
Fe (mg/L)	0.00	0.01	0.00	0.906619	3.402826
Mg (mg/L)	0.98	0.50	1.04	0.650005	3.38519
Mn (mg/L)	15.54	14.18	12.32	0.095563	3.38519
Zn (mg/L)	0.01	0.01	0.01	0.667518	3.38519

4.5.3 Microplastic Distribution across Land Use

A distinct gradient in microplastic abundance at different locations (Figure 4.26) was observed across different land-use settings. Settlement-dominated areas showed the highest concentrations and variability of MPs, indicating that urban landscapes function as primary sources and conduits for plastic debris.

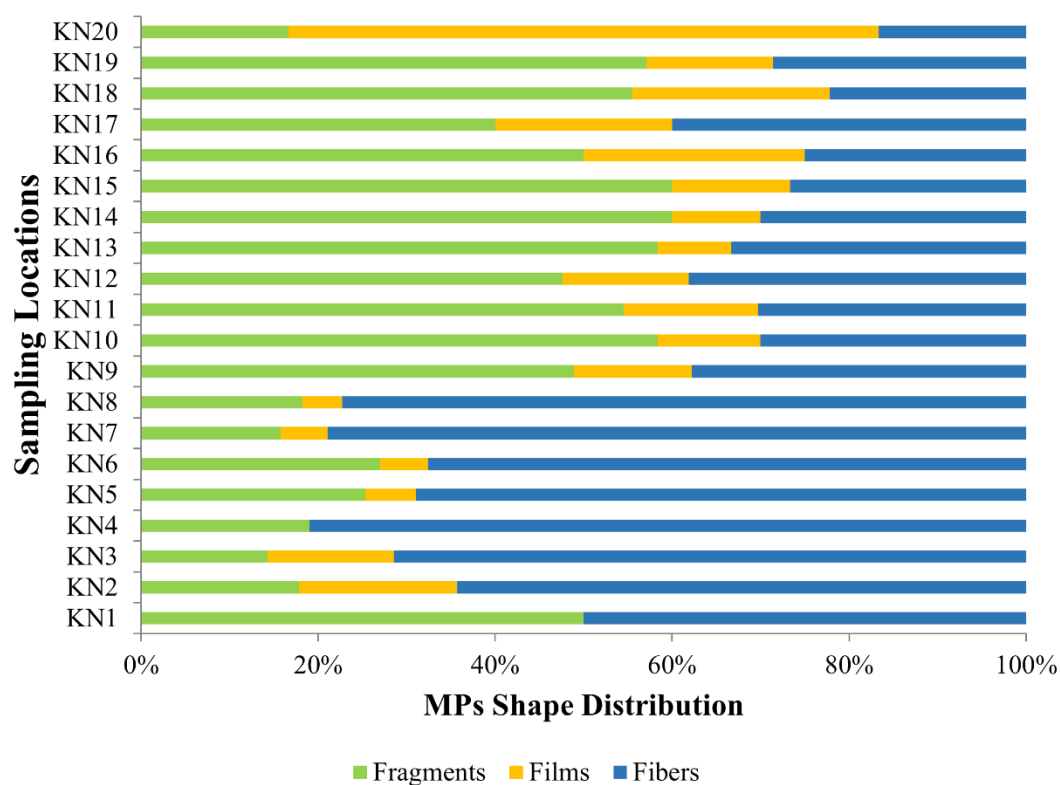


Figure 4.26 Percentage distribution of Microplastics type in Kahn River (KN1-KN20).

In such environments, high population density, inadequate solid waste management, and extensive drainage connectivity contribute to the continuous leakage and transport of microplastics into river systems. Rather than being isolated point sources, these inputs reflect systemic inefficiencies in urban material management and infrastructure design. In contrast,

agricultural regions exhibited moderate levels of microplastics, likely associated with the use of plastic-based agricultural inputs. Vegetation-dominated areas, on the other hand, showed comparatively lower microplastic abundance, suggesting reduced anthropogenic input intensity and the potential role of natural landscape elements in attenuating particulate transport. (Figure 4.27).

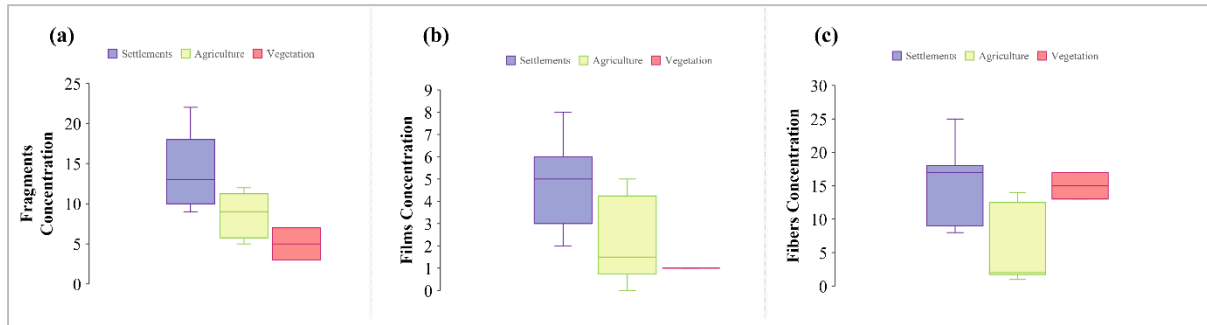


Figure 4.27 Distribution of microplastic types across different land-use categories.

The spatial distribution highlights how landscape configuration, particularly the interactions among built-up areas, drainage networks, and open spaces, controls the movement and accumulation of pollutants derived from solid waste. Unlike conventional dissolved pollutants, microplastics are closely linked to surface processes, underscoring the roles of urban design, waste-handling practices, and landscape connectivity in governing their transport. Table 4.12 illustrates the relationship between land-use classes and microplastic distribution, showing significant variation across settlements, agriculture, and vegetation. ANOVA results confirm that fibers ($p = 0.008$), films ($p = 0.010$), and fragments ($p = 0.018$) differ significantly with land use ($p < 0.05$). Vegetated areas exhibit the highest concentrations of films (14.00) and fragments (12.00), indicating their role as accumulation zones. Fibers are prominent in both vegetation (11.55) and settlements (11.27), likely due to atmospheric deposition and urban discharge. In contrast, agricultural areas show the lowest concentrations across all types, suggesting limited direct inputs.

Table 4.12 One-way ANOVA results for microplastic types across land-use classes.

Parameters	LULC Classification			ANOVA Results	
	Settlements	Agriculture	Vegetation	P value	F
Fibers	11.27	3.27	11.55	0.008133	3.591531
Films	6.33	2.17	14.00	0.010669	3.591531
Fragments	4.67	1.00	12.00	0.018475	3.591531

4.5.4 Microplastics - Water Quality Relationship

To examine whether microplastics follow the same environmental controls as conventional water quality parameters, the relationships between microplastics and derived parameters from ANOVA Results were evaluated using linear regression. (Barrows et al., 2018; Gonzalez-Saldias et al., 2024). The results indicate consistently weak associations ($R^2 < 0.25$) between microplastic abundance and most water quality parameters, suggesting that microplastics do not conform to the same governing mechanisms as dissolved pollutants. Among the variables, COD exhibited a weak positive relationship ($R^2 \approx 0.22$), while TSS showed a comparatively stronger association ($R^2 \approx 0.39$), indicating partial linkage through particulate transport pathways (Figure 4.28). This weak coupling highlights a fundamental distinction between dissolved and particulate pollution processes within urban river systems. Conventional water quality parameters, such as organic matter and nutrients, are largely governed by wastewater discharge, biochemical transformations, and land-use-driven inputs. In contrast, microplastics are primarily transported as physical particles, influenced by surface runoff, drainage connectivity, and the movement of suspended solids across the urban landscape.

The relatively stronger association with TSS suggests that microplastics are embedded in sediment and that particulate transport dynamics reflect the role of urban surface processes rather than chemical interactions. This indicates that landscape features that control erosion, flow velocity, and sediment mobilization, such as impervious surfaces, channel modification, and the lack of vegetative buffers, play a critical role in microplastic transport and accumulation.

Importantly, the observed decoupling between microplastics and most physicochemical parameters suggests that conventional water quality monitoring frameworks may not adequately capture the risks posed by emerging particulate pollutants. From a planning and management perspective, this highlights a gap in current assessment approaches, which predominantly focus on dissolved contaminants while overlooking material flow pathways linked to urban form and infrastructure.

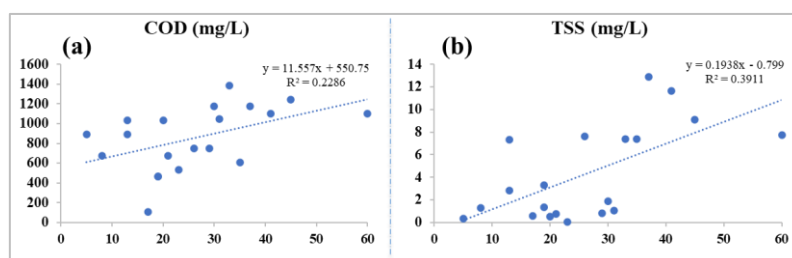


Figure 4.28 Linear regression analysis between microplastic abundance and (a) COD and (b) TSS in the Kahn River.

4.5.5 Landscape Metrics

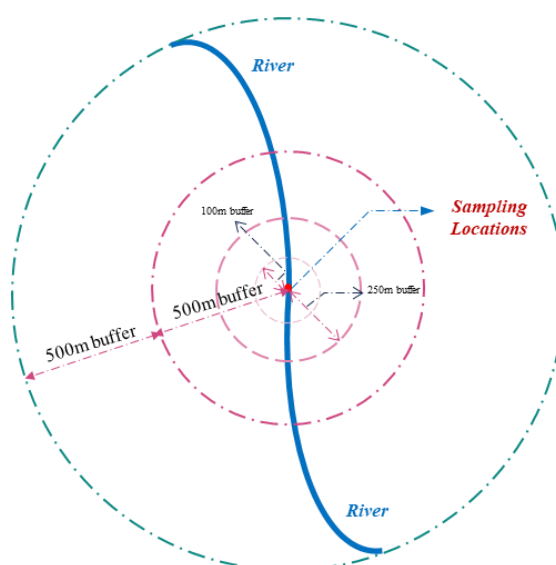


Figure 4.29 Multi-buffer zones around river sampling locations for landscape metric analysis.

Landscape metric analysis within the 500 m and 1000 m buffer zones around the Kahn River sampling locations (Figure 4.29) revealed clear spatial differences in land-use composition, fragmentation, and connectivity. The 500 m buffer showed higher Edge Density (ED) and Patch Density (PD), indicating greater landscape fragmentation and stronger localized urban disturbance near the river corridor, primarily due to the dominance of settlement areas. In contrast, the 1000 m buffer exhibited higher Patch Cohesion Index (PCI) and Shannon Diversity Index (SHDI), suggesting improved landscape connectivity and greater land-use heterogeneity at the broader watershed scale (Table 4.13). The analysis further indicated that fragmented urban landscapes were associated with increased microplastic abundance and altered physicochemical characteristics, highlighting the strong influence of surrounding land-use patterns on river pollution dynamics.

Table 4.13 Comparison of landscape metrics between 500 m and 1000 m buffers.

Metric	500 m Buffer	1000 m Buffer	Interpretation
ED	Higher	Lower	More local fragmentation
PD	Higher	Lower	More complexity near the river
PCI	Lower	Higher	Better regional connectivity
SHDI	Lower	Higher	Greater regional land-use diversity

4.5.6 Correlation analysis between the spatial metrics and Parameters

Correlation analysis between landscape metrics and water quality parameters demonstrated a strong influence of surrounding land-use structure on pollutant distribution within the river system (Table 4.14). ED and PD showed positive correlations with microplastic abundance, suggesting that fragmented, highly urbanized landscapes promote the accumulation and transport of MPs. In contrast, the PCI showed negative correlations with MPs, COD, and TSS, suggesting that well-connected landscapes are associated with relatively lower pollution intensity and improved environmental stability. SHDI exhibited comparatively weaker relationships with most parameters, indicating that landscape diversity alone may not strongly regulate pollution dynamics. Furthermore, stronger correlations observed within the 500 m and 1000 m buffer zones underscore the significant role of local and watershed-scale land-use patterns in driving water-quality deterioration and microplastic contamination.

Table 4.14 Correlation analysis between the spatial pattern metrics of land uses and water quality characteristics at the landscape level

Buffer	Location Buffer	MPs	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	K (mg/L)	phosphate (mg/L)	Nitrate (mg/L)
1000m	ED	0.45441	-0.1438	-0.19469	-0.09986	0.41896	-0.39965	-0.29802
	PD	0.44577	-0.05839	-0.1367	-0.079	0.39282	-0.4393	-0.42085
	PCI	-0.14914	-0.16445	-0.20503	-0.48196	0.25782	0.07303	0.21303
	SHDI	0.14397	-0.16123	-0.31444	-0.41867	0.35165	-0.33438	-0.31369
500m	ED	0.26776	-0.16656	-0.30212	-0.24467	0.2006	-0.57609	-0.38876
	PD	0.33683	-0.1652	-0.34086	-0.16856	0.38841	-0.58557	-0.4295
	PCI	-0.17933	-0.03596	-0.21688	-0.58447	0.41661	0.08765	0.22781
	SHDI	-0.07324	-0.0316	-0.3728	-0.59902	0.33459	-0.41357	-0.23384

4.5.7 Concluding Remark

The LULC analysis revealed a continuous increase in settlement areas, accompanied by a decline in vegetation cover and an increase in landscape fragmentation within the Kahn River Basin. ANOVA results showed significant variation in BOD, COD, nutrients, and microplastic abundance across land-use classes, with urban settlement regions exhibiting higher pollution levels. Furthermore, fragmented landscapes with higher edge and patch density were strongly

associated with deteriorated water quality and increased microplastic contamination, highlighting the dominant influence of urbanization on the aquatic environment.

Chapter 5

Conclusions, Implications, and Future Scope

5.1 Conclusions

This study provided a comprehensive assessment of water quality in two contrasting aquatic systems in Indore: the Kahn River (lotic system) and Sirpur wetland, integrating physicochemical parameters, heavy metals, microplastics, and land-use analysis.

The results clearly demonstrate that the Kahn River is severely impacted by anthropogenic activities, particularly within the urban stretch. Elevated levels of BOD, COD, nutrients, and microbial contamination confirm significant organic pollution from untreated domestic sewage, industrial discharges, and solid waste dumping. The spatial analysis further revealed that pollution intensity increases downstream, with major nalla confluences acting as critical hotspots. Microplastic analysis in the river confirmed the presence of fibers, fragments, and films, with polymers such as PE, PP, and HDPE, indicating dominant sources from urban runoff, textile fibers, and mismanaged plastic waste.

In contrast, Sirpur Lake exhibited relatively moderate pollution levels, reflecting its semi-closed wetland characteristics and partial buffering capacity. Most physicochemical parameters remained within acceptable limits; however, localized increases in organic pollution (BOD, COD) and fluoride in agricultural zones indicate the influence of surrounding land-use activities. The ANOVA results suggest that while many parameters do not show statistically significant variation, selected parameters are influenced by land-use patterns, particularly settlement and agricultural activities. Microplastic sampling in Sirpur Lake did not detect particles above 100 μm , primarily due to methodological limitations. This indicates that either microplastic contamination is lower at the detectable level or that finer particles ($<100\ \mu\text{m}$) that were not captured may still be present in the system.

5.2 Implications of the Study

The findings of this study clearly indicate that urban water quality degradation in Indore is not a standalone environmental issue but a systemic failure of urban planning, wastewater infrastructure, and land-use governance. Therefore, the implications extend beyond conventional treatment strategies and demand a restructuring of how urban water systems are planned, monitored, and managed.

5.2.1 Reframing Urban Water Bodies

The Kahn River and Sirpur Lake demonstrate two fundamentally different but complementary system behaviors: the river as a pollutant conveyor and the wetland as a pollutant sink.

- Rivers should be managed through strict source control (Decentralized wastewater treatment at source points (nallas, dense settlements) and flow-based pollutant interception systems
- Wetlands should be designed and maintained as functional ecological treatment units

This requires integrating urban water bodies into city-scale infrastructure planning, rather than treating them as incidental or aesthetic features. It supports the blue-green infrastructure as a core service network.

5.2.2 Embedding Land-Use Planning into Water Quality Governance

The study establishes a statistically significant link between land-use patterns and variation in water quality, particularly for organic pollution and fluoride. This has a critical implication: Water quality cannot be managed without regulating land use.

Urban expansion, peri-urban agriculture, and unregulated settlements are directly altering pollutant pathways. Therefore:

- Land-use plans incorporate hydrological sensitivity layers
- Buffer zones around water bodies should be legally enforced, not advisory
- Agricultural practices near wetlands must be regulated for nutrient and chemical loading

5.3 Future Scope

- Pre-monsoon, monsoon, and post-monsoon observations need to be carried out to understand the seasonal dynamics of pollution and microplastic transport.
- Future research needs to focus on the estimation of microplastic flux, sedimentation, and transport processes to improve the estimation of pollutant transfer to downstream rivers.
- The use of AI/ML-based pollution prediction and spatial modeling software needs to be explored for early warning systems and pollution source identification.
- Future research needs to focus on the assessment of nature-based solutions, decentralized wastewater treatment systems, and in-situ remediation technologies to develop sustainable restoration strategies for urban tributaries.

APPENDIX-A



Figure A. Instruments used in the Environmental Lab at IIT

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