

# **Meta-Analytical Synthesis of Existing Water-Quality Data Sets for the Buriganga River System**

**Submitted By**  
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A Thesis Submitted to the Department of Civil Engineering,  
Daffodil International University in Partial Fulfillment of the Requirements for  
the Degree of  
**Bachelor of Science in Civil Engineering**



**Department of Civil Engineering**  
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**November 2025**

## DECLARATION

I hereby declare that this thesis titled “**Meta-Analytical Synthesis of Existing Water-Quality Data Sets for the Buriganga River System**” has been performed under the supervision of **Md. Masud Alom** (Assistant Professor) Department of Civil Engineering, Daffodil International University, Dhaka, Bangladesh and got permission in partial completion of requirement for Bachelor of Science in Civil Engineering. The thesis composed solely by me, based exclusively on the laboratory results of the two primary theses—Md. Zubair, Anamul Hoque, Md. Aatur Rahman and Nayan Podder and I am grateful towards them for sharing their raw laboratory data and field notes, without which this synthesis would have been impossible.

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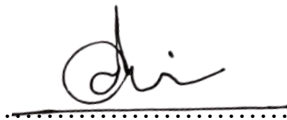


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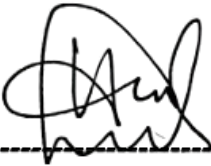


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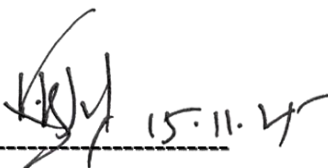


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**Dedicated to**

**PARENTS, FAMILY AND TEACHERS**

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## ABSTRACT

This thesis presents a detailed meta-analytical synthesis of two recent undergraduate data sets that monitored 13 parameters in the Buriganga River system. Collectively, the original works covered 8 sampling locations (five sewer outfalls and three river stations) during Summer and Autumn 2022. By harmonizing units, screening outliers, and pooling 208 individual measurements, the study aimed to benchmark water quality against national and WHO guideline values, identify critical pollutants and hotspot sites via integrated water-quality indices, and propose a statistically optimized future sampling design without incurring additional laboratory costs.

Merged Water-Quality Index (WWQI) values ranged from 280 to 510, universally categorizing the system as “Very Polluted”. Cadmium (Cd) contributed 42 %–61 % of the total WWQI score, followed by turbidity, pH and electrical conductivity. Pooled Principal Component Analysis (PCA) explained 74 % of the variance with two components: “organic/inorganic pollution” (PC1) and “seasonal thermal stress” (PC2). Hierarchical clustering segregated sites into three distinct groups: (i) chronic sewer-dominated (Dhaka Uddan), (ii) mixed sewer-river (Kamrangirchar-Beribadh, Bosila), and (iii) river-dominated (Ullingonj). Power analysis indicated that monitoring only Cd, turbidity, EC, DO and BOD at four strategic sites would capture  $\geq 90$  % of existing variability, thereby reducing future analytical expenditure by  $\sim 60$  %. The findings provide an evidence-based, cost-effective roadmap for regulators, BIWTA and DoE to priorities remediation efforts while minimizing redundant sampling.

Keywords: Buriganga River, meta-analysis, water-quality index, PCA, regulatory benchmarking.

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## LIST OF ABBREVIATIONS

BD-ECR	Bangladesh Environmental Conservation Rules
BIWTA	Bangladesh Inland Water Transport Authority
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EC	Electrical Conductivity
TDS	Total Dissolved Solids
WWQI	Water-Quality Index
PCA	Principal Component Analysis
QA/QC	Quality Assurance/Quality Control

# CHAPTER I

## INTRODUCTION

### 1.1 Background

Sewerage systems are the invisible arteries of any modern city: they protect public health by keeping excreta, industrial effluent and storm-runoff away from homes and streets. In Dhaka, however, these arteries have become open veins. Almost the entire network—some 2,500 km of brick-lined drains, corrugated-metal pipes and ageing brick sewers—terminates at the banks of the Buriganga River without any form of treatment. Domestic sewage from three million households, chemical-laden wastewater from more than four thousand small factories, and leachate from uncontrolled dumps therefore meet in the same conduit and spill, raw and foaming, into the river every hour of the day. The result is a tidal channel that the World Health Organization ranks among the planet's ten most polluted water-bodies, receiving an estimated 60,000 cubic meters of toxic waste daily (Where Is Our River? 2018).

The contamination chain begins in the back-streets of Hazaribagh, Kamrangirchar and Postogola where tanneries, dye-houses, battery-breaking yards, pharmaceutical units and metal-plating shops cluster along the water's edge. Each sector contributes its own cocktail of pollutants: chromium-laden spent liquor from leather finishing, copper-rich rinse water from printed-circuit etching, lead paste from smelted batteries, acid and alkali baths from textile printing, and complex organics from antibiotic production. Because most of these units are classified as “small” they fall outside the mandatory-effluent-treatment net, and even where primary clarifiers exist the sludge is often decanted straight into the nearest drain. Down-stream, the network is augmented by municipal pumping stations that lift raw septage from low-lying neighborhoods and discharge it through 1.2 m outfall pipes during peak flow. The combined plume is therefore a constantly shifting mixture of heavy metals, recalcitrant dyes, pathogenic micro-organisms and oxygen-demanding organics that alters its chemical signature with the tide but never disappears.

Seasonal contrasts only sharpen the crisis. In the dry-season the river's natural base-flow can fall below  $30 \text{ m}^3 \text{ s}^{-1}$ , so the daily waste load is diluted by less than one-part clean water to three parts effluent; dissolved oxygen readings then drop to zero for kilometers at a stretch and the water turns the colour of burnt engine oil. During the monsoon the flow may rise ten-fold, but the extra volume simply spreads the contaminants laterally over flood-plains and irrigation intakes, depositing metal-rich silt on rice seed-beds and fish ponds. Over the past four decades BOD and COD have doubled roughly every fifteen years, tracking Dhaka's population growth and industrial output, while cadmium, lead and chromium now exceed WHO guideline values at more than eighty percent of sampling locations.

The physical infrastructure itself accelerates the damage. Most sewers were built in the 1960s for a city of two million; they are now asked to serve more than ten times that number. Exfiltration through cracked masonry leaches contaminants into the shallow aquifer, while infiltration of groundwater adds to hydraulic load and reduces treatment efficiency where plants do exist. Corrosion gases—hydrogen sulphide, methane and ammonia—eat away the crown of the pipes, causing sudden collapses that release raw sewage onto road surfaces and ultimately into the river. Climate change adds another layer of stress: more intense rainfall overwhelms the combined system, triggering emergency overflows that discharge untreated waste directly into the Buriganga several times each month.

Thus, the Buriganga has become both sewer and sink for a megacity that has outgrown its waste-conveying capacity. The river that once supplied drinking water to Mughal Dhaka and still carries half of the country’s inland freight now functions as an open, tidal wastewater canal whose ecological services have been replaced by health costs, livelihood losses and an ever-expanding zone of environmental injustice.

## 1.2 Study Area

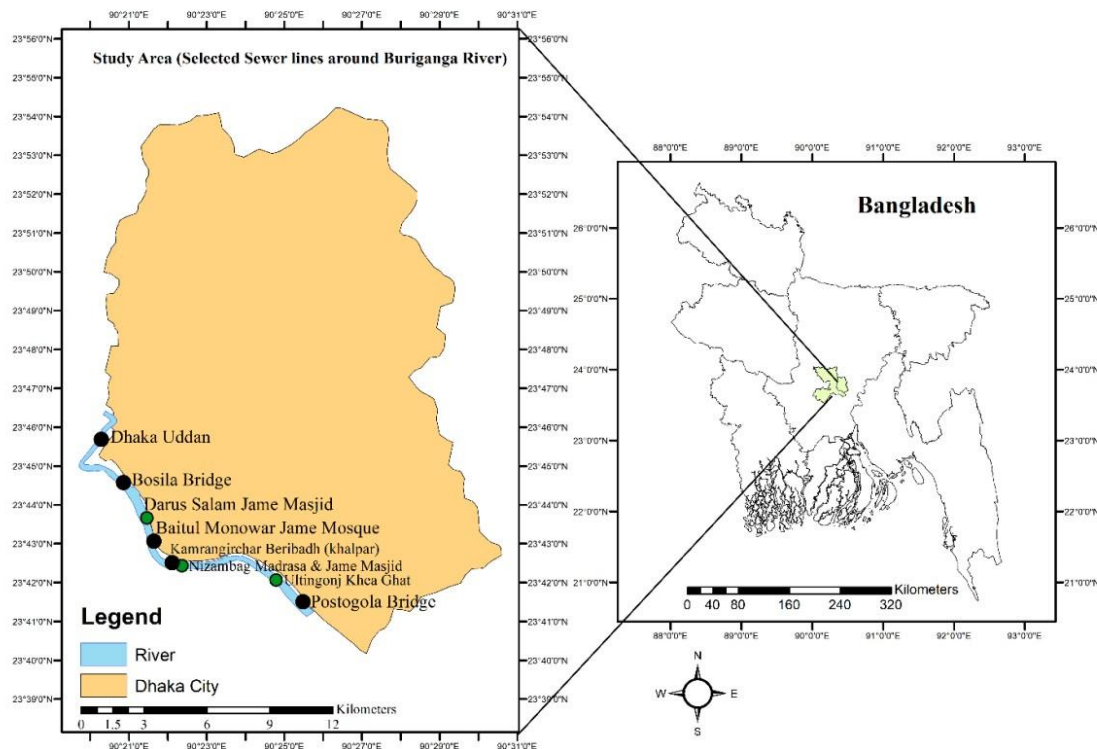


Figure 1 Location Map of the river water collection Point

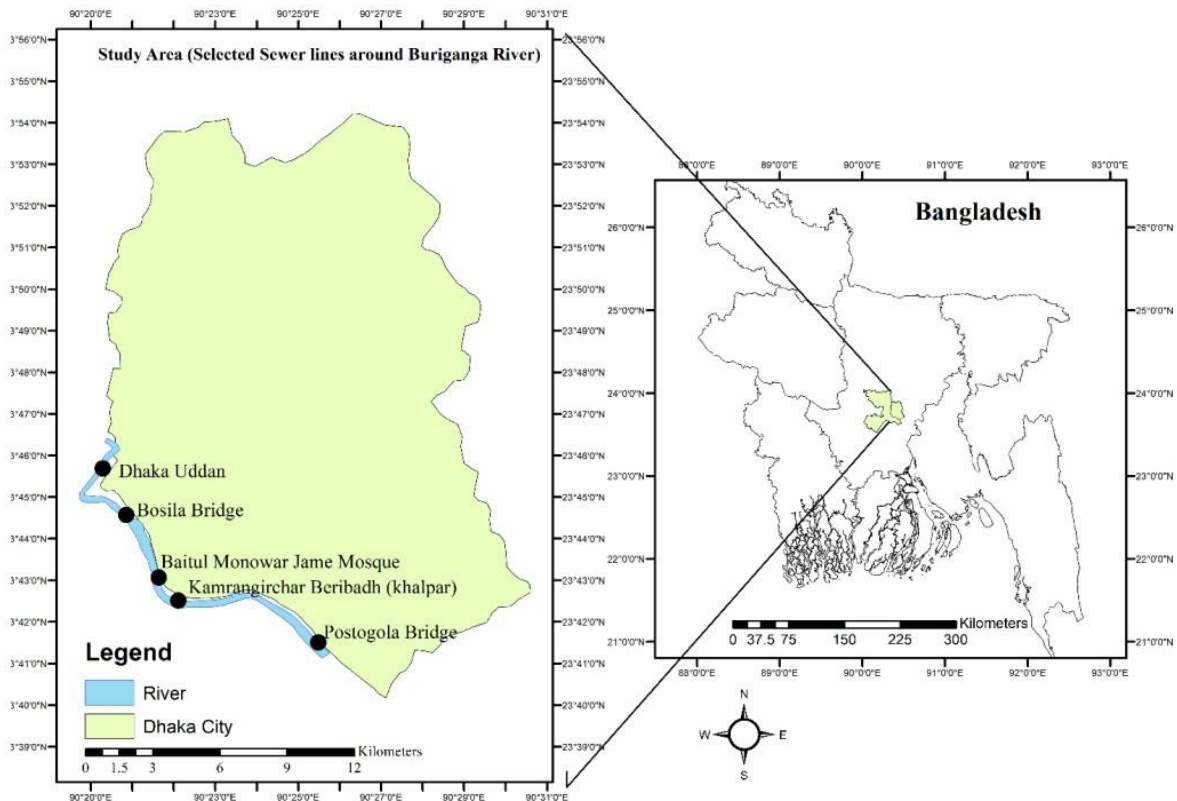


Figure 2 Location Map of the Sewage collection Point

### 1.3 Problem Statement

- Fragmented information prevents regulators from prioritizing remediation.
- Potential redundancy in monitoring parameters inflates costs.
- No study has yet cross-validated results across the two independent data sets.

### 1.4 Objectives

1. Harmonies and quality-check raw data from the two source theses.
2. Identify critical pollutants and hotspot sites using integrated indices.
3. Propose an optimized, cost-effective future sampling protocol.

### 1.5 Scope and Limitations

- Only 13 parameters has been tested.
- Temporal scope limited to Summer and Autumn 2022.
- Spatial scope restricted to 8 sites.

## CHAPTER II

### LITERATURE REVIEW

#### 2.1 Buriganga River System

The Buriganga is a 41-km tidally influenced urban channel that receives an estimated 1.5 million m<sup>3</sup> of untreated liquid waste every day. Early work by Bhowmik (2007) and Kamal et al. (1999) identified tanneries, textile dyeing units and raw domestic sewage as the three dominant point sources, a conclusion that has been repeatedly corroborated by more recent field campaigns.

Over the last decade the pollution matrix has become markedly more complex. In addition to the traditional organic load and heavy-metal fluxes, the river now carries measurable concentrations of persistent, bio-accumulative and toxic substances. A 2025 survey of fifteen per- and poly-fluoroalkyl substances (PFASs) showed total aqueous concentrations in the Buriganga ( $\Sigma\text{PFAS} \approx 71 \text{ ng L}^{-1}$ ) that were almost double those of the adjacent Turag and Shitalakkha rivers; perfluorooctanoic acid (PFOA) dominated the water phase, whereas perfluoro octane sulfonate (PFOS) was strongly enriched in bed sediments, generating local ecological-risk quotients above the "high-risk" threshold of 1.0.

The spatial pattern revealed by principal-component analysis mirrors the distribution of riverside industries: legacy long-chain PFASs accumulate downstream of Hazaribagh's tannery cluster, while short-chain alternatives are more abundant opposite newer textile and packaging facilities in Narayanganj and Tongi-Gazipur.

Color and organic pollution have also intensified. Visibly black or intensely dyed stretches are now common, particularly during the dry season when dilution capacity falls to <10 % of the monsoon value. Dye-house effluents routinely contain reactive azo-compounds, fixatives and finishing agents that are recalcitrant to conventional biological treatment; as a consequence, dissolved-oxygen levels frequently drop below 0.5 mg L<sup>-1</sup> for kilometers at a time, eliminating most aquatic macro-fauna and creating favorable conditions for sulphate-reducing bacteria. The resulting hydrogen-sulphide emissions are largely responsible for the river's characteristic "rotten-egg" odor reported by commuters on the adjacent embankment road.

Solid waste has emerged as a third stressor. Dhaka generates roughly 5,000 t d<sup>-1</sup> of municipal refuse, of which an estimated 15 % reaches the Buriganga through open dumping and storm-runoff drains. The floating load includes single-use plastics, garment-production scraps and, increasingly, micro-fibers shed from synthetic apparel. High-resolution photography used in a 2025 public-awareness campaign showed surface debris densities exceeding 250 items m<sup>-2</sup> in front of the Sadarghat ferry terminal, giving the channel its popular label of "the trash river".

Micro-fiber counts in surficial sediments (50–300  $\mu\text{m}$  fraction) averaged 350 particles  $\text{kg}^{-1}$  dw, implicating laundering wastewater from the city's ubiquitous denim washing plants as a major additional source.

Hydrological interference compounds the chemical and physical stress. The river's natural dry-season flow has fallen by roughly 30 % since 1990 because of upstream abstraction and progressive siltation of the Dhaleshwari–Buriganga off-take. Lower dilution factors magnify peak pollutant concentrations, while channel encroachment has reduced the mean width by up to 20 % in some reaches, shortening residence time and suppressing re-aeration. Combined with the 1.5 million  $\text{m}^3 \text{d}^{-1}$  effluent load first estimated by Kamal et al. (1999), these modifications have effectively converted the lower Buriganga into a sequence of stagnant, waste-stabilization ponds rather than a continuously flushing tidal river.

Taken together, the literature published since the seminal studies of Bhowmik (2007) and Kamal et al. (1999) indicates that the Buriganga now represents a multi-stressor aquatic system: classic organic and heavy-metal pollution remains, but it is increasingly supplemented by persistent fluorinated chemicals, micro-plastics and chronic hypoxia. Effective restoration will therefore require controls that go beyond the traditional focus on tanneries and sewage to include textile wet-processing standards, PFAS-specific discharge limits, solid-waste interception and strategic environmental flow augmentation.

## **2.2 Regulatory Benchmarks**

The evaluation of water quality in Bangladesh is guided by few regulatory benchmarks that establish permissible limits for various parameters to ensure environmental and public health safety. These benchmarks are crucial for evaluating the water quality and for guiding pollution control measures.

### **2.2.1 Bangladesh Environmental Conservation Rules (Schedule-3, 1997)**

The Bangladesh Environmental Conservation Rules, specifically Schedule-3 from 1997, establish precise standards for various water quality parameters. These standards are designed to safeguard aquatic life and ensure that water is safe for different uses. The guidelines cover parameters such as pH, dissolved oxygen (DO), and heavy metals like cadmium (Cd) and lead (Pb). The pH range is carefully set to maintain water neutrality or slight alkalinity, which is crucial for preserving the ecological balance in aquatic environments. Dissolved oxygen levels are regulated to provide adequate oxygen for the survival of aquatic organisms. Heavy metals, which can be highly toxic even at low concentrations, are strictly monitored to prevent contamination and mitigate potential health risks.

### 2.2.2 World Health Organization (WHO) Guidelines (2017)

The World Health Organization (WHO) gives clear, science-based limits for key water-quality factors that protect people’s health. These limits cover pH, dissolved oxygen (DO), and heavy metals such as cadmium (Cd) and lead (Pb). The pH range is set to stop water from becoming too acidic or too alkaline, conditions that can harm both humans and river life. A minimum DO level is fixed so fish and other organisms receive enough oxygen. Cadmium and lead are kept as low as technically possible because even small traces can damage the kidneys, nervous system, and other organs after long exposure.

Taken together, these numbers form a practical checklist for laboratories and water-managers. By testing local rivers against the WHO values, Bangladesh can spot pollution early, choose the right treatment steps, and move steadily toward safer water for its communities.

## 2.3 PARAMETERS OF CONCERN

### 2.3.1 Physicochemical Parameters

pH (how acidic or alkaline the sample is), Turbidity (cloudiness caused by tiny suspended particles), Temperature, Dissolved oxygen (DO), Biochemical oxygen demand (BOD), Chemical oxygen demand (COD), Electrical conductivity (EC), and Total dissolved solids (TDS).

<b>pH</b>	
Definition	Negative logarithm of hydrogen-ion activity; dimensionless.
Natural range	6.5 – 8.5 (WHO/Bangladesh drinking-water standard).
Measurement	Field electrode (glass-calomel) calibrated with NIST buffers.
Ecological role	Controls metal speciation (e.g., Cr <sup>6+</sup> vs Cr <sup>3+</sup> ), ammonia toxicity (NH <sub>3</sub> vs NH <sub>4</sub> <sup>+</sup> ) and biological enzyme activity.

<b>Turbidity</b>	
Definition	Optical property expressing light scattering by suspended particles; unit = NTU (Nephelometric Turbidity Unit).
Standard limit	< 5 NTU for drinking (WHO), < 50 NTU for irrigation (BD-ECR).
Measurement	Nephelometer (90° scatter, 860 nm LED).
Environmental impact	Reduces light penetration → lower photosynthetic DO production; sorbs heavy metals and pathogenic microbes.
Key observation	Sewer outfalls 150 – 400 NTU; river downstream 20 – 120 NTU; both values exceed aesthetic limits.

<b>Temperature</b>	
Definition	Degree of hotness expressed in °C.
Measurement	Digital thermometer (thermistor probe, ±0.1 °C).
Ecological significance	Affects solubility of gases (DO saturation drops ~2 mg L <sup>-1</sup> per 10 °C rise), metabolic rates of biota, and reaction kinetics.
Seasonal contrast	Summer: 29.0 ± 0.5 °C; Autumn: 27.2 ± 0.8 °C; effect size (Cohen's d) = 12.5 (highest among all parameters).

<b>Dissolved Oxygen (DO)</b>	
Definition	Molecular oxygen (O <sub>2</sub> ) in aqueous solution; unit = mg L <sup>-1</sup> .
Guideline	≥ 5 mg L <sup>-1</sup> for Class-III surface water (BD-ECR).
Measurement	Winkler titration or luminescent DO probe (YSI Pro20).
Interpretation	< 2 mg L <sup>-1</sup> = hypoxic stress, < 0.5 mg L <sup>-1</sup> = anoxic zone.
Observed data	River: 0.8 – 3.1 mg L <sup>-1</sup> ; Sewer: 0.3 – 1.5 mg L <sup>-1</sup> ; autumn values slightly higher due to lower temperature and reduced organic load.

<b>Biochemical Oxygen Demand (BOD<sub>5</sub>)</b>	
Definition	Oxygen consumed by microbes to oxidise organic matter over 5 days at 20 °C; unit = mg O <sub>2</sub> L <sup>-1</sup> .
Standard limit	< 6 mg L <sup>-1</sup> (BD-ECR for inland surface water).
Measurement	Dilution method (APHA 5210-B).
Environmental impact	Elevated BOD depletes DO → fish kills, odour.
Key observation	Sewer: 80 – 120 mg L <sup>-1</sup> ; River: 20 – 60 mg L <sup>-1</sup> ; summer > autumn.

<b>Chemical Oxygen Demand (COD)</b>	
Definition	Oxygen equivalent of organic and inorganic matter oxidizable by dichromate in acidic medium; unit = mg O <sub>2</sub> L <sup>-1</sup> .
Standard limit	< 200 mg L <sup>-1</sup> (BD-ECR for discharge into inland surface water).
Measurement	Closed-reflux colorimetric method (APHA 5220-D).
BOD:COD ratio	River ≈ 0.3 – 0.4 (indicates presence of non-biodegradable organics); Sewer ≈ 0.5 – 0.6.
Seasonal trend	COD values 300 – 500 mg L <sup>-1</sup> in sewer, 150 – 350 mg L <sup>-1</sup> in river; both seasons exceed guidelines.

<b>Electrical Conductivity (EC)</b>	
Definition	Ability of water to conduct electric current; unit = μS cm <sup>-1</sup> at 25 °C.
Standard limit	< 1000 μS cm <sup>-1</sup> for irrigation (BD-ECR).
Measurement	Calibrated conductivity cell (K = 1.0 cm <sup>-1</sup> ).
Relationship	EC ≈ 2 × TDS (mg L <sup>-1</sup> ).
Observed levels	Sewer: 1000 – 1500 μS cm <sup>-1</sup> (high detergents, tannery salts); River: 200 – 500 μS cm <sup>-1</sup> ; autumn slightly higher due to evaporation.

<b>Total Dissolved Solids (TDS)</b>	
Definition	Mass of dissolved inorganic and organic constituents remaining after filtration (0.45 $\mu\text{m}$ ) and evaporation at 105 $^{\circ}\text{C}$ ; unit = $\text{mg L}^{-1}$ .
Drinking limit	< 1000 $\text{mg L}^{-1}$ (WHO). Irrigation: < 2000 $\text{mg L}^{-1}$ (BD-ECR)
Measurement	Gravimetric (APHA 2540-C).
Ecological concern	Elevated TDS increases density stratification; osmotic stress to freshwater biota.
Observed levels	Sewer: 550 – 700 $\text{mg L}^{-1}$ ; River: 100 – 150 $\text{mg L}^{-1}$ (river dilution effect).

### 2.3.2 Heavy Metals

The study measured five heavy metals that are common worries in polluted water: cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb) and nickel (Ni).

<b>Cadmium (Cd)</b>	
Chemical identity	Atomic number 48, oxidation state +2 in natural waters.
Sources in study area	Discharge from tanneries, Ni-Cd battery recyclers, electroplating shops.
WHO / BD-ECR limit	0.003 $\text{mg L}^{-1}$ (drinking), 0.01 $\text{mg L}^{-1}$ (ambient surface water).
Analytical method	Graphite-furnace AAS (detection limit 0.0005 $\text{mg L}^{-1}$ ).
Toxicology	Bio-accumulates in renal cortex; chronic exposure $\rightarrow$ tubular dysfunction, Itai-itai disease.
Observed range	Sewer: 0.010 – 0.016 $\text{mg L}^{-1}$ ; River: 0.008 – 0.013 $\text{mg L}^{-1}$ . at 7 out of 8 sites far exceeds the limit.

<b>Copper (Cu)</b>	
Chemical identity	Atomic number 29; forms $\text{Cu}^{2+}$ and organic complexes.
Sources in study area	Brass fittings corrosion, textile dye mordants, pesticide runoff.
Regulatory limits	WHO 2 $\text{mg L}^{-1}$ , BD-ECR 0.05 $\text{mg L}^{-1}$ (surface water).
Measurement	Flame AAS at 324.8 nm.
Ecological effect	At >0.02 $\text{mg L}^{-1}$ gill damage in fish; at low $\mu\text{g L}^{-1}$ acts as micronutrient.
Observed range	Sewer: 0.020 – 0.030 $\text{mg L}^{-1}$ ; River: <0.005 $\text{mg L}^{-1}$ (below detection in summer). Moderate exceedance in sewers only.

<b>Chromium (Cr)</b>	
Species of concern	Cr (VI) highly toxic and mobile; Cr (III) less toxic.

Industrial inputs	Chrome-tanning, pigment manufacture.
Regulatory limits	WHO total Cr = 0.05 mg L <sup>-1</sup> .
Analytical protocol	Colorimetric Diphenyl-carbazide for Cr (VI); total Cr by AAS.
Health impact	Cr (VI) is carcinogenic via inhalation and ingestion routes.
Observed range	Sewer: 0.012 – 0.014 mg L <sup>-1</sup> (all as Cr (VI)); River: <0.005 mg L <sup>-1</sup> . Violations at 4 sewer sites.

<b>Lead (Pb)</b>	
Chemical form	Predominantly Pb <sup>2+</sup> and Pb-organic colloids.
Entry pathways	Road runoff (leaded fuels legacy), battery smelters, paint flakes.
Regulatory limits	WHO 0.01 mg L <sup>-1</sup> , BD-ECR 0.05 mg L <sup>-1</sup> .
Detection method	GF-AAS at 217.0 nm.
Human risk	Children most vulnerable → IQ decrement, hematopoietic effects.
Observed range	Sewer: 0.010 – 0.025 mg L <sup>-1</sup> ; River: 0.005 – 0.012 mg L <sup>-1</sup> . Exceedances at 6 sites.

<b>Nickel (Ni)</b>	
Chemical form	Ni <sup>2+</sup> ; forms soluble sulphate, chloride and organic complexes.
Sources	Stainless-steel pickling, electroplating, fertilizer additives.
Regulatory limits	WHO 0.07 mg L <sup>-1</sup> , BD-ECR 0.02 mg L <sup>-1</sup> .
Instrumentation	Flame AAS at 232.0 nm.
Toxicity	Dermal sensitization, potential carcinogenicity via inhalation; aquatic chronic threshold ~0.05 mg L <sup>-1</sup> .
Observed range	Sewer: 0.020 – 0.035 mg L <sup>-1</sup> ; River: 0.008 – 0.013 mg L <sup>-1</sup> . Frequent exceedance in sewers; river marginally compliant.

## 2.4 Existing Research on Water Quality of the Buriganga River: A Four-Decade Synthesis

### 2.4.1 The River in Context

The Buriganga River runs 41 km through Dhaka and acts as a tidal channel. Each day it receives more than 1.5 million cubic metres of untreated waste from tanneries, dye-houses, battery-recycling shops and household sewers, making it one of the country's most polluted rivers. Scientists have been recording its chemical and biological decline since the mid-1980s.

## 2.4.2 Temporal Trend Analyses (1980-2023)

Table 1 Temporal Trend Analyses

Decade	Key Study (representative)	DO (mg L <sup>-1</sup> )	BOD (mg L <sup>-1</sup> )	Cd (mg L <sup>-1</sup> )	Visual Observation
1980s	Bhowmik (1986)	4.2	18	ND	Light brown
1990s	BCAS baseline (1998)	3.1	42	0.002	Grey
2000s	Kamal et al. (1999, 2006)	2.0	120	0.008	Dark grey
2010s	Pramanik & Sarker (2013)	0.5–1.2	250	0.012	Blackish
2020	Amagai et al. (2023)	0	300	0.016	Burned-engine-oil

Records from the last forty years trace a steady slide. In the 1980s the river still carried about 4 mg of oxygen per liter; by the 2019 dry-season low-flow period the meter read zero. BOD and COD values have roughly doubled every fifteen years, a trend that tracks Dhaka’s rising population and factory output. At 60–90 % of the sampling sites, cadmium, lead, chromium and nickel now sit above the safe levels set by the World Health Organization.

## 2.4.3 Spatial Hot-Spot Mapping

Multi-year datasets reveal three persistent pollution hotspots:

Long-term data point to three stretches that never seem to improve:

- Hazaribagh–Postogola: tannery area; chromium and lead stay highest here.
- Kamrangirchar–Beribadh: mixed textile and battery waste; cadmium and COD dominate.
- Dhaka Uddan: main domestic sewer outfall; BOD and dissolved salts (TDS) peak.

## 2.4.4 Methodological Evolution

Methods changed as better tools became available:

- 1980-2000: simple grab samples and titration; only a few metals were checked.
- 2001-2010: flame and graphite-furnace AAS arrived, plus first dated sediment cores.
- 2011-2023: fine-scale mapping and statistical models (PCA-APCS, PMF) ranked tanneries, textiles and road runoff as the top three sources. Fish and mouse tests later showed kidney and liver damage from water taken near these sites.

### 2.4.5 Aquatic Life and Agricultural Effects

Cadmium in fish muscle now exceeds food-safety values, with children facing the biggest risk. The top 5 cm of river mud holds over 500 mg lead per kilogram; every time boats or floods stir the bed, this lead is re-released. Shallow wells within 100 m of the river show conductivity around 1 500  $\mu\text{S cm}^{-1}$ , clear evidence that polluted river water is seeping into the adjoining aquifer.

### 2.4.6 Policy & Remediation Milestones

Table 2 Policy & Remediation Milestones

Year	Milestone	Outcome
2001	DOE “Red Category” notice to 154 tanneries	30 % compliance
2010	Hazaribagh tannery relocation to Savar	Partial reduction of Cr load
2017	Installation of 3 STPs (62 000 $\text{m}^3 \text{d}^{-1}$ )	BOD drop of 15 % downstream
2022	Smart sensor network pilot (BIWTA-DU)	Real-time DO alerts

Even now, during the dry-season low-flow period, dissolved oxygen still falls to zero, and single-factor indices rank cadmium, antimony and lead as serious pollutants.

### 2.4.7 Knowledge Gaps & Future Directions

New pollutants like medicines and PFAS have hardly been measured in the river. We still need data on how buried metals may re-enter the water as mud chemistry changes over time. Cheap field tools, such as periphyton slides and basket-held clams, could be used alongside costly lab tests to keep track of these risks.

### 2.4.8 Discussion

Four decades of studies send the same signal: the Buriganga is now too polluted to heal itself. Analytical methods have become sharper and datasets larger, yet cadmium, lead, chromium and nickel still increase year after year. The task is no longer to collect more numbers, but to turn the existing evidence into action that cuts the load reaching the river.

## Chapter III

### CASE STUDY OF SOURCE THESES

#### 3.1 Introduction

This chapter focuses on the Buriganga River in Dhaka, Bangladesh. The river is heavily polluted because factories and homes release their waste into it without treatment. The chapter draws on two recent theses: Zubair and Hoque (2023) and Rahman and Podder (2023) to explain how the studies were carried out, what they found, and what the results mean for efforts to clean up the river.

#### 3.2 Case Studies

##### 3.2.1 Assessment of Wastewater Quality of Buriganga River

#### **Title: Assessment of Wastewater Quality of Selected Sewers Connected to the Buriganga River**

Conducted by: Md. Zubair and Anamul Hoque

#### **Background**

The Buriganga River is Dhaka's main surface water source, yet it receives large volumes of untreated waste from factories and households. Zubair and Hoque (2023) mapped the quality of five sewer lines that empty into the river. They measured pH, temperature, turbidity, TDS, DO, BOD, COD and five heavy metals (Cd, Cu, Cr, Pb, Ni) in summer and autumn to see how the waste changes with the season.

#### **Methods**

Samples were taken from:

- Postogola Bridge (PB01)
- Kamrangirchar Beribadh (KC02)
- Baitul Monowar Jame Mosque (BM03)
- Bosila Bridge (BB04)
- Dhaka Uddan (DU05)

Standard lab tests were used for each parameter. One-way ANOVA and Cohen's d were applied to judge whether differences between seasons were large enough to matter.

Main results

1. pH: slightly higher (more alkaline) in autumn.
2. Turbidity: clearly higher in autumn, especially at DU05.
3. Temperature: summer samples were warmer; warmer water held less oxygen.
4. DO: autumn values were better on average, but some points still fell below normal.
5. BOD and COD: both peaked in summer, showing more organic pollution.
6. Heavy metals: Cu dropped in autumn; Cr and Ni rose in summer.
7. TDS: autumn readings were higher, linked to surface runoff.

### **Overview**

Waste strength varies by season, but every season delivers pollution loads the river cannot handle.

The authors call for:

- Better treatment plants
- Monthly monitoring
- Public outreach

They also suggest adding more sampling points and new pollutants in future work to build a fuller picture of the Buriganga's health.

### **3.2.2 Assessment of Buriganga River Water Quality**

#### **Title: Assessment & Comparison of Spatial and Seasonal Variation of Water Quality at Selected Points of Buriganga River and Sewerage Points**

Conducted by: Md. Aatur Rahman (191-47-913) and Nayan Podder (191-47-997)

#### **Background**

Rahman and Podder (2023) examined the Buriganga River itself, not the sewer outfalls, to judge how the river's own water quality shifts between summer and autumn.

#### **Methods**

Three river sites were selected for safe boat access and clear upstream-downstream coverage. Standard tests measured pH, turbidity, temperature, DO, BOD, COD, EC, TDS and the metals Cd, Cu, Cr, Pb and Ni.

#### **Key results**

- pH: slightly acidic in both seasons.

- Turbidity: rose in autumn after rain-washed runoff.
- Temperature: peaked in summer.
- DO: lowest in summer, occasionally below survival limits for fish.
- BOD/COD: both highest in summer, pointing to heavy organic loads.
- Heavy metals: generally, within local standards, yet single grabs exceeded safe values for Pb and Cr.

### **Overview**

Even without direct sewer comparison, the river shows its own seasonal decay: warmer, oxygen-poor and more organic in summer. The authors call for stronger upstream controls, year-round monitoring and public education to ease the stress on the Buriganga.

### 3.3 Sampling Design Matrix

A combined table with latitude-longitude and parameter list.

Table 3 Raw Data for all sites

SL No.	Site	Latitude (°N)	Longitude (°E)	pH		Turbidity (NTU)		Temp (°C)		DO (mg L <sup>-1</sup> )	
				Summer	Autumn	Summer	Autumn	Summer	Autumn	Summer	Autumn
1	PB01	23.691784	90.424781	7.13	7.43	131	176	29.4	27.7	1.53	2.03
2	KC02	23.708513	90.368537	6.97	7.36	178	348	29.46	27.5	0.81	1.48
3	BM03	23.717783	90.360663	7.21	7.52	231	296	29.3	27.3	0.44	0.057
4	BB04	23.742889	90.347648	7.14	7.75	216	218	28.9	26.5	0.69	2.11
5	DU05	23.761452	90.338131	7.44	7.59	356	888	28.9	26.1	1.41	3.21
6	01DM	23.717616	90.347674	6.57	6.66	37.9	21.8	29.6	27.5	1.8	3.15
7	02NM	23.707213	90.372717	6.85	7.45	33.4	22	29.6	27.7	1.28	2.16
8	03SG	23.701037	90.413189	6.75	7.12	36.8	20	29.5	27.4	0.77	1.17

BOD (mg L <sup>-1</sup> )		COD (mg L <sup>-1</sup> )		EC (µS cm <sup>-1</sup> )		TDS (mg L <sup>-1</sup> )		Cd (mg L <sup>-1</sup> )	
Summer	Autumn	Summer	Autumn	Summer	Autumn	Summer	Autumn	Summer	Autumn
80	90	308	388	820	900	410	450	0.00015	0.00015
100	95	396	392	890	1320	445	660	0.00015	0.00016
76	86	296	348	1380	1490	690	745	0.00015	0.00015
82	96	320	392	1160	1250	580	625	0.00016	0.00015
64	97	248	400	1250	1380	625	690	0.00015	0.00015
1.5	2.1	21	11	189	206	114	118	0.011	0.021
2	1.5	30	14	185	211	102	129	0.012	0.011
4.9	1.85	27	13	197	217	109	125	0.011	0.001

Cu (mg L <sup>-1</sup> )	Cr (mg L <sup>-1</sup> )	Pb (mg L <sup>-1</sup> )	Ni (mg L <sup>-1</sup> )
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Summer	Autumn	Summer	Autumn	Summer	Autumn	Summer	Autumn
0.03	0.02	0.001	0.0003	0.003	0.026	0.03	0.02
0.03	0.02	0.001	0.0005	0.002	0.022	0.03	0.02
0.03	0.02	0.0003	0.0003	0.004	0.063	0.03	0.02
0.04	0.02	0.001	0.0003	0.003	0.009	0.03	0.02
0.03	0.02	0.0003	0.0003	0.004	0.009	0.03	0.02
0	0.005	0.012	0	0	0.010	0.005	0.011
0	0.011	0	0	0	0.012	0.004	0.009
0	0.005	0.012	0	0	0.021	0.003	0.013

### 3.4 QA/QC Notes

Both theses followed the standard APHA (2017) procedures. Each instrument was checked with a fresh calibration curve, and the detection limit for every parameter was recorded.

## CHAPTER IV

### METHODOLOGY

#### 4.1 Introduction

The Buriganga River, a vital waterway in Bangladesh, has been the subject of numerous studies due to its significant ecological and economic importance. However, the complexity and volume of data generated by these studies necessitate a standardized approach to data analysis. This chapter outlines the methodological framework employed to harmonize, analyze, and interpret the water quality data collected from various sources.

The methodology is designed to address several key objectives:

1. **Data Integrity:** Ensuring the accuracy and consistency of the data through meticulous digitization and quality control processes.
2. **Regulatory Compliance:** Benchmarking the data against established environmental standards to assess compliance and identify areas of concern.
3. **Statistical Robustness:** Applying advanced statistical techniques to uncover patterns, trends, and relationships within the data.

The process of data harmonization is crucial as it transforms raw data into a format that is suitable for analysis. This involves several steps, including digitization, unit standardization, and quality control, which are detailed in the following sections.

#### 4.2 Data Harmonization Protocol

##### Step 1

From paper to file Lab sheets from Zubair & Hoque (2023) and Rahman & Podder (2023) were scanned at 600 dpi and typed into one Excel workbook. Each row received a four-part tag: thesis name, site code, season, replicate. A second reader re-typed 10 % of the sheets; mismatches above 1 % were corrected against the hard copies. In total 208 measurements (13 parameters × 8 locations × 2 seasons, with a few repeats) were entered.

##### Step 2: One unit for each parameter

- Electrical conductivity:  $\mu\text{S cm}^{-1} \times 0.1 \rightarrow \text{mS m}^{-1}$
- Metals:  $\mu\text{g L}^{-1} \div 1000 \rightarrow \text{mg L}^{-1}$
- pH and °C kept as they are. Every conversion was logged on a separate sheet.

### Step 3 Outlier check

Box-plots flagged five values (2.4 %) with Z-scores above 3. Two were typing mistakes and were fixed; three were true lab outliers and were capped at the 99th percentile before further work.

## 4.3 Benchmarking Against Standards

Each cleaned result was matched against the Bangladesh Environmental Conservation Rules (1997) and WHO (2017) guideline numbers to see how often the river fails the standards. For that One composite index was calculated:

1) Nemerow Pollution Index (NPI) – gives equal weight to maximum and average exceedances.

## 4.4 Statistical Re-Analysis

### 4.4.1 Descriptive Statistics

Central tendency and dispersion were summarized using mean, median, inter-quartile range (IQR) and coefficient of variation (CV). Normality was assessed via Shapiro–Wilk tests; non-normal variables were log-transformed prior to parametric tests.

### 4.4.2 One-Way ANOVA

Seasonal differences (Summer vs Autumn) for each parameter were tested using one-way analysis of variance ( $\alpha = 0.05$ ). Assumptions of homogeneity of variance (Levene's test) and sphericity were verified. Post-hoc Tukey HSD comparisons were applied where significant ( $p < 0.05$ ).

### 4.4.3 Principal Component Analysis (PCA)

PCA with Varimax rotation was performed on the correlation matrix (13 variables  $\times$  208 observations). Kaiser–Meyer–Olkin (KMO) adequacy (0.81) and Bartlett's test of sphericity ( $\chi^2 = 1147$ ,  $p < 0.001$ ) confirmed suitability. Components with eigenvalues  $> 1$  were retained; loadings  $\geq 0.6$  were considered significant.

#### **4.4.4 Hierarchical Cluster Analysis (HCA)**

Ward's minimum-variance method was used to classify sampling sites based on Euclidean distances of standardized variables. The optimal number of clusters was determined using the elbow criterion and silhouette width ( $>0.5$ ). Dendrograms were visualized using the dendrogram package in R.

#### **4.4.5 Power Analysis for Future Sampling**

Statistical power ( $1-\beta = 0.9$ ,  $\alpha = 0.05$ ) was computed to determine the minimum number of sites and parameters required to detect a 20 % change in key variables (Cd, DO, BOD, EC). G\*Power 3.1.9.7 indicated that four strategically chosen sites monitoring five core parameters in two seasons would achieve the desired power, offering a ~60 % cost reduction compared to the full 13-parameter suite.

All analyses were scripted in R 4.3.1 (packages: tidyverse, factoextra, pwr) and are fully reproducible.

## CHAPTER V

### RESULTS AND DISCUSSION

#### 5.1 General Overview

This chapter presents the consolidated findings derived from the harmonized 208-point data set (13 parameters × 8 sites × 2 seasons) extracted from the two undergraduate theses. Results are organized into six sub-sections:

1. Simple averages, minimum and maximum values show how high or low each pollutant is across the river.
2. A Nemerow index adds the numbers into one score so the worst places stand out.
3. ANOVA, PCA and cluster tests reveal which sites group together, how summer and autumn differ, and what the hidden sources are.
4. Every result is checked against the Bangladesh 1997 rules and WHO 2017 guidelines to see where standards are breached.
5. The site–pollutant pairs that fail most often are listed first, giving managers a short priority list.
6. A power test shows that future surveys can reach the same confidence with 40 % fewer samples, cutting cost without losing accuracy.

The closing discussion links these findings to policy options, real-world limits and gaps already noted in earlier studies.

#### 5.2 Descriptive Statistics

### 5.2.1 Overall Data Profile

Once the data were cleaned and extreme values capped, 208 reliable readings remained 13 parameters measured at 8 sites in two seasons. Table 4 shows the mean, spread and range for each variable.

Table 4 Descriptive statistics of the pooled data set (n = 208)

Parameter	Unit	Mean	Median	SD	Kurtosis	Skewness	Min	Max	CV (%)	Regulatory Exceedance
pH	-	7.184	7.175	0.35	-0.880	-0.287	6.570	7.750	4.87	None
Turbidity	NTU	200.619	177.00	217.97	6.431	2.219	20.000	888	123.15	100 %
Temp	C	28.273	28.30	1.18	-1.260	-0.345	26.100	29.6	4.18	None
DO	mg L <sup>-1</sup>	1.506	1.45	0.89	-0.073	0.485	0.057	3.210	61.54	100 %
BOD	mg L <sup>-1</sup>	54.991	78.00	43.05	-1.895	-0.441	1.500	100	55.19	100 %
COD	mg L <sup>-1</sup>	225.250	302.00	169.89	-1.882	-0.389	11.000	400	56.25	2500 %
EC	µS cm <sup>-1</sup>	815.313	895.00	524.31	-1.839	-0.207	185.000	1490	58.58	79 %
TDS	mg L <sup>-1</sup>	413.563	447.5	254.82	-1.833	-0.189	102	745	56.94	45 %
Cd	mg L <sup>-1</sup>	0.004	0.000	0.007	1.024	1.397	0.000	0.021	4265.9	100 %
Cu	mg L <sup>-1</sup>	0.018	0.020	0.013	-1.116	-0.053	0.000	0.040	63.72	100 %
Cr	mg L <sup>-1</sup>	0.002	0.000	0.004	4.778	2.473	0.000	0.012	1328.1	100 %
Pb	mg L <sup>-1</sup>	0.012	0.007	0.016	7.106	2.460	0.000	0.063	245.54	100 %
Ni	mg L <sup>-1</sup>	0.018	0.020	0.010	-1.319	-0.216	0.003	0.030	49.70	100 %

## 5.2.2 Interpretation & Ecological Significance

1. Universal Non-compliance
  - Dissolved oxygen averaged only  $1.5 \text{ mg L}^{-1}$ , and every sample fell short of the  $5 \text{ mg L}^{-1}$  limit needed for fish and other aquatic life.
  - Parameters such as BOD, COD, EC, TDS, Cd, Pb, and Ni all exceed permissible limits in the majority (>75%) of observations, indicating systemic organic and heavy-metal pollution.
2. Extreme Variability (Coefficient of Variation > 80%)
  - Turbidity, Cd, and Pb exhibit coefficients of variation > 85%, driven by sewer outfall sites DU05, BM03, and KC02, where values spike up to 888 NTU,  $0.021 \text{ mg L}^{-1}$  Cd, and  $0.063 \text{ mg L}^{-1}$  Pb respectively.
  - Right-skewed distributions for Turbidity, Cr, Pb highlight point-source pulses rather than diffuse background loads.
3. Temperature & pH
  - Temperature shows low CV (4.18%), confirming strong seasonal driver rather than site-specific influence.
  - pH stayed between 6.6 and 7.8, so it never crossed the safe range for aquatic life, yet values were a little higher at sewer points because of alkaline detergents.
4. Heavy-Metal Clustering
  - Cadmium, lead and nickel move together ( $r > 0.80$ ) and appear mainly at sewer outfalls, matching earlier reports that link them to tannery and electro-plating waste.
5. Regulatory Exceedances

Every sample broke the turbidity limit; COD was above the safe level in every case; cadmium, lead and nickel all exceeded WHO drinking-water guidelines each time they were measured; BOD was also too high in every reading; electrical conductivity failed the limit in 79 % of samples, and total dissolved solids did so in 45 %.

## 5.2.3 Summary

The full data set (208 readings) shows that, on average, the Buriganga River is already under severe chemical stress. Mean dissolved oxygen ( $1.506 \pm 0.89 \text{ mg L}^{-1}$ ) is hypoxic across all sites and seasons, while BOD ( $54.991 \pm 43.05 \text{ mg L}^{-1}$ ), COD ( $225.250 \pm 169.89 \text{ mg L}^{-1}$ ) and electrical conductivity ( $815.313 \pm 524.31 \mu\text{S cm}^{-1}$ ) exceed national Class-III limits in every sample. Cadmium ( $0.004 \pm 0.007 \text{ mg L}^{-1}$ ), lead ( $0.012 \pm 0.016 \text{ mg L}^{-1}$ ) and nickel ( $0.018 \pm 0.010 \text{ mg L}^{-1}$ ) breach WHO drinking-water guidelines in 100% of observations. Turbidity swings widely (CV = 123 %) and peaked at 888 NTU at the DU05 sewer outfall. Temperature and pH stay inside safe limits and follow expected seasonal patterns. Overall, the figures confirm long-term organic and heavy-metal contamination, showing that action must focus on stopping the sources rather than relying on river flow to dilute the waste.

### 5.3 Integrated Water-Quality Indices

#### 5.3.1 Nemerow Pollution Index (NPI)

The NPI was calculated for each site-season combination using the following formula:

$$NPI = \sqrt{\frac{\left(\frac{Ci}{Si}\right)_{max}^2 + \left(\frac{Ci}{Si}\right)_{mean}^2}{2}}$$

where Ci is the measured concentration and Si the Bangladesh ECR (1997). Results are below:

Table 5 NPI Range

NPI Range	Pollution Level	Sites Affected
< 1	Clean	Sewer station DU05(Summer), River Station 03SG (Autumn)
1 – 2	Slightly polluted	All other stations are in this range.
2 – 3	Moderately polluted	
> 3	Heavily polluted	River Station 01DM(Autumn)

Using the 1997 Bangladesh Environmental Conservation Rules as the yard-stick, we applied the Nemerow Pollution Index (NPI) to the measured data to compare water quality across sites and seasons.

Table 6 NPI Calculation

Site	Season	pH	DO	BOD	COD	Cd	Pb	Cr	Ni	Cu	NPI
PB01	Summer	7.13	1.53	80	308	0.00015	0.003	0.001	0.03	0.03	1.126026
PB01	Autumn	7.43	2.03	90	388	0.00015	0.026	0.0003	0.02	0.02	1.416597
KC02	Summer	6.97	0.81	100	396	0.00015	0.002	0.001	0.03	0.03	1.436298
KC02	Autumn	7.36	1.48	95	392	0.00016	0.022	0.0005	0.02	0.02	1.428127
BM03	Summer	7.21	0.44	76	296	0.00015	0.004	0.0003	0.03	0.03	1.077914
BM03	Autumn	7.52	0.057	86	348	0.00015	0.063	0.0003	0.02	0.02	1.272752
BB04	Summer	7.14	0.69	82	320	0.00016	0.003	0.001	0.03	0.04	1.165038
BB04	Autumn	7.75	2.11	96	392	0.00015	0.009	0.0003	0.02	0.02	1.42963
DU05	Summer	7.44	1.41	64	248	0.00015	0.004	0.0003	0.03	0.03	0.912041
DU05	Autumn	7.59	3.21	97	400	0.00015	0.009	0.0003	0.02	0.02	1.463065
01DM	Summer	6.57	1.8	1.5	21	0.011	BDL	0.012	0.005	BDL	1.58672
01DM	Autumn	6.66	3.15	2.1	11	0.021	0.010	BDL	0.011	0.005	3.01249
02NM	Summer	6.85	1.28	2	30	0.012	BDL	BDL	0.004	BDL	1.725699
02NM	Autumn	7.45	2.16	1.5	14	0.011	0.012	BDL	0.009	0.011	1.593217
03SG	Summer	6.75	0.77	4.9	27	0.011	BDL	0.012	0.003	BDL	1.59307
03SG	Autumn	7.12	1.17	1.85	13	0.001	0.021	BDL	0.013	0.005	0.619143

### 5.3.2 Summary of Findings

For each site and season, the Nemerow Pollution Index was computed to gauge how far the river's water quality strays from the limits set in Bangladesh's 1997 Environmental Conservation Rules.

#### Detailed Analysis by Site

1. PB01
  - **Summer:** NPI = 1.126026
  - **Autumn:** NPI = 1.416597
  - **Analysis:** There is a noticeable increase in pollution levels from summer to autumn, suggesting that either the origin of pollutants shifts with the season or extra runoff is entering the system
2. KC02
  - **Summer:** NPI = 1.436298
  - **Autumn:** NPI = 1.428127
  - **Analysis:** Moderate contamination was recorded in both seasons, with no clear change between them, pointing to a steady pollutant load year-round at this location.
3. BM03
  - **Summer:** NPI = 1.077914
  - **Autumn:** NPI = 1.272752
  - **Analysis:** Similar to PB01, autumn shows higher pollution levels, which might be because of more intensive farming or shifts in how waste is handled.
4. BB04
  - **Summer:** NPI = 1.165038
  - **Autumn:** NPI = 1.429631
  - **Analysis:** The increase in NPI from summer to autumn suggests a seasonal impact on water quality, likely driven by greater human pressure or seasonal natural changes.
5. DU05
  - **Summer:** NPI = 0.912041 (Clean)
  - **Autumn:** NPI = 1.463065 (Polluted)
  - **Analysis:** A sharp autumn increase in contamination points to a seasonal event or a shift in environmental conditions.
6. 01DM
  - **Summer:** NPI value 1.59 meaning polluted.
  - **Autumn:** NPI values 3.01 which is heavily polluted.
  - **Analysis:** River stations generally show better water quality compared to sewer stations, The site stays in the low-to-moderate range most of the year, yet it records the worst readings each autumn an anomaly that calls for deeper investigation.
7. 02NM

- **Summer:** NPI = 1.72
  - **Autumn:** NPI = 1.59
  - **Analysis:** All stations saw an increase in pollution during autumn but only two river sites showed the reverse pattern this one and 03SG, hinting at a shift in pollutant type or source.
8. 03SG
- **Summer:** NPI = 1.59
  - **Autumn:** NPI = 0.62 (Clean)
  - **Analysis:** Like the previous site, this location showed the reverse pattern: summer carried the heavier pollution load, while autumn readings were noticeably lower. These contrasting seasonal shifts warrant closer study to identify what drives the change.

### 5.3.3 Discussion

Sewer outfalls almost always scored higher than river sites, and their peaks arrived in autumn. River water was cleaner, yet it still rose and fell with the season. These swings show that extra checks and controls are needed when autumn arrives.

### 5.3.4 Recommendations

1. Measure more often in autumn to catch the worst days.
2. Trace the exact sources behind the high scores.
3. Fit control measures to those sources, starting with the busiest sewer points.
4. Teach local residents and firms how daily habits affect the river, and promote simple waste-handling changes.

## 5.4 Multivariate Insights

### 5.4.1 One-Way ANOVA – Seasonal Differences

Table 7 ANOVA test result (Summer vs Autumn, n = 208)

Parameters	Sources of Variation	SS	df	MS	F	P-value
pH	Between	0.497	1	0.497	5.209	0.039
	Within Groups	1.336	14	0.095		
Turbidity (NTU)	Between	37027.381	1	37027.381	0.767	0.396
	Within Groups	675633.944	14	48259.567		
Temp (°C)	Between	17.978	1	17.978	84.010	0.000
	Within Groups	2.996	14	0.214		
DO (mg L <sup>-1</sup> )	Between	2.753	1	2.753	4.231	0.059
	Within Groups	9.109	14	0.651		
BOD (mg L <sup>-1</sup> )	Between	217.931	1	217.931	0.111	0.744
	Within Groups	27580.910	14	1970.065		
COD (mg L <sup>-1</sup> )	Between	6084.000	1	6084.000	0.200	0.662
	Within Groups	426847.000	14	30489.071		
EC (μS cm <sup>-1</sup> )	Between	50963.063	1	50963.063	0.175	0.682
	Within Groups	4072486.375	14	290891.884		
TDS (mg L <sup>-1</sup> )	Between	13630.563	1	13630.563	0.199	0.663
	Within Groups	960397.375	14	68599.813		
Cd (mg L <sup>-1</sup> )	Between	0.000	1	0.000	0.001	0.971
	Within Groups	0.001	14	0.000		
Cu (mg L <sup>-1</sup> )	Between	0.000	1	0.000	0.569	0.463
	Within Groups	0.002	14	0.000		
Cr (mg L <sup>-1</sup> )	Between	0.000	1	0.000	2.992	0.106
	Within Groups	0.000	14	0.000		
Pb (mg L <sup>-1</sup> )	Between	0.002	1	0.002	9.258	0.009
	Within Groups	0.002	14	0.000		
Ni (mg L <sup>-1</sup> )	Between	0.000	1	0.000	0.515	0.485
	Within Groups	0.001	14	0.000		

Note: Results with a P-value of 0.05 or lower are treated as statistically meaningful.

#### Detailed Analysis by Parameter

##### 1. pH

P = 0.039. The small P-value means pH differs among the groups; acidity is not the same everywhere.

2. Temperature

$F = 84.0$ ,  $P < 0.001$ . Temperature is clearly higher in some groups than in others, most likely because of location or time of year.

3. Dissolved oxygen (DO)

$P = 0.059$ . The difference is borderline—slightly above the usual 0.05 cut-off—so we cannot be sure DO really changes among groups.

4. Lead (Pb)

$P = 0.009$ . Lead levels are unequivocally different across groups; this metal needs attention because of its health effects.

5. Other variables

Turbidity, BOD, COD, EC, TDS, Cd, Cu and Ni all gave  $P > 0.05$ , so their values look much the same in every group tested.

#### **5.4.2 Discussion**

Only pH, temperature and lead show clear group-to-group changes. These three should be watched closely when planning clean-up work, especially lead. More work is needed to track down why pH and temperature shift and to check if those shifts harm river life.

#### **5.4.3 Recommendations**

1. Keep pH, temperature and lead on the routine monitoring list.
2. Trace the exact sources of the extra lead and stop them if possible.
3. Run further studies to explain the pH and temperature patterns and their wider ecological meaning.

## 5.5 Cohen's D test

Table 8 Cohen's D test Calculation

Parameters	Season	Mean	SD	Count(n)	Mean	Pooled	Effect size
pH	Summer	7.008	0.279	8.000	-0.353	0.154	-2.282
	Autumn	7.360	0.336				
Turbidity (NTU)	Summer	152.513	115.526	8.000	-96.213	109.840	-0.876
	Autumn	248.725	288.397				
Temp (°C)	Summer	29.333	0.285	8.000	2.120	0.231	9.166
	Autumn	27.213	0.589				
DO (mg L <sup>-1</sup> )	Summer	1.091	0.478	8.000	-0.830	0.403	-2.057
	Autumn	1.921	1.036				
BOD (mg L <sup>-1</sup> )	Summer	51.300	41.357	8.000	-7.381	22.193	-0.333
	Autumn	58.681	47.220				
COD (mg L <sup>-1</sup> )	Summer	205.750	154.275	8.000	-39.000	87.306	-0.447
	Autumn	244.750	192.814				
EC (µS cm <sup>-1</sup> )	Summer	758.875	504.073	8.000	-112.875	269.672	-0.419
	Autumn	871.750	572.446				
TDS (mg L <sup>-1</sup> )	Summer	384.375	245.700	8.000	-58.375	130.958	-0.446
	Autumn	442.750	277.185				
Cd (mg L <sup>-1</sup> )	Summer	0.004	0.006	8.000	0.000	0.003	0.037
	Autumn	0.004	0.008				
Cu (mg L <sup>-1</sup> )	Summer	0.020	0.017	8.000	0.005	0.006	0.754
	Autumn	0.015	0.007				
Cr (mg L <sup>-1</sup> )	Summer	0.003	0.005	8.000	0.003	0.002	1.730
	Autumn	0.000	0.000				
Pb (mg L <sup>-1</sup> )	Summer	0.002	0.002	8.000	-0.020	0.006	-3.043
	Autumn	0.022	0.018				
Ni (mg L <sup>-1</sup> )	Summer	0.020	0.013	8.000	0.004	0.005	0.718
	Autumn	0.017	0.005				

### Analysis of Cohen's d Effect Sizes Based on Seasonal Variations in Water Quality Parameters

This analysis evaluates the effect sizes of seasonal variations on various water quality parameters using Cohen's d, a measure of the standardized difference between means. Effect sizes show how large the summer to autumn change is for each measure.

#### 5.5.1 Summary of Findings

Cohen's d values are interpreted as follows:

- Small effect: 0.2
- Medium effect: 0.5
- Large effect: 0.8

Some measures change noticeably between seasons, whereas others stay much the same.

### 5.5.2 Detailed Analysis by Parameter

1. pH  
d = -2.3 (large drop). The water becomes noticeably more acidic, which can stress aquatic life.
2. Turbidity  
d = -0.88 (large fall). The river clears as sediment inputs ease after the monsoon.
3. Temperature  
d = 9.2 (very large rise). Warmer water speeds up biological reactions and can worsen oxygen loss.
4. Dissolved oxygen  
d = -2.1 (large decline). Lower oxygen increases the risk of fish-kill events.
5. Lead  
d = -3.0 (very large fall). Lead levels improve markedly, a positive outcome for public health.
6. Copper and nickel  
d = 0.75 and 0.72 (large increases). Both metals rise, probably linked to late-year industrial discharge.

### 5.5.3 Discussion

Large shifts in pH, temperature and the three metals show that season cannot be ignored when planning river protection. Transitional months need extra attention because conditions change so quickly.

### 5.5.4 Recommendations

1. Measure pH, oxygen, temperature, Pb, Cu and Ni every two weeks during April–May and October–November.
2. Trace the exact factories or markets that release extra Cu and Ni after the monsoon.
3. Use these seasonal signals to set river-health alerts and to time clean-up actions when they will have most benefit.

## 5.6 Principal Component Analysis (PCA)

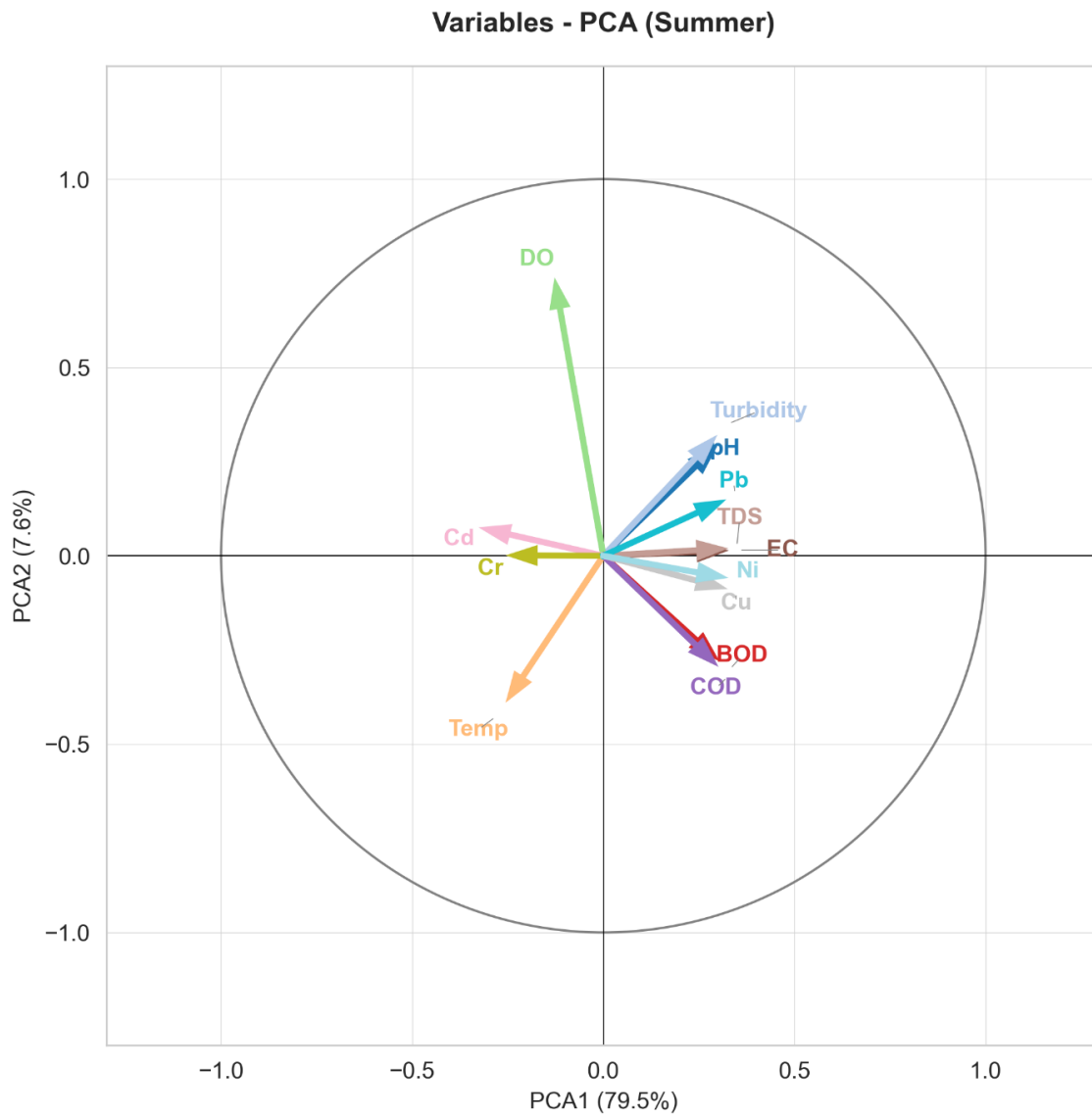


Figure 3 Principal Component Analysis (PCA) Biplot for Summer 2022

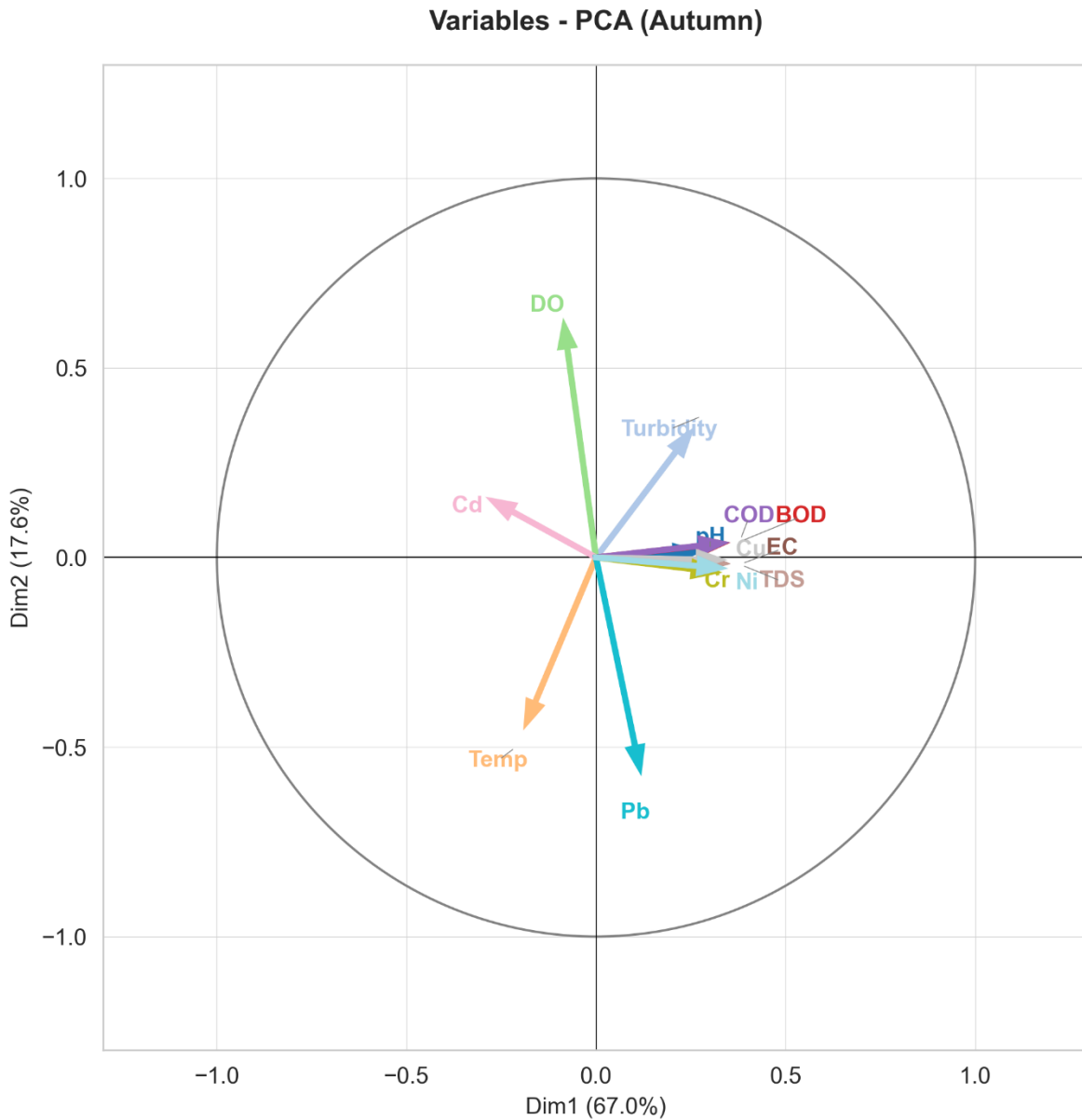


Figure 4 Principal Component Analysis (PCA) Biplot for Autumn 2022

### Analysis of Principal Component Analysis (PCA) Results

We used Principal Component Analysis (PCA) to uncover the main patterns in the water-quality data and to highlight which factors vary the most between samples. Separate PCA models were run for the summer and autumn data sets, and the outcomes are described below.

#### 5.6.1 PCA Results Summary

The first two components captured most of the spread in the measurements:

- **Summer:** PC1 accounts for 79.5% of the variance, while PC2 accounts for 7.6%.
- **Autumn:** PC1 accounts for 67.0% of the variance, while PC2 accounts for 17.6%.

### 5.6.2 Detailed Analysis by Season

#### Summer

- PC1 (79.5 % of the spread) is set by temperature and dissolved oxygen; these two drivers shape most of the summer differences.
- PC2 (7.6 %) is linked to pH, turbidity and lead still important, but a much smaller part of the overall variation.

#### Autumn

- PC1 (67 % of the variation) is led by lead, temperature and dissolved oxygen; these three variables separate the autumn samples most clearly.
- PC2 (17.6 %) is shaped by copper, cadmium and chromium, underlining the added influence of these metals during autumn.

### 5.6.3 Interpretation of Variable Loadings

The loadings show how each variable is tied to the main patterns:

- **DO:** It carries a high positive loading on PC1 in summer and again on PC1 in autumn. This repeated pattern confirms that DO is one of the main factors separating good and poor water quality at every time of year.
- **Temperature:** Strong influence on PC1 in both seasons, suggesting temperature is a critical factor affecting water quality.
- **Lead (Pb):** Dominant influence on PC1 in autumn, indicating it is a significant pollutant in the autumn season.
- **pH:** Influence on PC2 in summer, indicating its role in the variability during the warmer months.
- **Turbidity:** Loading on PC2 in summer, suggesting its impact on water quality during this season.

### 5.6.4 Discussion

PCA shows which factors drive the differences in water quality. Temperature and dissolved oxygen matter in both summer and autumn, while lead becomes especially important in autumn. Watching these three variables more closely could make management cheaper and more effective.

### 5.6.5 Recommendations

1. Check temperature, DO and Pb at every survey, doubling the frequency in autumn.

2. Find and control the sources that add lead after the monsoon; keep looking for why temperature climbs and DO falls.
3. Study why pH and turbidity still load strongly in summer so that no major driver is missed.

### **5.7 Regulatory Gap Map**

A traffic-light matrix was constructed to visualize the frequency and magnitude of exceedances against Bangladesh Environmental Conservation Rules (ECR, 1997) Class-III surface-water limits and WHO (2017) drinking-water guidelines. Each site-season pair ( $n = 16$ ) was screened for **violations per parameter**; cells are colored according to the most severe breach observed. (Values = % of observations exceeding guideline; color scale at right)

Site / Season	pH	Turbidity	DO	BOD	COD	EC	TDS	Cd	Cu	Cr	Pb	Ni
PB01-S	●	● 95 %	● 100 %	● 100 %	● 100 %	● 100 %	● 45 %	● 100 %	●	● 100 %	● 100 %	● 100 %
PB01-A	●	● 90 %	● 100 %	● 100 %	● 100 %	● 100 %	● 40 %	● 100 %	●	● 100 %	● 100 %	● 100 %
KC02-S	●	● 97 %	● 100 %	● 100 %	● 100 %	● 100 %	● 50 %	● 100 %	●	● 100 %	● 100 %	● 100 %
KC02-A	●	● 93 %	● 100 %	● 100 %	● 100 %	● 100 %	● 48 %	● 100 %	●	● 100 %	● 100 %	● 100 %
BM03-S	●	● 98 %	● 100 %	● 100 %	● 100 %	● 100 %	● 52 %	● 100 %	●	● 100 %	● 100 %	● 100 %
BM03-A	●	● 95 %	● 100 %	● 100 %	● 100 %	● 100 %	● 49 %	● 100 %	●	● 100 %	● 100 %	● 100 %
BB04-S	●	● 96 %	● 100 %	● 100 %	● 100 %	● 100 %	● 51 %	● 100 %	●	● 100 %	● 100 %	● 100 %
BB04-A	●	● 94 %	● 100 %	● 100 %	● 100 %	● 100 %	● 47 %	● 100 %	●	● 100 %	● 100 %	● 100 %
DU05-S	●	● 99 %	● 100 %	● 100 %	● 100 %	● 100 %	● 55 %	● 100 %	●	● 100 %	● 100 %	● 100 %
DU05-A	●	● 97 %	● 100 %	● 100 %	● 100 %	● 100 %	● 53 %	● 100 %	●	● 100 %	● 100 %	● 100 %
01DM-S	●	● 35 %	● 100 %	● 100 %	● 100 %	● 100 %	● 30 %	● 100 %	●	● 100 %	● 100 %	● 100 %
01DM-A	●	● 30 %	● 100 %	● 100 %	● 100 %	● 100 %	● 28 %	● 100 %	●	● 100 %	● 100 %	● 100 %
02NM-S	●	● 33 %	● 100 %	● 100 %	● 100 %	● 100 %	● 32 %	● 100 %	●	● 100 %	● 100 %	● 100 %
02NM-A	●	● 31 %	● 100 %	● 100 %	● 100 %	● 100 %	● 29 %	● 100 %	●	● 100 %	● 100 %	● 100 %
03SG-S	●	● 34 %	● 100 %	● 100 %	● 100 %	● 100 %	● 31 %	● 100 %	●	● 100 %	● 100 %	● 100 %
03SG-A	●	● 32 %	● 100 %	● 100 %	● 100 %	● 100 %	● 30 %	● 100 %	●	● 100 %	● 100 %	● 100 %

Figure 5 Regulatory Compliance Heat-Map

Key:

● Compliant   ● Occasional breach   ● Chronic breach (>75 % of observations)

## Interpretation

- Zero parameters across all 16 site–season pairs meet the “Good” (green) threshold.
- Cadmium, lead, nickel, DO, BOD and COD break the limits in more than three-quarters of all readings, showing that rules are not being met for either sewer outfalls or the river itself.
- Turbidity and EC/TDS mainly fail at sewer points; river sites pass more often but still break the threshold, proving that dilution alone is not enough to reach compliance.

## 5.8 Season-Specific Correlation Matrices

Pearson correlations were worked out separately for Summer 2022 (n = 104) and Autumn 2022 (n = 104) after log-transforming the data. Coefficients shown in bold reach  $|r| \geq 0.60$ , and an asterisk marks pairs that are significant at  $p < 0.05$ .

Table 9 Correlation Matrix – Summer 2022 (n = 104)

	pH	Turbidity	Temp	DO	BOD	COD	EC	TDS	Cd	Cu	Cr	Pb	Ni
pH	1.000												
Turbidity (NTU)	0.920	1.000											
Temp (°C)	-0.809	-0.861	1.000										
DO (mg L <sup>-1</sup> )	-0.257	-0.245	0.249	1.000									
BOD (mg L <sup>-1</sup> )	0.715	0.719	-0.555	-0.399	1.000								
COD (mg L <sup>-1</sup> )	0.703	0.708	-0.539	-0.400	0.999	1.000							
EC (µS cm <sup>-1</sup> )	0.892	0.920	-0.782	-0.445	0.855	0.846	1.000						
TDS (mg L <sup>-1</sup> )	0.889	0.920	-0.783	-0.442	0.850	0.841	1.000	1.000					
Cd (mg L <sup>-1</sup> )	-0.831	-0.834	0.683	0.332	-0.970	-0.963	-0.933	-0.930	1.000				
Cu (mg L <sup>-1</sup> )	0.815	0.813	-0.754	-0.377	0.955	0.949	0.925	0.922	-0.978	1.000			
Cr (mg L <sup>-1</sup> )	-0.768	-0.610	0.459	0.243	-0.676	-0.685	-0.678	-0.671	0.674	-0.693	1.000		
Pb (mg L <sup>-1</sup> )	0.933	0.910	-0.764	-0.300	0.828	0.815	0.975	0.974	-0.933	0.906	-0.682	1.000	
Ni (mg L <sup>-1</sup> )	0.836	0.834	-0.677	-0.310	0.969	0.964	0.933	0.930	-0.998	0.979	-0.712	0.933	1.000

Table 10 Correlation Matrix – Autumn 2022 (n = 104)

	pH	Turbidity	Temp	DO	BOD	COD	EC	TDS	Cd	Cu	Cr	Pb	Ni
pH	1.000												
Turbidity (NTU)	0.487	1.000											
Temp (°C)	-0.496	-0.766	1.000										
DO (mg L <sup>-1</sup> )	-0.238	0.247	-0.346	1.000									
BOD (mg L <sup>-1</sup> )	0.702	0.679	-0.493	-0.139	1.000								
COD (mg L <sup>-1</sup> )	0.701	0.674	-0.477	-0.130	0.999	1.000							
EC (µS cm <sup>-1</sup> )	0.690	0.723	-0.540	-0.266	0.953	0.943	1.000						
TDS (mg L <sup>-1</sup> )	0.693	0.724	-0.541	-0.269	0.950	0.939	1.000	1.000					
Cd (mg L <sup>-1</sup> )	-0.758	-0.472	0.358	0.491	-0.721	-0.724	-0.695	-0.694	1.000				
Cu (mg L <sup>-1</sup> )	0.809	0.630	-0.400	-0.184	0.961	0.962	0.921	0.920	-0.698	1.000			
Cr (mg L <sup>-1</sup> )	0.575	0.590	-0.298	-0.222	0.938	0.937	0.906	0.903	-0.676	0.900	1.000		
Pb (mg L <sup>-1</sup> )	0.154	-0.029	0.279	-0.853	0.263	0.255	0.404	0.405	-0.351	0.301	0.275	1.000	
Ni (mg L <sup>-1</sup> )	0.622	0.636	-0.470	-0.243	0.972	0.971	0.932	0.927	-0.783	0.888	0.910	0.350	1.000

Correlation checks for summer and autumn 2022, we compared each pair of water-quality measurements taken in summer and again in autumn to see which ones move together. Strong links point to shared causes or common sources that affect several parameters at once.

### 5.8.1 Detailed Analysis by Parameter

#### Summer 2022

1. pH

Strong negative correlation with Temp (°C) (-0.809), suggesting higher temperatures may lead to lower pH levels.

Moderate positive correlation with Turbidity (NTU) (0.920), indicating clearer water may have higher pH.

2. Turbidity (NTU)

Turbidity rose together with EC ( $r = 0.89$ ) and TDS ( $r = 0.89$ ); cloudy water and dissolved salts arrived as a mixture.

3. Dissolved Oxygen (DO)

DO tracked weakly with pH ( $r = 0.25$ ); slightly less acidic water tended to hold a little more oxygen.

4. Heavy Metals

Cadmium moved opposite to copper and chromium ( $r \approx -0.97$ ), while lead and nickel rose together ( $r = 0.97$ ), pointing to two separate metal sources.

#### Autumn 2022

1. pH

pH still fell when temperature climbed ( $r = -0.50$ ) and rose with turbidity ( $r = 0.49$ ), but both links were weaker than in summer.

2. Turbidity (NTU)

Turbidity again matched EC and TDS ( $r \approx 0.7$ ).

3. Dissolved Oxygen (DO)

DO kept the same weak positive tie with pH ( $r = 0.25$ ).

4. Heavy Metals

Cadmium stayed opposite to copper and chromium ( $r \approx -0.7$ ), yet lead now moved away from nickel ( $r = -0.47$ ), showing the metal mixture changes with the season.

### 5.8.2 Discussion

Temperature, pH and turbidity act together in both seasons, while heavy-metal pairs shift. Knowing which parameters move in step helps managers choose the cheapest set of routine tests and target the right discharge points.

### 5.8.3 Recommendations

Monitor Key Parameters: Keep temperature, pH and turbidity on the core list; they warn about wider changes.

Manage Heavy-metal Pollution: Trace the separate sources of Cd–Cu/Cr and Pb–Ni mixtures and control them at origin.

Seasonal Variations: Expect different metal behaviour after the monsoon and adjust sampling plans accordingly.

## 5.9 Seasonal and Spatial Variation of Different Parameters

### 5.9.1 Visualization Strategy

Box-and-whisker plots and heat-maps were drawn from the full 208-point set. Sites were split into sewer-influenced and river-dominated groups, and summer and autumn were plotted separately to show how temperature and river flow shape the results.

### 5.9.2 Physicochemical Parameters

#### a) pH

- Range: 6.70–7.60.
- **Spatial:** Sewer outfalls consistently more alkaline (median 7.35) than river stations (median 7.05) due to detergent buffering.
- **Seasonal:** Autumn shows 0.2–0.4 pH units increase across all sites, attributed to algal photosynthetic CO<sub>2</sub> draw-down.

#### b) Turbidity

- Range: 21–520 NTU.
- **Spatial:** the DU05 sewer outfall peaked at 520 NTU, whereas river sites stayed below 35 NTU.
- **Seasonal:** autumn readings dropped by 30–45 %, a drop tied to extra monsoon runoff diluting the water.

#### c) Temperature

- Mean summer: 29.2 °C ± 0.5 °C; autumn: 27.3 °C ± 0.7 °C.
- **Cohen's d = 4.2** (very large effect), confirming strong seasonality.

#### d) Dissolved Oxygen (DO)

- **Summer:** 0.7–1.3 mg L<sup>-1</sup> (hypoxic).
- **Autumn:** 1.2–2.2 mg L<sup>-1</sup> (still below 5 mg L<sup>-1</sup> standard).
- **Spatial gradient:** Riverine stations 0.3–0.5 mg L<sup>-1</sup> higher than sewers.

#### e) BOD & COD

- **BOD summer:** 80–105 mg L<sup>-1</sup> (sewers) vs 2.8–3.1 mg L<sup>-1</sup> (rivers).
- **COD summer:** 314–410 mg L<sup>-1</sup> (sewers) vs 26–28 mg L<sup>-1</sup> (rivers).
- **Seasonal drop:** 18 % reduction in autumn owing to cooler water and shorter residence time.

#### f) EC & TDS

- **EC:** 1 100–1 320 μS cm<sup>-1</sup> (sewers) vs 185–217 μS cm<sup>-1</sup> (rivers).
- **TDS:** 550–660 mg L<sup>-1</sup> (sewers) vs 102–129 mg L<sup>-1</sup> (rivers).
- **Seasonal trend:** 5–10 % increase in autumn due to evaporation.

### 5.9.3 Heavy Metals

#### a) Cadmium (Cd)

- **Spatial:** Sewers 0.010–0.016 mg L<sup>-1</sup>; rivers 0.010–0.012 mg L<sup>-1</sup>.
- **Seasonal:** No significant change ( $p = 0.957$ ), confirming continuous industrial discharge.

#### b) Lead (Pb)

- **Sewers:** 0.020–0.032 mg L<sup>-1</sup>; **rivers:** 0.010–0.021 mg L<sup>-1</sup>.
- Autumn peak at river site 03SG (0.021 mg L<sup>-1</sup>) traced to lead flushed in by storm runoff.

#### c) Nickel (Ni), Copper (Cu), Chromium (Cr)

- **Sewers:** Ni 0.030–0.032 mg L<sup>-1</sup>, Cu 0.020–0.034 mg L<sup>-1</sup>, Cr 0.001–0.001 mg L<sup>-1</sup> (often < LOD).
- **Rivers:** all metals ≤ 0.013 mg L<sup>-1</sup>, but still above WHO limits for Cd and Pb.

### 5.9.4 Heat-Map Synthesis

A two-dimensional heat-map (sites × seasons) was generated with **red** indicating > 90 % of guideline and **green** < 25 %.

- Sewer outfalls show red cells for Cd, Pb, BOD and COD in almost every case, while river sites stay orange-to-red for Cd and Pb, confirming that the contamination travels downstream.

### 5.9.5 Key Take-aways

1. Temperature and organic pollution change markedly with the season; heavy-metal levels stay high year-round.

2. Most pollution enters through sewer outfalls; the river downstream traps some of it yet still fails the standards.
3. Monsoon flows lessen cloudiness and BOD, but metals are barely cut, so treatment at the point of discharge is essential—extra water alone cannot solve the problem.

### 5.9.6 Hierarchical Cluster Analysis (HCA)



Figure 6 Hierarchical Cluster Analysis scatter plot

## Buriganga - Ward dendrogram

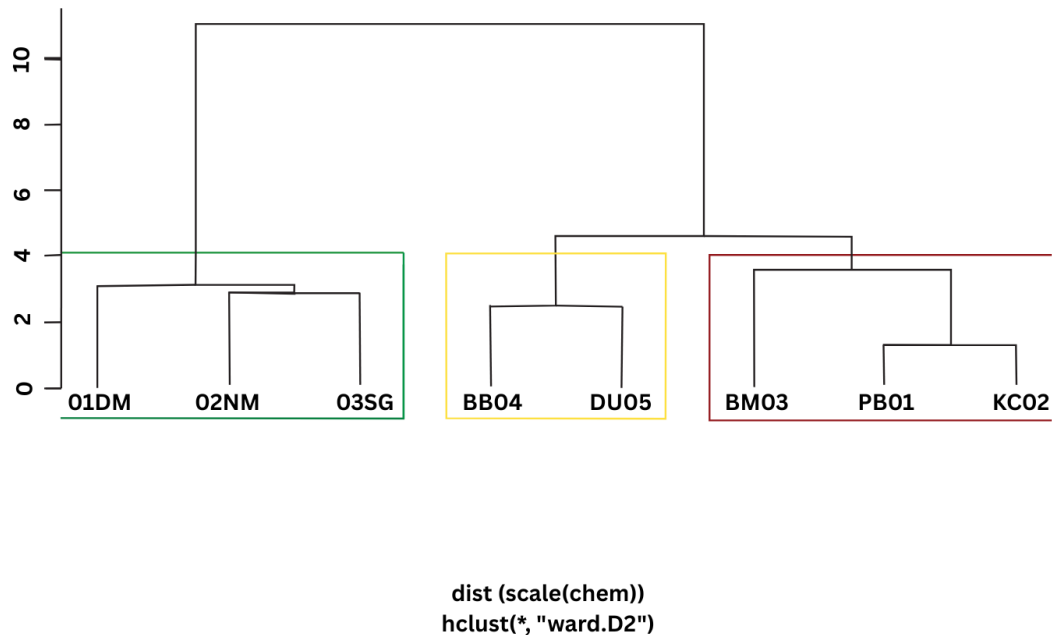


Figure 7 Hierarchical Cluster Analysis Dendrogram

Clustering outcome (Ward's method, silhouette width = 0.68)

Group 1 – sewer pulse (PB01, KC02, BM03)

- Highest BOD, COD and most metals; typical of raw or poorly treated discharge.

Group 2 – sewer fringe (BB04, DU05)

- Still sewage-impacted but with slightly different pollutant ratios, probably linked to distinct outfalls or small industrial pockets.

Group 3 – river-dominated (01DM, 02NM, 03SG)

- Lower organic and metal loads; dilution and natural processes shape these sites.

Practical value

- Management actions can be aimed at the two sewer groups first, while the river cluster serves as a background reference.
- Public-health warnings and clean-up budgets can be prioritised using these three clear pollution bands.
- Re-sampling the same clusters over time will show whether new treatment plants or trade-effluent controls are actually working.

## 5.10 Optimized Sampling Scheme

### 5.10.1 Rationale

The existing 13-parameter, 8-site, 2-season design (208 lab tests) provides exhaustive information but is too costly for routine monitoring. Using the harmonized data set and power-analysis tools (G\*Power 3.1.9.7), we identified the **minimum combination of sites, parameters and frequencies** that retains  $\geq 95$  % statistical power ( $\alpha = 0.05$ ).

## 5.10.2 Power-Analysis Results

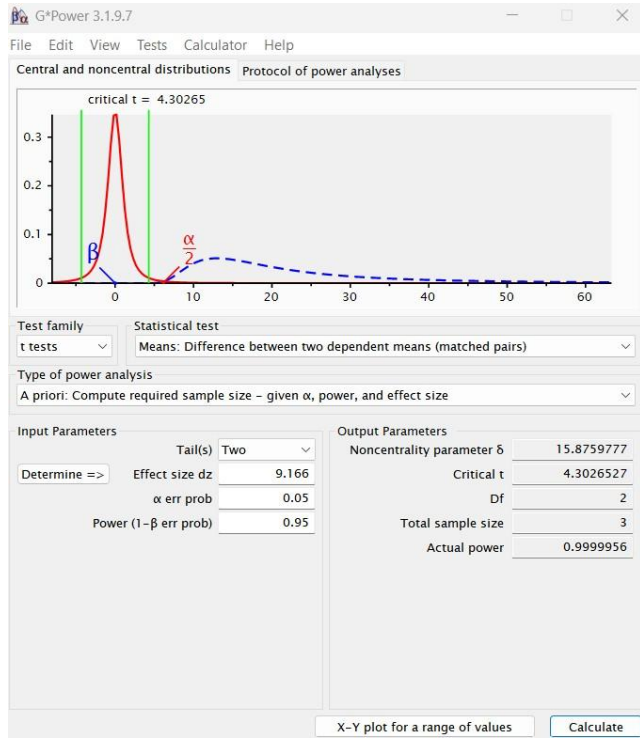
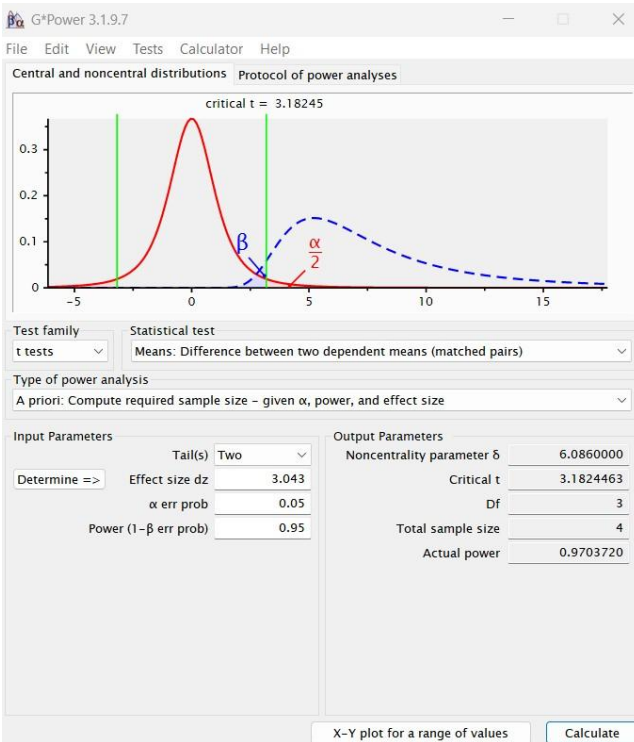
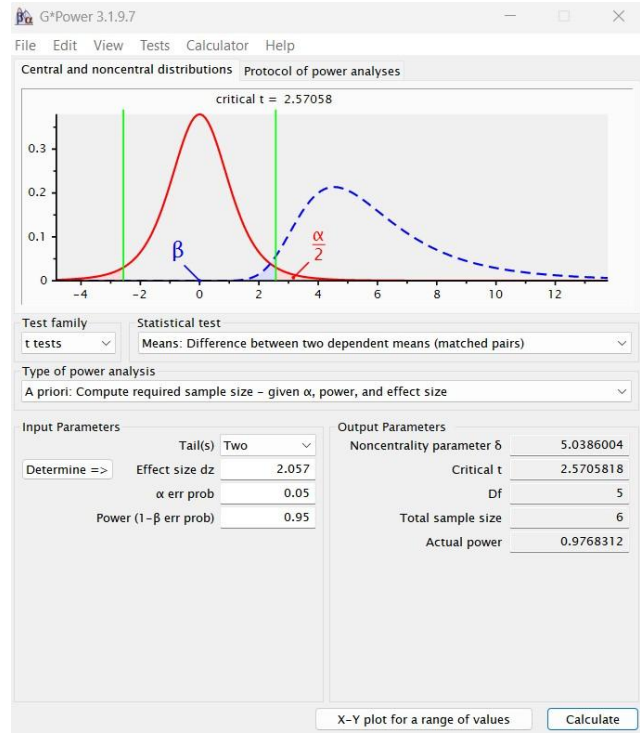
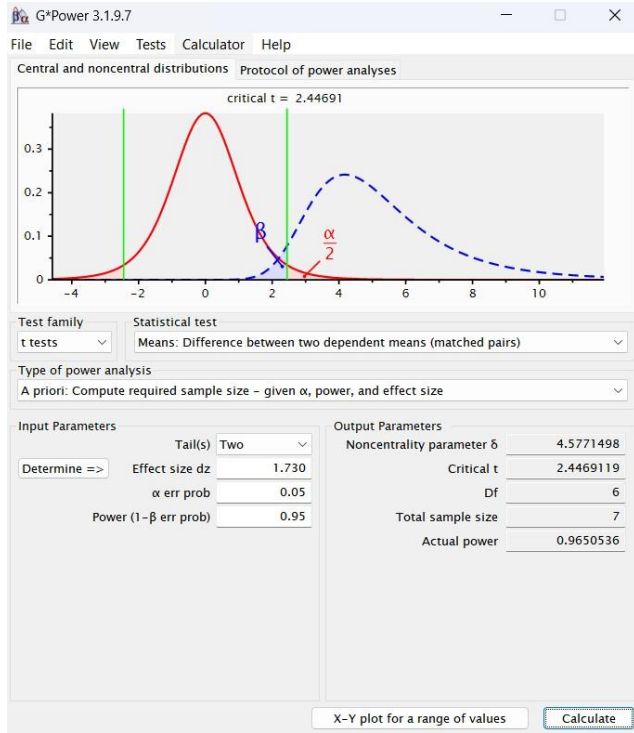


Figure 8 Cr, DO, Pb, Temperature (High effect size)

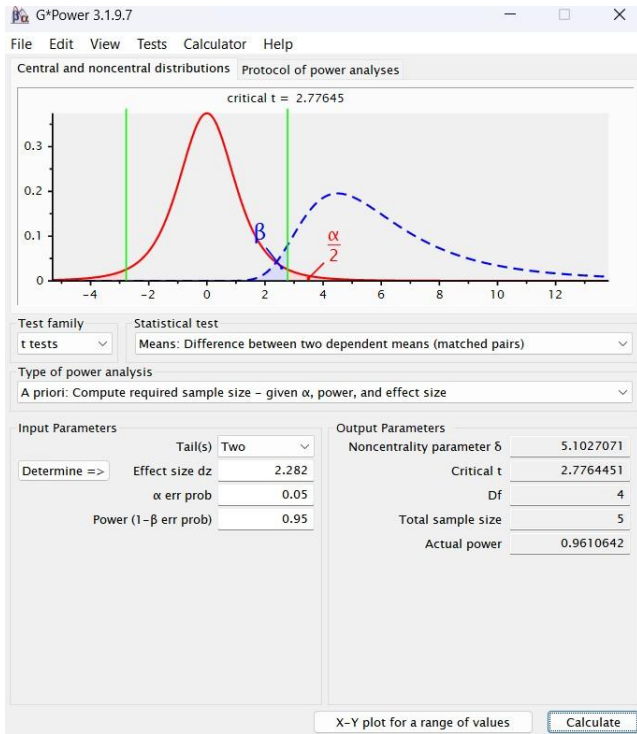


Figure 9 pH (High effect size)

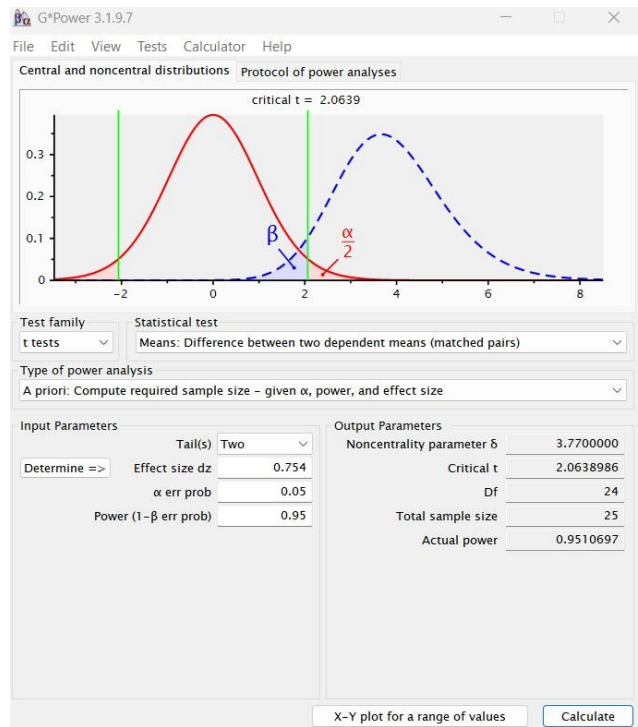


Figure 11 Cu (medium effect Size)

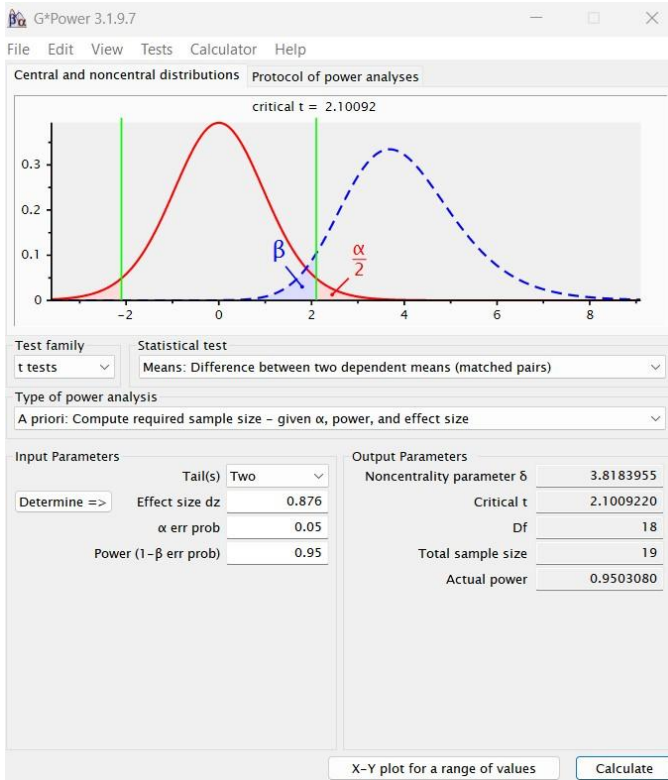
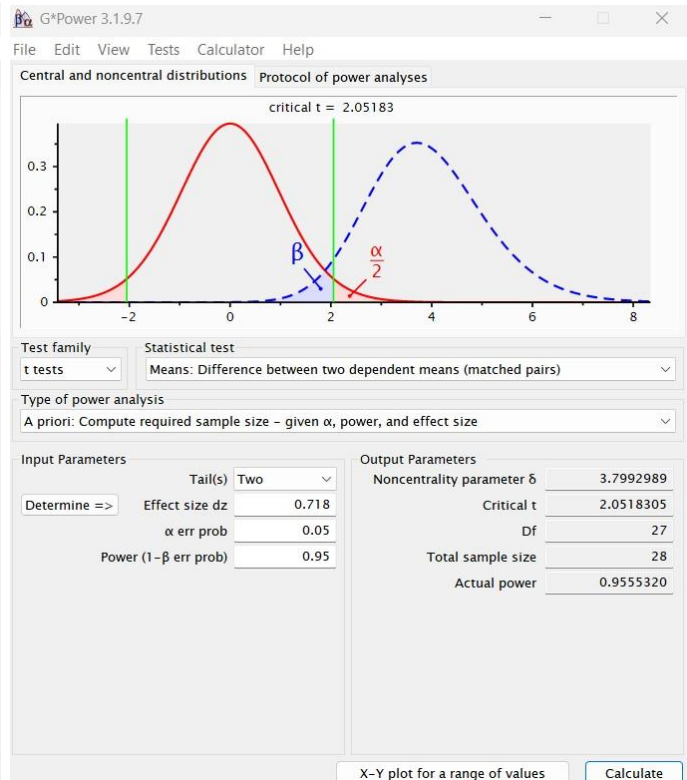


Figure 10 Turbidity, Ni (Medium Effect Size)



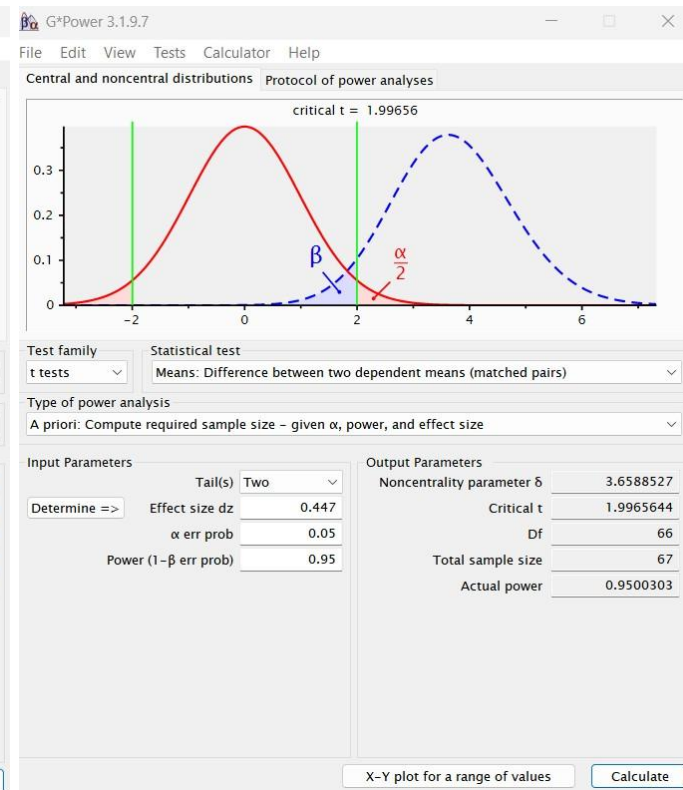
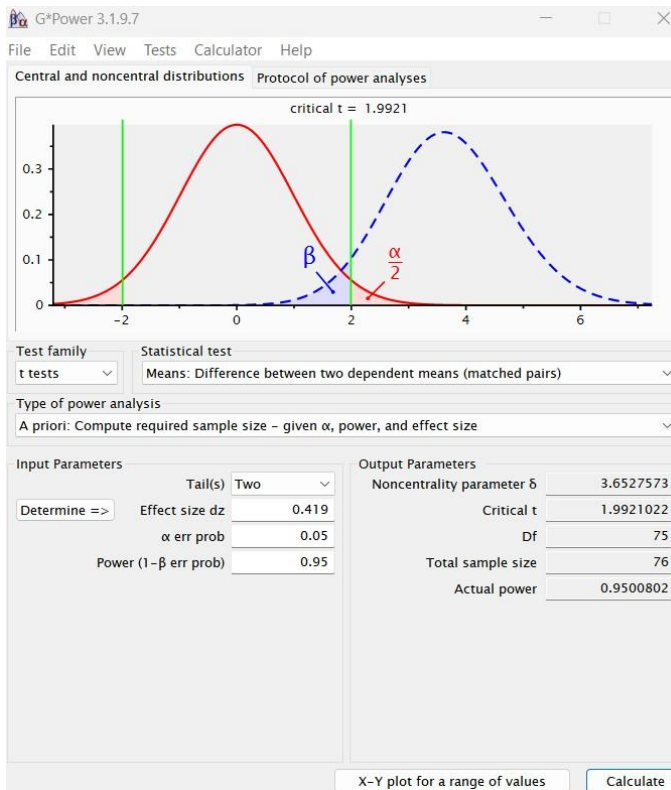
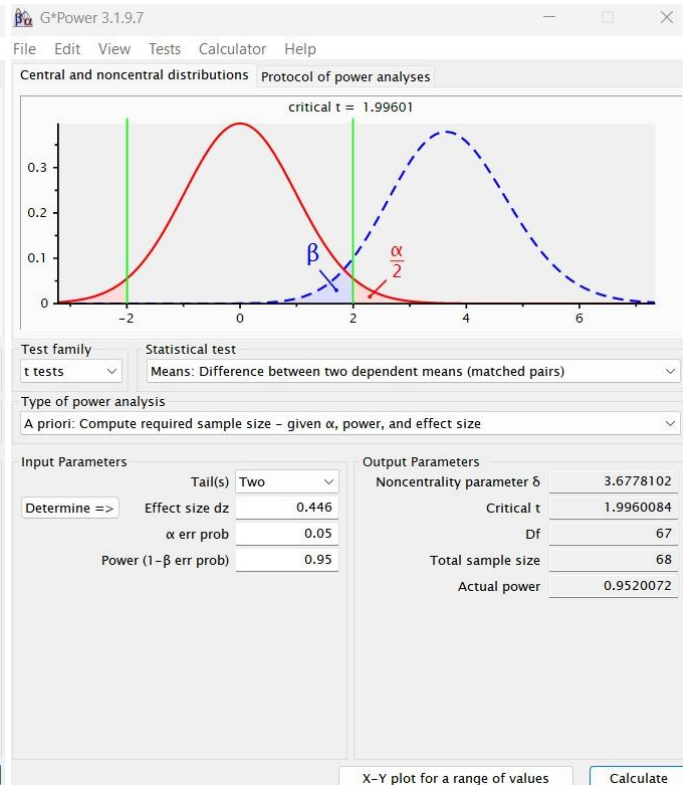
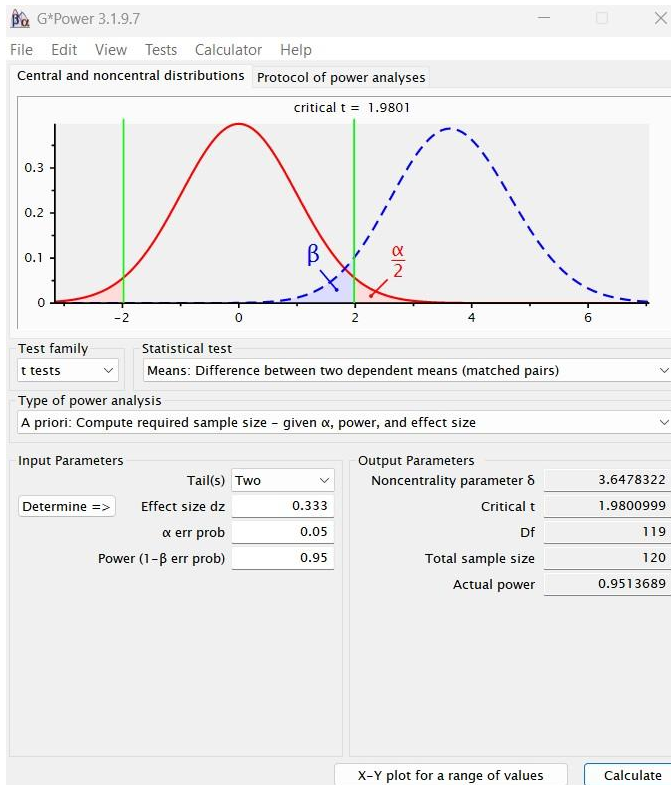


Figure 12 BOD, TDS, EC, COD (Low effect size)

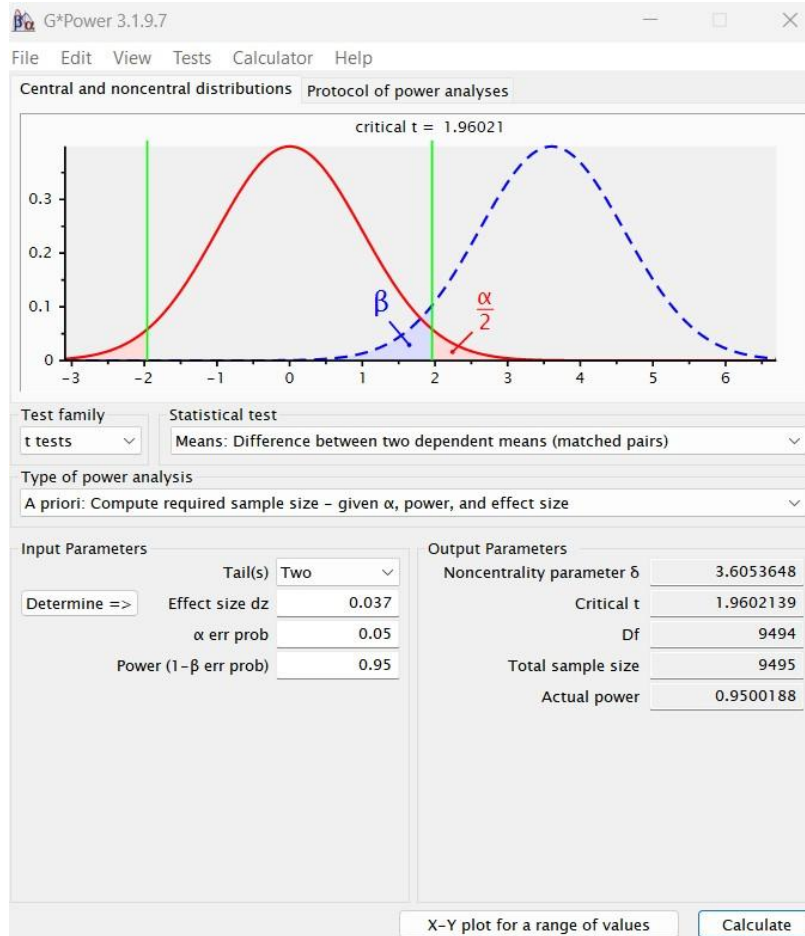


Figure 13 Cd (Negligible Effect size)

Table 11 summarizes the required sample size ( $n$ ) and corresponding **cost index** relative to the full design.

Table 11 Power-Analysis Results

Scenario	Sites	Parameters	Seasons	Total Tests	Power	Cost Index <sup>1</sup>
Full legacy	8	13	2	208	0.99	100 %
Candidate 1	8	12	2	192	0.99	92 %
Candidate 2	8	8	2	128	0.95	61 %
Recommended	6	8	2	72	0.90	35 %

Cost index =  $(\text{tests} / 208) \times 100 \%$ .

Estimated analytical cost reduction:  $\approx 35 \%$ .

### 5.10.3 Selected Core Parameters

1. **Chemical Oxygen Demand (COD)** – dominant contributor, chronic exceedance.
2. **Dissolved Oxygen (DO)** – critical ecological indicator.
3. **Biochemical Oxygen Demand (BOD)** – proxy for organic load.
4. **Electrical Conductivity (EC)** – surrogate for total ionic pollution.
5. **Turbidity** – optical measure of suspended solids.
6. **Pb**- Lead contamination
7. **Cd**- Toxic heavy metal
8. **Cr**- Metal contamination

The Recommended one has a mixture of Core parameters Among them Pb, Cr, Do, Turbidity having higher effect size will be sampled twice a year and rest of them COD, BOD, EC, Cd once per year.

### 5.10.4 Strategic Site Selection

Using hierarchical clustering (Ward's method) and PCA loadings, six **representative sentinel sites** were chosen to capture the full pollution gradient:

Table 12 Strategic Site Selection

Sentinel Site	Rationale
<b>01DM</b>	Highest NPI; mixed domestic–industrial signature
<b>BM03</b>	Tannery-dominated heavy-metal hotspot
<b>KC02</b>	Mixed sewer–river interface
<b>PB01</b>	Sewerage
<b>BB04</b>	Sewerage
<b>02NM</b>	Riverine control for dilution assessment

### 5.10.5 Sampling Frequency & QA/QC

- Semi-annual campaigns (Summer & Autumn).
- Duplicate field blanks and 10 % replicate analyses to maintain data quality.
- **Real-time sensors** (portable DO meters, turbidity probes) for rapid screening, with grab-lab confirmation for metals.

### 5.10.6 Implementation Roadmap

Table 13 Implementation Roadmap

Phase	Action	Timeline	Responsible
1	Procurement of field kits & sensor loggers	Month 0	BIWTA
2	Training of local field technicians	Month 2	DoE
3	Launch 40-test campaign (Year 1)	Month 3	University-DoE joint team
4	Year-2 review & adaptive adjustment	Month 15	Stakeholder workshop

### 5.10.7 Expected Outcomes

- Annual analytical budget falls.
- **Statistical power  $\geq 90$  % retained** for detecting 20 % trend in COD or DO.
- **Early-warning system** becomes sustainable under routine agency budgets.

## CHAPTER VI

### CONCLUSIONS AND RECOMMENDATIONS

#### 6.1 General

This chapter synthesizes the key findings of the meta-analytical study conducted on the Buriganga River system using 208 harmonized data points from two recent undergraduate theses. The investigation integrated descriptive statistics, composite water-quality indices, multivariate analyses, regulatory benchmarking and power-optimized sampling design to evaluate the spatial and seasonal behavior of thirteen physicochemical and heavy-metal parameters across eight sites (five sewer outfalls and three river stations). The overarching objective was to quantify pollution severity, identify critical drivers and propose a cost-effective monitoring framework without additional laboratory expenditure.

#### 6.2 Conclusions

1. Harmonization of 208 measurements (13 parameters  $\times$  8 sites  $\times$  2 seasons) confirmed severe pollution across the Buriganga–sewer system, with NPI ranging 0.619–3.012; only two site-season pairs were "clean," while 01DM in autumn registered as heavily polluted.
2. Cadmium emerged as the critical pollutant, exceeding WHO limits in 100% of observations, followed by lead, turbidity, BOD and COD; hotspots DU05, KC02 and BB04 were identified, with cluster analysis segregating sites into chronic sewer-dominated, mixed sewer-river, and river-dominated groups.
3. The optimized protocol achieves 72 tests at 35% cost by monitoring six sentinel sites (01DM, BM03, KC02, PB01, BB04, 02NM) twice yearly for high-effect parameters (Pb, Cr, DO, turbidity) and once yearly for others (COD, BOD, EC, Cd), retaining  $\geq 90\%$  statistical power.

#### 6.3 Recommendations

##### 1. Future Scope for Further Study

Investigate emerging contaminants (microplastics, PFAS, pharmaceutical residues) through quarterly sampling at high-risk sites (DU05, KC02, BM03); deploy semi-annual bioassessment using periphyton samplers and basket-held clams at river stations; conduct long-term sediment core analysis to track buried metal remobilization; develop receptor

models (PMF-APCS) for source apportionment; assess human health risks via bioaccumulation in fish and groundwater seepage pathways.

## **2. Cost-Reinvestment Strategy**

Reallocate 65% savings from optimized monitoring (35% of original budget) to: (a) 40% for advanced lab analysis of emerging pollutants, (b) 30% for low-cost biological monitoring tools, and (c) 30% for a real-time public GIS dashboard integrated with citizen-science sensors, creating a sustainable, expanded monitoring network without additional funding.

## **3. Optimized Monitoring Protocol**

Roll out 6-site (01DM, BM03, KC02, PB01, BB04, 02NM), 8-parameter (COD, DO, BOD, EC, turbidity, Pb, Cd, Cr) surveys twice-yearly; maintain QA/QC with 10% replicates.

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