Comparative Reliability Analysis of Effluent Treatment Plants in Pulp and Paper Industrial Sector: A Case Study of West Bengal

A thesis submitted towards partial fulfilment of the requirements

for the degree of

MASTER OF ENGINEERING
In Water Resources and Hydraulic Engineering
Course affiliated to Faculty of Engineering & Technology
Jadavpur University

Submitted by

DEBU ADDHYA
Exam Roll No: **M4WRE24012**
Reg. No.: **163864** of **2022-2023**

Under the guidance of

PROF. (DR.) ASIS MAZUMDAR
Professor & Director
School Of Water Resources Engineering, Jadavpur University

DR. GOURAB BANERJEE
Assistant Professor
School of Water Resources Engineering, Jadavpur University

School of Water Resources Engineering
M.E. (Water Resources & Hydraulic Engineering) course affiliated to
Faculty of Engineering & Technology
Jadavpur University
Kolkata 700032, India
2024

M.E. (Water Resources & Hydraulic Engineering) course affiliated to
Faculty of Engineering & Technology
Jadavpur University
Kolkata, India

Certificate of Recommendation

This is to certify that the thesis entitled "**Comparative Reliability Analysis of Effluent Treatment Plants in Pulp and Paper Industrial Sector: A Case Study of West Bengal"** is a bonafide work carried out by **Mr. Debu Addhya** our supervision and guidance for partial fulfilment of the requirement for the Post Graduate Degree of Master of Engineering in Water Resources & Hydraulic Engineering during the academic session 2022-2024.

THESIS ADVISOR
Prof. (Dr.) Asis Mazumdar
Professor & Director
School of Water Resources Engineering
Jadavpur University
Kolkata-700032

THESIS ADVISOR
Dr. Gourab Banerjee
Assistant Professor
School of Water Resources Engineering
Jadavpur University
Kolkata-700032

DIRECTOR
Prof. (Dr.) Asis Mazumdar
Professor & Director
School of Water Resources Engineering
Jadavpur University
Kolkata-700032

DEAN
Faculty of Interdisciplinary Studies, Law & Management
Jadavpur University

M.E. (Water Resources & Hydraulic Engineering) course affiliated to
Faculty of Engineering & Technology
Jadavpur University
Kolkata, India

CERTIFICATE OF APPROVAL **

This foregoing thesis is hereby approved as a credible study of an engineering subject carried out and presented in a manner satisfactorily to warranty its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not endorse or approve any statement made or opinion expressed or conclusion drawn therein but approve the thesis only for purpose for which it has been submitted.

Committee

_____

Final Examination for the evaluation of the thesis

_____

_____

** Only in case the thesis is approved.

DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of my **Master of Engineering** in **Water Resources & Hydraulic Engineering** in the Faculty of Interdisciplinary Studies, Jadavpur University during academic session 2022-2024.

All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

NAME : **DEBU ADDHYA**

EXAM ROLL NUMBER : **M4WRE24012**

THESIS TITLE : **Comparative Reliability Analysis of Effluent Treatment Plants in Pulp and Paper Industrial Sector: A Case Study of West Bengal**

SIGNATURE :

DATE : **31st May, 2024**

ACKNOWLEDGEMENT

I express my sincere gratitude and thanks to my supervisor **Prof. (Dr.) Asis Mazumdar,** Professor & Director of School of Water Resources Engineering, Jadavpur University and **Dr. Gourab Banerjee,** Assistant Professor of School of Water Resources Engineering, Jadavpur University. Without their support and guidance, it was impossible for me to carry out this project.

I would also like to express my sincere gratitude to **Prof. (Dr.) Arunabha Majumder,** Emeritus Professor, School of Water Resources Engineering, **Prof. (Dr.) Pankaj Kumar Roy,** Professor, School of Water Resources Engineering, **Dr. Subhasish Das,** Associate Professor, School of Water Resources Engineering, and **Dr. Rajib Das,** Assistant Professor, School of Water Resources Engineering, Jadavpur University for their valuable suggestions.

Moreover, I would like to express my sincere thanks to my seniors **Mr. Nilanjan Saha**, **Prasun Mukherjee** and **S M Hidayetullah** for their support and help during my thesis work.

Thanks, are also due to all staff of School of Water Resources Engineering of Jadavpur University and the Regional center for their help and support.

In addition, I express my very profound gratitude to my family members for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Most significantly I would like to express my gratitude, thanks and gratefulness to my parents without whom I would not be able to do anything in my life.

Date :

DEBU ADDHYA
Examination Roll No- M4WRE24012

ABSTRACT

The pulp and paper industry is a significant contributor to industrial wastewater pollution, necessitating efficient and reliable effluent treatment plants (ETPs) to ensure environmental sustainability. This study conducts a comparative reliability analysis of ETPs in the pulp and paper sector in West Bengal, focusing on the water quality parameters such as TSS, TDS, BOD and COD. The research aims to enhance ETP efficiency and reliability through systematic reliability analysis, aiming for consistent compliance with environmental discharge standards. Data was collected from multiple ETPs across various pulp and paper mills in West Bengal. Laboratory analyses, conducted in the University lab, measured TSS, TDS, BOD, and COD to calculate the COR. The COR values provided insights into the stability and operational performance of these treatment plants. Statistical methods were employed to interpret these values and suggest design improvements for achieving the necessary discharge standards. The findings indicate significant variability in the reliability of different ETPs. For instance, Location 1 (L1) demonstrated high reliability with COR values of 0.771518 for TSS, 0.869748 for TDS, 0.782366 for BOD, and 0.912692 for COD, reflecting stable and effective operations. Conversely, Location 5 (L5) showed the lowest reliability, with COR values of 0.488927 for TSS, 0.749464 for TDS, 0.589809 for BOD, and 0.699398 for COD, indicating significant operational challenges. It suggests that while some ETPs consistently meet environmental discharge standards, others require targeted improvements in their operational controls to enhance performance. The findings indicate that reliability analysis is crucial for enhancing the operational stability of ETPs. By implementing design improvements based on COR values, ETPs can achieve significant reductions in pollutants and ensure better compliance with environmental regulations. The study establishes performance benchmarks and provides recommendations for future ETP design and operational practices, contributing to improved environmental management and sustainability in the pulp and paper industry.

Keywords: Effluent Treatment Plants, Reliability Analysis, Pulp and Paper Industry, Total Suspended Solids, Total Dissolved Solids, Biochemical Oxygen Demand, Chemical Oxygen Demand.

.

TABLE OF CONTENTS

ABSTRACT v
TABLE OF CONTENTS vi
FIGURE TABLE viii
LIST OF TABLES ix
LIST OF PHOTOGRAPHS x
LIST OF ABBREVIATIONS xi
Chapter 1: Introduction 1
1.1. Background of the study 2
1.2. Industry Description 4
1.3. Research Gap 5
1.4. Research Objective 6
1.5. Overall Methodology 6
1.6. Propose Outcome 7
1.7. Thesis Outline 7
Chapter 2: Literature Review 8
Chapter 3: Theoretical Background 19
3.1. Characteristics of Industrial Wastewaters 23
3.1.1. Physical Characteristics 23
3.1.2. Chemical Characteristics 24
3.2. Water Quality Regulation in India 25
3.2.1. Water pollution legislation and institutions 25
3.2.2. Regulatory standards for protection of water quality 25
3.3. Industrial Wastewater Treatment: current practices in paper mill 28
3.3.1. Primary Treatment 29
3.3.2. Secondary Treatment 33
3.3.3. Advanced Research of Treatment Mechanism 39
3.4. Reliability 42
Chapter 4: Methodology 44
4.1. Sample Collection 46
4.2. Sample Analysis 50
4.2.1. Total suspended solids 50
4.2.2. Total dissolved solids 52
4.2.3. Biochemical oxygen demand (BOD) 53

4.2.4. Chemical oxygen demand (COD) 54
4.3. Reliability Analysis and coefficient of reliability 56
4.4. Design and operational concentrations to achieve the discharge standards 58
Chapter 5: Result and Discussion 59
5.1. Monitoring data from the treatment plants 60
5.2. Interpretation of the coefficient of reliability (COR) 63
5.3. COR values obtained in the study 64
5.4. Design and operation concentrations required to achieve the discharge standards 66
5.5. Some statistical concepts in the assessment of COR and design mean concentration 68
5.5.1. Value of COR closer to 1.0 68
5.5.2. COR values greater than 1.0 69
Chapter 6: Conclusions 70
6.1. Conclusion 71
6.2. Limitation of the study 72
6.3. Future scope of the study 72
References 73

FIGURE TABLE

FIGURE 1 INDIA'S MEGA CITIES: DOMESTIC AND INDUSTRIAL WASTEWATER GENERATED VS TREATED 20
FIGURE 2 FLOWCHART OF CONVENTIONAL PULP AND PAPER-MILL EFFLUENT TREATMENT. 29
FIGURE 3 EQUALIZATION BASIN 31
FIGURE 4 TYPICAL CROSS-SECTION OF CIRCULAR AND RECTANGULAR CLARIFIER 32
FIGURE 5 TYPICAL ACTIVATED SLUDGE PROCESS: 1. COMPLETELY MIX REACTOR AND 2. PLUG FLOW REACTOR 33
FIGURE 6 OPERATIONAL LAYOUT OF L1, L2, L4 & L6 RESPECTIVELY 41
FIGURE 7 CALCULATION PROCEDURE FOR COEFFICIENTS OF RELIABILITY (COR) 56
FIGURE 8 VARIATION OF AVERAGE INFLUENT AND EFFLUENT CONCENTRATION WITH MEAN REMOVAL EFFICIENCY IN DIFFERENT PLANT LOCATION FOR THE PARAMETERS E.G. TSS, TDS, BOD AND COD RESPECTIVELY 62
FIGURE 9 MEAN (DESIGN) EFFLUENT CONCENTRATIONS TO ACHIEVE 95% COMPLIANCE WITH THE STANDARDS AND THE OBSERVED ACTUAL CONCENTRATIONS 67

LIST OF TABLES

TABLE 1 LOCATION AND GENERAL CHARACTERIZATION OF THE ETPS STUDIED 4
TABLE 2 COMPOSITION OF PAPER-MILL EFFLUENT (PAL, 2017) 22
TABLE 3 GENERAL STANDARDS FOR DISCHARGE OF ENVIRONMENTAL POLLUTANTS 26
TABLE 4 VALUES OF STANDARDIZED NORMAL DISTRIBUTION (NIKU ET AL. 1979) 57
TABLE 5 MEAN CONCENTRATIONS AND MEAN REMOVAL EFFICIENCIES IN THE SIX ETPS 60
TABLE 6 COEFFICIENT OF RELIABILITY AS A FUNCTION OF C_V AND RELIABILITY LEVEL 63
TABLE 7 C_V AND COR FOR THE TREATMENT UNIT IN DIFFERENT LOCATION 64
TABLE 8 MEAN DESIGN EFFLUENT CONCENTRATIONS TO ACHIEVE 95% COMPLIANCE WITH THE STANDARDS AND OBSERVED ACTUAL EFFLUENT CONCENTRATIONS 66

LIST OF PHOTOGRAPHS

PHOTOGRAPH 1 SCREENING UNIT IN ONE THE LOCATION 30
PHOTOGRAPH 2 CIRCULAR CLARIFIER IN ONE OF THE LOCATIONS 32
PHOTOGRAPH 3 AERATION UNIT 35
PHOTOGRAPH 4 SAMPLE COLLECTION FROM THE ETP INLET AT LOCATION 5 46
PHOTOGRAPH 5 SAMPLE COLLECTION FROM THE AT AT LOCATION 5 46
PHOTOGRAPH 6 SAMPLE COLLECTION FROM THE ETP OUTLET AT LOCATION 47
PHOTOGRAPH 7 13 SAMPLE COLLECTION FROM THE ETP AT LOCATION 4 47
PHOTOGRAPH 8 SAMPLE COLLECTION FROM THE ETP OUTLET AT LOCATION 6 47
PHOTOGRAPH 9 SAMPLE COLLECTION FROM THE ETP INLET AT LOCATION 6 47
PHOTOGRAPH 10 SAMPLE COLLECTION FROM THE ETP INLET AT LOCATION 3 48
PHOTOGRAPH 11 SAMPLE COLLECTION FROM THE ETP OUTLET AT LOCATION 3 48
PHOTOGRAPH 12 SAMPLE COLLECTION FROM THE ETP INLET AT LOCATION 2 48
PHOTOGRAPH 13 SAMPLE COLLECTION FROM THE AT AT LOCATION 2 48
PHOTOGRAPH 14 SAMPLE COLLECTION FROM THE ETP INLET AT LOCATION 1 49
PHOTOGRAPH 15 SAMPLE COLLECTION FROM THE ETP OUTLET AT LOCATION 1 49
PHOTOGRAPH 16 SAMPLE COLLECTION FROM THE AT AT LOCATION 1 49
PHOTOGRAPH 17 LABORATORY SETUP, SCHOOL OF WATER RESOURCES ENGINEERING, JADAVPUR UNIVERSITY 50
PHOTOGRAPH 18 SETUP FOR TSS MEASUREMENT 51
PHOTOGRAPH 19 HM- 200 52
PHOTOGRAPH 20 DURING TDS DETERMINATION 52
PHOTOGRAPH 21 BOD INCUBATOR 53
PHOTOGRAPH 22 HACH HQ40D 53
PHOTOGRAPH 23 DRB200 REACTOR 54
PHOTOGRAPH 24 DR1900 SPECTROPHOTOMETER 54
PHOTOGRAPH 25 SAMPLE PREPARATION FOR COD TEST 55
PHOTOGRAPH 26 DURING COD TEST 55

LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
COR	Coefficient of Reliability
CV	Coefficient of Variation
ETP	Effluent Treatment Plant
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
DO	Dissolved Oxygen
MLSS	Mixed Liquor Suspended Solid
MLVSS	Mixed Liquor Suspended Solid
ASP	Activated Sludge Process
WSP	Waste Stabilization Pond
CETP	Common Effluent Treatment Plant
CPCB	Central Pollution Control Board
SPCB	State Pollution Control Board
WWTP	Wastewater Treatment Plant
ETP	Effluent Treatment Plant
UNESCO	United Nations Educational, Scientific and Cultural Organization
USEPA	United States Environmental Protection Agency

Chapter 1: Introduction

1.1. Background of the study

The global demand for clean water is surging, with the world facing significant challenges due to water scarcity and pollution. It is estimated that over 80% of untreated wastewater is discharged into water bodies worldwide (WWAP, 2017). In India, the Central Pollution Control Board (CPCB) reports that the available operational treatment capacity can only treat 37% of the estimated sewage generated from urban centres, highlighting a significant gap in wastewater management infrastructure (CPCB, 2021). Industries such as pulp and paper contribute substantially to environmental pollution. The Indian pulp and paper industry, comprising over 759 mills, consumes 100–250 m^3 of freshwater per ton of paper produced, generating 75–225 m^3 of wastewater per ton of paper (Singh, 2004; Ansari, 2004). This industry is classified as a significant environmental polluter, with effluents containing high concentrations of suspended solids, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) (Bharagava & Mishra, 2017). In response to the escalating water pollution crisis, wastewater treatment plants (WWTPs) are under increasing pressure to improve resource efficiency and meet stringent discharge standards. Reliability analysis has emerged as a critical tool for assessing the performance of WWTPs. For instance, a study analysing 16 Portuguese WWTPs found that only 17% of the plants consistently met prescribed discharge standards (Silva et al., 2021). The novelty of the current work lies in using a simple and consolidated reliability-based method to trigger decision-making on operational improvements and asset management for maintaining or improving treatment effectiveness and efficiency. This method enables diagnosing WWTP reliability, estimating it for different discharge requirement scenarios, determining the mean value of each parameter for meeting requirements with a given reliability, and establishing stability cut-off points to achieve the necessary reliability for compliance.

Reliability analysis methodologies, such as those developed by Niku et al., play a crucial role in evaluating WWTP performance. By utilizing probabilistic methods, such as the coefficient of reliability (COR), these approaches enable the estimation of WWTP reliability under different discharge scenarios. The COR method relates mean constituent values (i.e., design or operational values) to the standards that must be achieved on a probability basis. This methodology has been used and recommended in two important textbooks (Crites & Tchobanoglous, 2000; Metcalf & Eddy, 2003) and consulted by several authors over the last 25 years (Quek et al., 1995; Naval & Wanderley, 2000; Etnier et al., 2005; Gupta & Shrivastava, 2006). For example, the COR method has been applied to assess the compliance of WWTP effluents with regulatory standards, revealing the extent of deviations and aiding in prioritizing operational improvements (Niku et al., 1979). Moreover, reliability analysis extends to water treatment plants (WTPs), where it facilitates the evaluation of compliance with potability standards. For instance, a study analysing five real WTPs using direct filtration technology found that reliability analysis helped assess compliance with different potability standards, enhancing the overall performance evaluation of WTPs (Oliveira & Von Sperling, 2008).

In this study, the COR for effluent concentrations of parameters such as TSS, TDS, BOD, and COD related to six treatment units has been determined. The design concentrations necessary to meet the prevailing TSS, TDS, BOD, and COD discharge standards have also been calculated from the COR values achieved. These numerical insights underscore the critical role of reliability analysis in enhancing the effectiveness and efficiency of effluent treatment plants (ETPs), thereby addressing the pressing challenges of water pollution and scarcity. We hope that the considerations of this study will contribute to both the design of new systems and the definition of reasonable discharge standards by regulatory agencies.

1.2. Industry Description

The study focuses on six pulp and paper industries located in various districts of West Bengal, all categorized by the Central Pollution Control Board (CPCB) as Grossly Polluting Industries (GPI) due to their substantial wastewater discharge exceeding 100 KLD directly into the Ganga River or its tributaries. The first two industries are situated in Paschim Bardhhaman, known for its industrial activities and proximity to the Damodar River, necessitating stringent effluent management. The third industry is in North 24 Parganas, close to Kolkata, where the effluents can impact the Hooghly River. The fourth industry is located in Purbo Bardhhaman, where industrial effluents pose a threat to both soil and water resources in an agriculturally rich area. In Howrah, the fifth industry's dense industrial setting adds pressure to local water bodies, requiring effective treatment solutions. The sixth industry in Nadia, amidst a culturally and agriculturally significant landscape, highlights the critical need for balancing industrial growth with environmental protection. This study's comparative reliability analysis of the effluent treatment plants (ETPs) in these locations aims to ensure compliance with environmental standards, safeguard public health, and promote sustainable industrial practices.

Table 1 Location and general characterization of the ETPs studied

ETP Location	Designation	Average effluent generation (m^3/day)	Design capacity (m^3/day)	Average flow (m^3/day)
Paschim Bardhhaman	L1	235.48	288	179.39
Paschim Bardhhaman	L2	39.18	160	39.18
North 24 Parganas	L3	629	1852	629.00
Purbo Bardhhaman	L4	4861.23	6000	4861.23
Howrah	L5	63.2	120	63.2
Nadia	L6	2351	7200	2489.12

1.3. Research Gap

Effluent treatment plants (ETPs) in India, particularly those serving pulp and paper mills, face significant challenges due to outdated technologies and inadequate performance evaluations. Many of these plants were built a long time ago and struggle to cope with the changing raw materials used in manufacturing processes. As a result, they often fail to effectively remove harmful pollutants from wastewater, leading to environmental contamination. Despite the widespread use of ETPs, there is a lack of regular assessments to identify shortcomings and ensure their proper functioning. This gap highlights the need for systematic reliability and performance evaluations, ideally conducted every 3-5 years, to guide necessary upgrades and replacements.

Furthermore, while advanced effluent treatment techniques are implemented internationally, their adoption in the Indian context remains limited. This discrepancy underscores the importance of bridging the gap between global best practices and domestic realities to enhance the effectiveness of ETPs in India. In regions like West Bengal, where industries are major contributors to water pollution, the situation is particularly dire. Compliance with environmental regulations, set by agencies like the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs), is often a challenge for these industries, necessitating innovative solutions tailored to local conditions. Another critical gap is the lack of previous studies conducting comparative performance evaluations of ETPs installed in pulp and paper mills. Understanding the existing operational conditions and performance levels of these plants is crucial for identifying specific areas needing improvement and for benchmarking against best practices. Such comparative analyses are essential for developing targeted strategies to enhance the efficiency and effectiveness of effluent treatment processes.

Moving forward, there is a growing recognition of the need for efficient treatment options that not only meet regulatory standards but also offer practical advantages over existing technologies. These advancements should prioritize affordability, ease of implementation, and sustainability to ensure widespread adoption by industries. By addressing these gaps and challenges, research in this area can play a vital role in promoting environmental sustainability and facilitating responsible industrial growth.

1.4. Research Objective

The objective of this study is to comparatively assess the performance of effluent treatment plants installed in various pulp and paper industries in West Bengal. This assessment will be based on a reliability analysis of key water quality parameters, including TSS, TDS, BOD and COD. The specific objectives to achieve this include:

- Assessing the reliability and performance of ETPs through water quality parameters (TSS, TDS, BOD, COD), calculating COR values to gauge consistency and stability of effluent concentrations.
- Determining design concentrations needed to meet discharge standards, using mean design concentrations derived from COR values to ensure compliance
- Applying statistical methods, such as probability and reliability analysis, to establish and achieve wastewater discharge standards, evaluating the feasibility of probabilistic approaches for designing treatment plants to meet environmental regulations confidently.

These objectives aim to provide a comparative analysis of the efficiency and reliability of effluent treatment processes in the pulp and paper industry, contributing to improved environmental management and sustainability practices.

1.5. Overall Methodology

The total research process is essentially broken down into five components: literature review for goal and objective identification, primary and secondary surveys to gather information about the current condition, field visits to various mills in West Bengal for sample collection, laboratory analyses, and data interpretation. Wastewater samples collected during field visits were stored as per the norms to prevent degradation. Laboratory analyses were performed in a university lab to measure key parameters such as TSS, TDS, BOD, and COD. Then the COR values were calculated using statistical methods to assess the stability of ETP performance. Data interpretation involved comparing effluent concentrations against regulatory standards and analysing COR values to understand operational reliability. The research concluded with key findings, their significance, and recommendations for improving ETP design and operation to achieve better compliance with environmental standards. This methodology provided valuable insights for enhancing environmental management practices in the industry.

1.6. Propose Outcome

Effluent treatment plants (ETPs) play a vital role in ensuring environmental sustainability, particularly in industries like pulp and paper production. This project focuses on enhancing ETP efficiency, reliability, and environmental compliance. The following outcomes outline key objectives of this research work-

- Derive the COR values for each of the treatment unit in order perform the comparative analysis.
- Enhance the efficiency and reliability of effluent treatment plants (ETPs) to consistently meet environmental discharge standards through systematic reliability analysis.
- Increase the operational stability of ETPs by implementing design improvements based on reliability analysis.
- Utilize statistical methods to drive data-informed improvements and upgrades in effluent treatment processes.
- Observe the variation between the design mean concentration and the actual mean concentration for each ETP in different paper mills.

1.7. Thesis Outline

The research for the comparative reliability analysis of ETPs in the pulp and paper industry is organized into six chapters. Chapter 2 contains a literature review. Chapter 3 details the conceptual framework behind the study. Chapter 4 explains the research methodology. Chapter 5 presents the results and discussion. The conclusion is given in Chapter 6, with references provided at the end of the dissertation.

Chapter 2: Literature Review

LITERATURE REVIEW

A literature review is a comprehensive examination of academic books, journals, and other relevant materials focused on a specific problem, field of study, or theory. Its aim is to provide a description, synopsis, and critical evaluation of these works. By doing so, it demonstrates how your research contributes to the existing body of knowledge and offers an overview of the sources used to investigate a particular issue.

Essentially, a literature review summarizes the relevant literature on a subject or field, highlighting significant authors, prevalent ideas, hypotheses, questions, and methodologies. For instance, in the context of assessing the reliability of various wastewater treatment plants and informing decision-making for their improvement, numerous technical papers have been published. These papers serve as valuable resources in my study and are referenced below.

International Research Paper

- ***Silva et. al (2022)*** proposes a reliability-based method for assessing wastewater treatment plant (WWTP) performance to facilitate decision-making regarding operational improvements and asset management. Five-year data from 16 Portuguese activated sludge WWTPs were analyzed, focusing on BOD5, COD, and TSS parameters. Mostly two type of treatment technique has been adopted within the WTP: (i) activated sludge after primary sedimentation, designed for conventional aeration (CAS) and (ii) activated sludge without primary sedimentation, designed for extended aeration (EA). Extended aeration WWTPs were found to be more reliable and stable than conventional aeration WWTPs (0.98 reliability vs. 0.82 for BOD5, 0.97 vs. 0.91 for COD, and 0.94 vs. 0.89 for TSS), with lower reliabilities and stabilities observed in smaller WWTPs. The computed coefficient of variation aids in establishing mean effluent concentrations for compliance with discharge requirements. The results obtained demonstrate that the nine EA-WWTPs were significantly more reliable and stable than the seven CAS-WWTPs analyse. In addition, EA-WWTPs treating more than 15,000 m3/d and EA and CAS-WWTPs treating more than 20,000m3/d are more reliable (>0.90) and stable. These results provide valuable insights for strategic asset management, design, and rehabilitation of WWTPs, as well as tactical and operational decisions regarding resource allocation and operating conditions. The findings serve as reference ranges for WWTP performance benchmarking and plant design based on influent characteristics, capacities, and operating conditions.

- ***Veronika Yordanova et al. (2022)*** have discussed the repercussions of treated wastewater discharge in Bulgaria's Upper Iskar sub-catchment, critical for supplying drinking water to Sofia. The study reveals various risk factors affecting water quality, including discharge from the Samokov Wastewater Treatment Plant (WWTP), agricultural pollution, and untreated sewage from small villages. Chemical and microbiological indicators were utilized to assess the impact on water quality and ecological conditions downstream of the WWTP. Results indicate increased levels of urban wastewater-associated parameters, although the ecological state remains generally "good," with localized deterioration observed. The sediment microbiome exhibits high metabolic activity, suggesting its significance in self-purification processes but also posing risks as a potential refuge for pathogenic microorganisms. Despite the effectiveness of current self-

purification processes, the ecological status and water quality have deteriorated due to combined effects of WWTP discharge and intensive agriculture. The study emphasizes the need for expanded monitoring programs to comprehensively evaluate the environmental impact of wastewater discharge and implement better control measures to mitigate future consequences.

- ***Melo et. al. (2021)*** set out the performance of water treatment plants (WTPs) employing direct filtration systems, analyzing key parameters such as turbidity, apparent color, and pH. Utilizing data from real-scale WTPs, the research employs reliability analysis to assess turbidity and compliance with potability standards. Findings reveal significant variability among evaluated WTPs, with coefficients of variation indicating operational challenges. While parameters like pH and apparent color show high compliance rates (>99%), turbidity poses challenges in meeting stricter standards set by regulatory bodies such as the United States Environmental Protection Agency, with most WTPs showing an expected compliance of 0% for standards as stringent as 0.1 NTU. The study underscores the importance of adopting combined methods for performance evaluation and advocates for flexible regulatory standards to accommodate variations in WTP performance, ultimately emphasizing the need for ongoing research to enhance water treatment efficacy and reliability.

- ***Matheus Sales Alves et al (2020)*** examines the reliability of Waste Stabilization Ponds (WSP) for wastewater treatment and suggests a novel approach to WSP design using the coefficient of reliability (COR) derived from acceptable discharge standard violations. Data from 10 full-scale systems in Northeast Brazil, primarily treating domestic effluent, were analysed. Different levels of restriction for effluent discharge were considered for parameters such as BOD, COD, total suspended solids, ammonia, and thermotolerant coliforms. The Log-normal Probability Distribution Function (PDF) facilitated COR calculation, highlighting the challenges of adopting a single COR value due to result dispersion. Comparisons between observed and design concentrations revealed the 95% reliability scenario to be less achievable for WSP systems. It has found that these WSP systems exhibited considerable variability in meeting quality standards for final effluent, with algae-related particulate material negatively impacting compliance with BOD and COD limits. Challenges were also observed in meeting restrictive discharge standards for thermotolerant coliforms and ammonia. The potential use of COR in designing similar WSP systems was discussed, emphasizing the need to account for effluent variability. Thermotolerant coliforms exhibited the highest coefficients of variation and lowest COR values. The study underscores the importance of considering COR variability and technology's ability to achieve desired reliability levels when applying this methodology.

- ***Kurek et. al. (2019)*** analyzes the reliability of pollution removal in a wastewater treatment plant in Mińsk Mazowiecki, focusing on the removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) using activated sludge. Over a two-year period from 2016 to 2017, the study conducted physical and chemical analyses of raw wastewater and treated effluent. With a designed capacity equivalent to 82,200 residents, 50 wastewater samples were collected and analyzed. Descriptive statistics, percentage reduction, and reliability factors (WN) for each pollution indicator were calculated. The average effectiveness of BOD5,

COD, and TSS removal during the study period were found to be 99.1%, 96.3%, and 98.9% respectively. Additionally, a reliability analysis was conducted using the Weibull probability model.

- ***Andraka et. al. (2019)*** has explained the reliability of the "Wastewater Treatment Plant (WWTP) – Receiver" system using probabilistic modelling and Monte Carlo simulations to predict the probability of the river maintaining required purity after receiving WWTP discharge. The probabilistic model yields lower reliability values than Monte Carlo simulations, indicating its conservatism. Conversely, Monte Carlo simulations provide more realistic results by capturing the stochastic nature of the process, highlighting the river's quality as a more sensitive factor than WWTP reliability. Analysis suggests that the WWTP-Receiver system's overall reliability is more influenced by the river's quality than the WWTP's reliability, as the river acts as a buffer. Thus, even with fluctuating WWTP reliability due to operational conditions, the WWTP-Receiver reliability remains relatively stable.

- ***Graham et. al. (2019)*** has discussed the treatment performance and ecological impact of small wastewater treatment plants (WWTPs) compared to larger ones, aiming to enhance their management. A year-long sampling campaign in rural UK reveals that effluent quality from smaller WWTPs is significantly poorer across various parameters compared to larger ones. Random forest classification models accurately predict the likelihood of smaller WWTPs becoming unreliable, with population equivalence emerging as a critical predictor. The study highlights the importance of understanding and managing smaller WWTPs for sustainable wastewater management. The research underscores the limited understanding of small WWTPs due to a lack of operational data. It demonstrates that smaller systems exhibit poorer stability and effluent quality compared to larger ones, with package plants, particularly RBCs, performing better. Reliability of effluent quality from small WWTPs can be predicted using influent pH, population equivalence, and influent NH4-N concentration. The study advocates for using simple mathematical techniques to improve operational efficiency and achieve regulatory compliance in rural and remote catchments. Overall, the findings emphasize the significance of decentralized wastewater infrastructure and provide insights and models to support wastewater and asset managers in optimizing the performance of smaller WWTPs. These approaches can contribute to achieving ecological goals in remote locations effectively and cost-efficiently.

- ***S. Zainith et al (2018)*** review the significant environmental impact of the pulp and paper industry, highlighting the release of large quantities of wastewater laden with recalcitrant pollutants like BOD, COD, TS, phenols, lignin, and its derivatives, which contribute to severe aquatic and soil contamination. The summary provides a comprehensive overview of the sources, characteristics, toxicity, and treatment methods for pulp and paper mill wastes and wastewaters. Various physio-chemical treatment methods, including sedimentation, flotation, adsorption, coagulation, oxidation, ozonation, electrolysis, reverse osmosis, ultrafiltration, and nanofiltration, are discussed with the aim of removing suspended solids, colloidal particles, floating matter, colour, and toxic compounds. While conventional methods may encounter challenges in colour removal and degrading recalcitrant compounds like lignin, biological treatment methods are highlighted for their effectiveness in reducing COD, BOD, and lignin levels. These biological processes,

categorized as aerobic and anaerobic treatments, rely on microorganisms such as bacteria, fungi, and algae for efficient wastewater treatment.

- ***Bugajski et al. (2016)*** have performed a study to assess the reliability of two on-site sewage treatment facilities (BCT S-12 and TJ EP-4) serving two school buildings located in rural. The reliability was determined using Weibull reliability method. The research was conducted for 24 months and it involved the collection and analysis of 48 samples of raw and treated sewage from each facility. The analyses included organic and biogenic pollution, i.e. BODS, COD, and total nitrogen. Reliability assessment revealed the following effectiveness for BCT S-12 facility: 77% for BODS, 96% for COD and 25% for total nitrogen. For TJ EP-4 facility, the effectiveness was 81%, 88% and 72% for BOD5, COD and total nitrogen, respectively. Both facilities used the activated sludge process and experienced periodic disturbances in the treatment flow that resulted in reduced sewage treatment efficiency. Considering the above, the processes of nitrification and denitrification in the biological reactor should be streamlined to provide more effective removal of organic and nitrogen-based compounds in the investigated facilities.

- ***Hegazy et. al. (2016)*** evaluates and analyses the performance and the efficiency of Shoubra Al Khaima (Balqus) wastewater treatment plant (WWTP). Based on the results, it shows that Balqus WWTP operates with removal efficiencies higher than 90% for biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and oil & grease (O&G) were established. This analysis applied to define a performance measuring plan based on the most important parameters that can be reliable and applicable for any WWTP.

- ***M.P. Alderson et al. (2015)*** evaluates the reliability coefficients of fifty-six low-cost, full-scale wastewater treatment plants, examining nine different treatment technologies for wastewater reuse in aquaculture and agriculture in northeast Brazil. The aim is to assess alternatives for sustainable wastewater reuse in communities facing water scarcity. Technologies include septic tanks, anaerobic filters, chlorination, facultative ponds, and various combinations thereof. Parameters analysed encompass chemical oxygen demand, total suspended solids, Escherichia coli, and biochemical oxygen demand. Applying an 80% reliability level for standard compliance, the study establishes achievable targets based on international and Brazilian guidelines. Results reveal variability among treatment plants of the same type, emphasizing the importance of effective management. Waste stabilization ponds demonstrate the highest reliability for wastewater reuse, followed by other systems like septic tanks with anaerobic filters and chlorination. Overall, low-cost, full-scale wastewater treatment plants can provide suitable effluent for reuse in agriculture and aquaculture when adhering to the 80% reliability standard.

  The reliability analyses offer a straightforward methodology for sanitation companies to select appropriate treatment processes for reuse purposes. The 80% reliability target is deemed pertinent for water-scarce communities, particularly in developing regions facing climate change impacts. However, the study focuses solely on treatment performance and does not address potential health impacts. To formulate cost-effective public health policies on wastewater reuse, empirical epidemiological studies and microbiological analyses of pathogen transmission, coupled with model-based quantitative risk assessment, are essential. Overall, while the study highlights the feasibility of wastewater reuse, further research is needed to address health implications comprehensively.

- ***O. Ashrafi et al. (2015)*** describe different wastewater treatment processes in the pulp-and-paper industry, comparing their contaminant removal efficiencies and greenhouse gas (GHG) emissions. Operating parameters' impact on process performance is evaluated, with mathematical models used to estimate GHG emissions in common biological treatment processes. Nutrient removal and sludge treatment methods are also discussed, with associated GHG emissions calculated. While aerobic and anaerobic biological processes are suitable for wastewater treatment, hybrid processes demonstrate superior contaminant removal capacity, higher efficiencies, and reduced GHG emissions and energy costs under optimized conditions.

- ***M. Niero et al. (2014)*** explores the environmental performance of four types of wastewater treatment plants (WWTPs) in Denmark through Life Cycle Assessment (LCA). These WWTPs vary in size and treatment technology, including aerobic versus anaerobic and chemical versus combined chemical and biological methods. The study addresses the challenges of assessing the environmental impact of WWTPs due to intrinsic variability in the wastewater treatment process. Trade-offs in environmental performance were identified, particularly regarding sludge management options such as combustion with energy production versus agricultural application. Monte Carlo simulation and sensitivity analysis were utilized to address uncertainties related to effluent and sludge quality, choice of Life Cycle Impact Assessment (LCIA) method, and data sources. The results suggest that recycling phosphorus to agricultural soils may be more sustainable than sludge incineration for climate change and fossil depletion impact categories. However, uncertainties remain regarding eutrophication and toxicity-related impact categories. The study emphasizes the need for robust methodologies and data to draw reliable conclusions and inform decision-making in wastewater treatment planning and management.

- ***Olieveira et. al (2014)*** investigates the operational parameters and performance of a pilot-scale Moving Bed Biofilm Reactor (MBBR) for treating pulp and paper mill wastewater. The MBBR process combines suspended and adhered biomass, allowing for higher biomass retention and substrate degradation. The pilot plant operated within recommended limits for Volumetric and Superficial Organic loads, achieving stable conditions without carrier clogging. The removal efficiencies for Soluble Biochemical Oxygen Demand (soluble BOD) and Soluble Chemical Oxygen Demand (soluble COD) were 56% and 35%, respectively. The study quantified adhered biomass, indicating a high number of microorganisms adhered to the carriers. Despite stable organic substance removal, the MBBR system may not meet design efficiency and stability requirements for use as the first unit of biological treatment in the wastewater treatment plant of Company Suzano.

- ***E. E. O. Odjadjare et al. (2010)*** analyse the physicochemical qualities of the final effluent from an urban wastewater treatment plant in South Africa and its impact on the receiving watershed. Conducted between August 2007 and July 2008, the study found that pH values across all sampling points ranged between 6.8 and 8.3, with temperatures varying from 18°C to 25°C. Electrical conductivity (EC) ranged from 29 to 1,015 µS/cm, and turbidity varied between 2.7 and 35 NTU. Salinity and TDS ranged from 0.36 to 35 psu and 16 to 470 mg/L, respectively.

While the treated effluent met recommended standards for pH, temperature, TDS, nitrate, and nitrite, it fell short for parameters such as EC, turbidity, salinity, COD, DO, and phosphate. The study highlights the negative impact of discharged effluent on the receiving watershed, emphasizing the need for regular and consistent monitoring programs to ensure best practices in wastewater treatment and discharge into the aquatic milieu in South Africa.

- **Oliveira et. al (2007)** conduct a reliability analysis of 166 wastewater treatment plants in Brazil, utilizing a methodology by Niku et al. (1979) to determine coefficients of reliability (COR) for effluent parameters. The study integrates stochastic concepts into design and operation, selecting parameters based on performance expectations from past experience or similar plants. Results indicate activated sludge (AS) technology with the lowest COR values, attributed to low effluent concentrations, while AS and UASB+POST show compliance with BOD, COD, and TSS standards. Septic tanks, facultative ponds, and anaerobic ponds exhibit deviations from required concentrations. The conclusion highlights the superior performance of AS and UASB+POST, emphasizing stable operation importance. Integrating into a literature survey, the research aligns with Niku et al. (1979) and emphasizes practical applications for designers, operators, and regulators. Potential gaps include limited focus on nutrient removal, suggesting future research in this area.

- ***Eisenberg et. al (2001*)** addresses the imperative need for a unified methodology to assess the reliability of treatment processes and facilities in water resource, wastewater treatment, and reuse projects, focusing on recent technological advancements such as membrane processes and alternative disinfection methods. The methodology involves a comprehensive evaluation of mechanical reliability and plant performance, serving as a valuable tool for risk assessments in proposed water reuse schemes and disposal plans. It enables project decision-makers to accept, reject, or implement additional measures based on treatment reliability evaluations. The study discusses the application of this methodology to compare different treatment processes and identifies the need for effective treatment units, particularly emphasizing membrane processes and alternative disinfection methods in the results. The conclusion underscores the increasing importance of quantitative reliability analyses in water-related projects, positioning the methodologies as essential tools for water quality engineers and decision-makers. However, gaps in the existing research are identified, especially concerning the limited means to determine equivalent treatment unit or process performance for new technologies, suggesting a need for further exploration in evaluating and comparing treatment trains, including innovative technologies. The study also hints at potential complications with innovative technologies requiring fewer treatment units, indicating the necessity to consider the impact on product quality characterization. So, while the study gives a good way to check reliability, it shows we still have more to explore and understand.

National Research Paper

- ***Bhattacharya et. al. (2022)*** discussed current wastewater management practices in industrial and municipal sector with treatment methodology and various technological aspects. Different Biological Treatment technology based on conventional, fixed, and fluidized bed using media as a carrier of biological population have been covered. Advance waste water treatment technology like membrane bioreactor; application of membrane-based separation technology during tertiary treatment for recycle and reuse issues have also been taken into consideration. With the help of one case study a comparison of Performance efficiency, space availability and cost economic factor of different technologies during primary, secondary, and tertiary/advance treatment have been highlighted. Finally, concept of zero liquid discharge leading to sustainable water management practices has also been incorporated in this paper.

- ***Sathya at. Al (2022)*** presents a comprehensive review on comparison among effluent treatment methods and modern methods of treatment of industrial wastewater effluent from different sources. The research paper explores the impact of industrial effluents on the environment and human health, emphasizing the challenges posed by toxic elements like nitrogen, phosphorus, hydrocarbons, and heavy metals. It advocates for advanced treatment methods, particularly hybrid systems, to efficiently recover resources from effluents while remaining economically viable. The study reviews the composition and quantity of effluents across various industries and discusses the latest advancements in treatment methods, focusing on contaminants removal efficiency and degradation mechanisms. Furthermore, it underscores the need for action to address disposal problems and implement integrated water reuse designs for a reliable water supply. While traditional treatment methods exist, the paper suggests promoting the use of retrieved wastewater in industrial processes and guides future research efforts in wastewater management towards techniques, efficiency, design parameters, and specificities of effluent treatment plants.

- ***K. M. Nahiun et. al. (2021)*** presents their discussion on the possible techniques available for the treatment of wastewater to remove contaminants such as halogenated hydrocarbon compounds, heavy metals, dyes, pigments etc. from the wastewater. Categorization of the industrial waste water has been discussed based on sector of industries such as Iron and steel, Textile and leathers, pulp and paper, petrochemical, and refineries etc. It is apparent that a variety of options are feasible for use in the developing world and even more apparent that many low-technology options can be mixed and matched for very high efficiencies. As well as natural treatment technologies are seeking attraction to a significant level of interest by environmental managers. Natural treatment technologies are considered viable because of their low capital costs, their ease of maintenance, their potentially longer life-cycles, and their ability to recover a variety of resources.

- ***D.P. Ghumra et al. (2021)*** have performed a study on the common Effluent Treatment Plants (CETPs), with the objective of evaluating their effectiveness in treating industrial wastewater and supporting small/medium-scale industries. The methodology involves a thorough analysis of processing steps, design considerations, and drawbacks of existing CETPs, prompting the exploration of novel treatment techniques. Advanced oxidation processes, improved coagulation-

flocculation, and enhancements in biological treatment methods are discussed, along with potential applications of bioremediation, membrane technologies, and physicochemical treatments. The survey identifies gaps in research, emphasizing the need for cost-effective and efficient treatment methods to address increasing organic loads and effluent capacities. The economic aspects of CETP transformation are considered, underlining the importance of implementing novel processing units with both cost-effectiveness and high contaminant removal efficacy. This comprehensive overview provides valuable insights for future research directions, focusing on the improvement and sustainability of industrial wastewater treatment practices.

- ***Patel et. al. (2021)*** discusses the challenges posed by wastewater generated by the pulp and paper industry and advocates for eco-friendly treatment methods. Traditional physicochemical treatments are considered inadequate due to their high energy requirements and questionable ecological impact. Instead, microbial technology, particularly membrane bioreactor (MBR) and moving-bed biofilm reactor (MBBR) technologies, are recommended for their potential to efficiently treat wastewater while supporting sustainable growth. These novel methods can be integrated with advanced hybrid systems to enable energy and water recovery, making wastewater recycling economically and environmentally feasible. Additionally, addressing the complexity of pulp and paper wastewater, the paper highlights the toxicity of its organic and inorganic compounds. Hybrid MBR technology emerges as a promising solution, alongside MBBR-MFCs, which can simultaneously treat wastewater and generate electricity. To reduce freshwater consumption, blending treated wastewater with fresh water is proposed as a solution to overcome economic and ecological challenges associated with excessive freshwater use.

- ***Garg et. al. (2020)*** explores wastewater treatment efficiency in iron and steel plants, emphasizing the need for effective management strategies. Conventional methods like sedimentation are common, but advanced techniques such as membrane filtration are gaining traction. However, the potential of advanced treatments like membrane bioreactors remains underutilized. Integrating chemical treatment with membrane separation shows promise for pollutant removal. Challenges include increasing water demand and environmental impacts, necessitating sustainable management actions like optimizing water systems and increasing recycling. Each treatment method has pros and cons, with selection based on factors like contaminant concentration and discharge standards. Future research should focus on developing comprehensive, sustainable treatment methods tailored to different wastewater compositions.

- ***Padalkar et al. (2019*)** evaluated the reliability and removal efficiencies of ten Common Effluent Treatment Plants (CETPs) in Maharashtra, India. By calculating coefficients of reliability (COR) for various parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and oil and grease (O&G), the study assessed the operational performance of these CETPs. A novel approach was introduced to compare the relationship between removal efficiencies and reliability using regression equations, with coefficient of determination values (R^2) indicating optimal functioning. Additionally, the study examined probability distributions for CETP effluent parameters and identified key indicators affecting effluent quality. The derived COR values for BOD, COD, TSS, and O&G were 0.972, 0.968, 0.976, and 0.828, respectively. It was also found that the mean design concentration should be 97.2 mg/L for BOD, 242.0 mg/L for COD, 97.6 mg/L for TSS, and 16.6 mg/L for O&G to

achieve standard discharge limits prescribed by PCB under a given confidence threshold, although these values are fully dependent on the incoming effluent characteristics, removal efficiencies of treatment units, reliability, and the point of effluent discharge. The findings underscored the importance of designing treatment units tailored to the characteristics of member industries and addressing challenges such as effluent variability. The study suggested enhancing maintenance practices and reducing variability in effluent quality to improve the overall reliability and performance of CETPs.

- ***Padalkar et. al (2018)*** perform the reliability of a CETP and evaluate the performance in terms of removal efficiency. An established methodology was adopted to determine the effectiveness of the CETP in terms of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and oil and grease (O&G) concentrations. Based on the software used in this study i.e. IBM SPSS and Microsoft Excel the relationship between reliability and RE was also discussed to assess the overall working of the CETP. It can be concluded from the study that it may not always possible the run the CETP in optimum condition however it will reduces the chances of failure and for that few suggestions also maintained in the paper.

- ***Das et. al (2018)*** have explained the environmental challenges associated with the iron and steel industry and examines various effluent treatment methods. It underscores the limitations of conventional approaches and highlights the potential of advanced treatments, particularly membrane separation. The conclusion emphasizes the importance of selecting treatment techniques based on optimization of parameters such as contaminant concentration and discharge standards. Membrane technology, coupled with chemical or biological treatments, is recommended for treating complex industrial wastewaters, with a focus on integrating alternative energy sources for enhanced efficiency and environmental benefits. The paper advocates for the integration of low-cost treatment options with membrane-based techniques to produce high-quality reusable water with minimal sludge generation.

- ***Kumar et. al. (2016)*** has explained possible solutions for treatment and reuse for waste water coming from rice mill. Various treatment technique such as physiochemical treatment, microbial treatment and phytoremediation have been discussed with overall removal efficiency data.

- ***Banerjee et. al (2012)*** presents a comprehensive analysis of industrial effluent impacts on the Damodar River, revealing substantial pollution levels. Heavy metal distribution in the effluent discharge channel is characterized, with sediments showing enrichment levels in the order of Cd (39.904) > Pb (33.156) > Mn (0.164) > Fe (0.013). Geoaccumulation index (Igeo) values for Cd (4.733) and Pb (4.466) indicate moderate to high pollution levels. The pollution load index (PLI) of 1.305 underscores significant heavy metal contamination attributed to industrialization and urbanization. The negative impact of discharged effluent on the receiving river, particularly near industrial complexes, is emphasized, with pollution indices such as EF, Igeo, and PLI significantly elevated. Continuous monitoring and mitigation efforts are deemed imperative to safeguard the Damodar River ecosystem against the adverse effects of elevated heavy metal levels.

- ***Rahangdale et. al. (2012)*** presents a case study on the effluent treatment processes happening in the lead acid battery industry specifically in Exide industry, Chinchwad, Pune. In this study all

the major pollutant like pH, COD, BOD, TDS, Chloride and other heavy metals that comes from a battery manufacturing plant are discussed and their treatment processes have also been present. It was found that all effluent parameters were within the permissible limits and all treatment units within the ETP plant running properly without any problem, Industry has appropriate waste disposal system and ETP has zero discharge of effluent.

- ***Kusuma et. al. (2010)*** evaluates performance efficiency of a waste water treatment plant. A sewage treatment plant operating on biological treatment method (Activated Sludge Process) with an average wastewater inflow of 23MLD bas been considered for case study. Waste water samples were collected at different stages of treatment units and analyzed for the major water quality parameters, such as biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and total dissolved solids (TDS). The performance efficiency of each unit in treating the pollutants was calculated. Overall performance of the plant also has been estimated. The obtained results were very much useful in identification and rectification of operational and maintenance problems as well as the future expansion to be carried out in the plant to meet the increased hydraulic and organic loadings.

- ***P. Govindasamy et al (2006)*** evaluates the performance efficiency of a common effluent treatment plant (CETP) for tanneries by analysing water samples collected at different treatment stages. Parameters such as pH, biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and total dissolved solids (TDS) were examined. The data indicated that the CETP complies with TNPCB norms and meets discharge standard limits. Additionally, the study reveals significant reductions in major pollutants, including odour, during the treatment process. The pH, BOD, COD, TSS, and TDS levels in raw effluents were notably higher than those in treated effluents. The BOD/COD ratio decreased from 0.32 to 0.108, indicating effective organic matter removal. The study calculates removal percentages for various pollutants, with TDS removal showing room for improvement. Suggestions for enhancing the CETP include implementing a reverse osmosis (RO) plant to optimize TDS levels and exploring treated water reuse options for activities like gardening.

Chapter 3: Theoretical Background

THEORETICAL BACKGROUND

The industrial revolution and rapid urbanization have escalated rapidly and resulted in the generation of huge quantities of wastewater all over the world. Approximately 80% of the overall wastewater generated is discharged into water channels that create environmental pollution and threat to human health and aquatic life (International Water Association, 2018). In the developed countries like North America and Europe, the industrial water consumption is higher than the developing countries i.e., 50% and 4–12%, respectively. The United States of America (USA) has remarkable achievements in treating wastewater due to its advanced technologies and technical know-how. According to the study conducted by (Acumen Research and Consulting, 2019), the market size of the global industrial wastewater treatment is poised to increase up to the US $16.5 billion by 2026 with an average growth rate of 4.5% CAGR. A report published by (UN Water, UNESCO , 2017), highlighted that approximately 70% of the wastewater both municipal and industrial is treated in high-income countries as compared to upper-middle-income countries (38%) and lower-middle-income countries (28%), whereas, the lower-income countries are limited to only 8%. Considering the existing patterns, it is anticipated that approximately 80% of the global wastewater is discharged without any treatment.

In India, about 44 million m^3/day of industrial wastewater is generated of which nearly 6.2 million m^3 remain untreated and gets discharged into the natural aquatic bodies (Ranade and Bhandari, 2014). Recent data, shown in *Figure 1* (CPCB, 2009–10; Frost and Sullivan, 2011, www.frost.com), also depicts a huge gap between wastewater generated and wastewater treated.

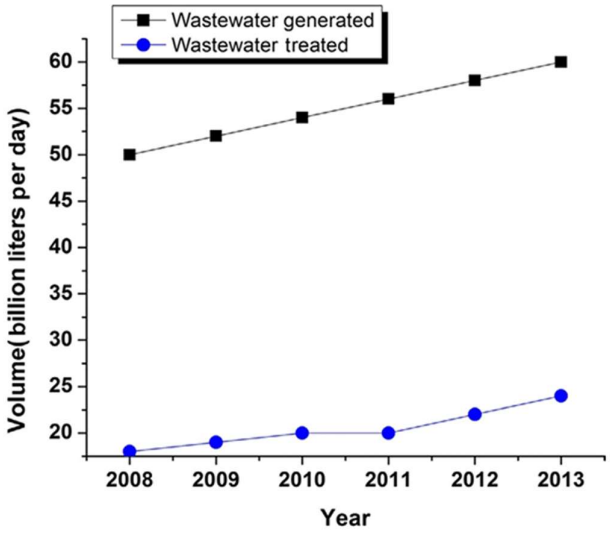


Figure 1 India's mega cities: domestic and industrial wastewater generated vs treated

Industries such as chemical, distillery, sugar, food and dairy, paper and pulp, textile bleaching and dyeing, mining and quarries, battery manufacturing, nuclear power, organic chemical, leather/tannery, iron and steel, soap and detergent, electric power plant, metal refining, pesticide and biocide, petroleum and petrochemical, pharmaceutical, metal processing, and electroplating are major sources of water pollution. Among all of these industries, the pulp and paper industry, which I have chosen as the focus of my thesis, stands out as an integral part of industrial development in regions like West Bengal, India. It presents a dual narrative of economic prosperity and environmental responsibility. For instance, the industry utilizes approximately 60 to 230 cubic meters of freshwater per ton of paper production, resulting in the generation of substantial wastewater volumes.

It is the sixth largest polluter (after oil, cement, leather, textile and steel industries), discharging a variety of wastes into the environment (D.V. Savant a, 2006). The black liquor produced from the pulping process contains a large volume of water and the ratio of the liquid waste produced for the pro duction of paper pulp is about 7:1 by weight in tons (Biermann, 1993). On average, about 35 m^3 of freshwater is required for per ton production of any quality of paper while around 36 m^3 of waste Kraft black liquor is produced for the production of the same quantity of paper. The high consumption of fresh water and generation of a huge volume of toxic wastewater are the most important environmental concerns related to the pulp and paper industry. According to the annual report of the Central Pollution Control Board (Delhi, India), the whole papermaking sector consumes approximately 905.83106 m^3 of freshwater and discharges about 695.73106 m^3 of wastewater per year. Moreover, due to the use of old technology, the current average water consumption is about 150 m^3/ton of paper and allied products (National Productivity Council, 2006).

Left untreated, this wastewater poses severe environmental risks, characterized by elevated levels of total suspended solids, chemical oxygen demand, biological oxygen demand, and various pollutants. The discharge of such untreated wastewater into surrounding water bodies threatens ecosystems, disrupts aquatic life, and compromises water quality, thereby jeopardizing environmental sustainability and public health. The typical composition of paper-mill effluent is listed in *Table 2*.

Table 2 Composition of paper-mill effluent (Pal, 2017)

Sl. No.	Parameters	Value	Units
1.	COD	465–2126	mg/L
2.	BOD	142–450	mg/L
3.	TDS	310–5000	mg/L
4.	TSS	40–1300	mg/L
5.	BOD/COD	>10,000	–
6.	pH	8.0–13.0	–
7.	DOC	131–575	mg/L
8.	AOX	8.9–80.2	mg/L
9.	Color	660–3220	mg Pt-Co/L
10.	Conductivity	1200–2000	µS/cm
11.	TOC	234–445	mg/L
12.	Alkalinity	83–86	$mgCaCO_3/L$
13.	Total phenolic compounds	294–440	mg/L
14.	Turbidity	70–108	NTU
15.	Cationic demand (CD)	1065.4	µmol/L
16.	MTBE extract	236.8	mg/L
17.	Lignin	133–265	mg/L
18.	SO_4^{2-}	150–542	mg/L
19.	Cl^-	85–1324	mg/L
20.	Inorganic matter	800–1100	mg/L
21.	Ca^{2+}	17–27	mg/L

The need for effective wastewater treatment within the pulp and paper industry is thus paramount, necessitating rigorous evaluation of existing treatment facilities and also for the future design of treatment unit. In response to these challenges, this thesis, titled "**Comparative Reliability Analysis of Effluent Treatment Plants in Pulp and Paper Industrial Sector: A Case Study of West Bengal"** aims to explore how dependable the wastewater treatment is. By assessing the performance and effectiveness of wastewater treatment units within pulp and paper mills, this study aims to provide insights for enhancing treatment processes, ensuring consistent operation, adhering to regulatory standards, and safeguarding environmental and public health interests. Through this holistic approach, the thesis seeks to contribute to sustainable industrial practices, informed decision-making, and environmental problems.

3.1. Characteristics of Industrial Wastewaters

Industrial wastewater poses unique challenges due to its varied composition and potential environmental impact. Understanding its important characteristics is crucial for effective management and mitigation strategies. In this discussion, we'll explore key attributes of industrial wastewater, highlighting its diverse nature and implications for environmental conservation

3.1.1. Physical Characteristics

Colour, odour, temperature, and solids content are the most important physical features of wastewater.

- Colour

Because of considerable bacterial breakdown, wastewater appears dark grey or black in colour, indicating that it is septic. Under anaerobic septic conditions, sulphides such as ferrous sulphide, hydrogen sulphide, and the creation of divalent metal irons increase the colour of the effluent.

- Odour

Odour in wastewater usually caused by gases produced by the decomposition of organic matter or by compound during the process of wastewater treatment. In the past few years, the control of odours become a major consideration in the design and operation of wastewater collection, treatment and disposal facilities, especially with respect to the public acceptance of these facilities.

- Solid content

Insoluble or suspended solids, as well as soluble chemicals dissolved in water, make up total solids in wastewater. The suspended solids concentration is determined by drying and weighing the residue left after the sample has been filtered. Proteins, carbohydrates, and lipids make up the majority of organic matter.

- Temperature

Temperature measurement is critical because most wastewater treatment plans contain temperature-sensitive biological processes. The temperature of wastewater varies depending on the season and geographic region. Temperatures in colder places will range from 7 to 18°C, while temperatures in warmer regions will range from 13 to 24°C.

- Turbidity

Turbidity is the cloudiness or haziness of fluids with suspended solid matter, which is made up of particles of various sizes; it is caused by suspended and colloidal particles in wastewater. A nephlometer with a light source and one or more photoelectric detectors read out mechanism at right angles to the stream of light can be used to measure it.

3.1.2. Chemical Characteristics

- Organics

Many organic materials are soluble in water and its generally expressed in terms of BOD and COD. The biodegradability of the organic matter contained in the wastewater is measured by BOD. It is reflected by the microorganism's consumption of oxygen to oxidize the waste present in the wastewater at a specific period. A high BOD level in wastewater indicates a considerable amount of degradable organic matter. The amount of oxygen required for the full breakdown of organic matter is also represented by COD. COD produces dissolved raw materials during different stages of production, all of which have major environmental consequences. The BOD/ COD ratio is a critical statistic for determining the biodegradability of a contaminant in wastewater. When the ratio is larger than 0.5, the organic pollutant contained in the wastewater has a high biodegradability, while when it is less than 0.3, it has a low biodegradability.

- Inorganic chemicals

For reusing treated wastewater, inorganic phosphorus, chloride, sulphate, pH, and alkalinity are being evaluated. The growth of aquatic plants is fuelled by nitrogen and phosphorus. Different type of metals is also soluble to some extent in water. While excessive amount of metal may present health hazards, only those metals that are harmful in relatively small amount are commonly labelled toxic such as arsenic, cadmium chromium, lead, mercury etc; other metals fall into nontoxic group e.g. zinc, iron, manganese, copper, sodium, aluminium etc. Measurement of these such metals is usually made by atomic absorption spectrophotometry. As a result, characterization of treated effluent and settling sludge is critical.

3.2. Water Quality Regulation in India

Countries around the world have framed their water quality policy to work in the following manner:

1. Frame legislation and form institutions to deal with water pollution.
2. Institutions frame acceptable standards of water quality and assess surface and ground water quality around the country through monitoring.
3. Design strategies to attain acceptable water quality by setting and enforcing limits for specific categories of pollutant discharges from industrial, municipal and other sources.

In India components of the above-mentioned process are carried out without the required correlation between them, hence the Central Pollution Control Board (CPCB) Monitors water quality around the country and sets uniform discharge standards minimum acceptable standards (MINAS) (CPCB, 2019) for industrial and Municipal Discharges to be enforced by State Pollution Control Boards (SPCBs) unrelated to the water quality observed in various locations.

3.2.1. Water pollution legislation and institutions

The main legislations that are relevant to water pollution are the Water (prevention and control of pollution) Act, 1974, the Water (prevention and control of pollution) Cess Act, 1977 and the Environment (protection) Act (1986), The CPCB has oversight powers over the various SPCBs. It sets emission/discharge standards, and lays down ambient standards. The CPCB also conducts nation-wide surveys about the status of pollution, and of pollution mitigation. The implementation of the national environmental laws and the enforcement of the standards set by the CPCB are decentralized at the level of each state, with the SPCB in charge of this role.

3.2.2. Regulatory standards for protection of water quality

The ambient water quality in India i.e. the quality of water found in rivers, lakes and groundwater is governed by the ambient standards for water quality which designates the water quality as Classes A, B and C (CPCB) as per the level of various water quality parameters. For control of industrial and municipal discharges the CPCB has issued a set of standards to be enforced by the SPCBs expressed in terms of effluent concentration and are called MINAS as shown in *Table 3*.

Table 3 General standards for discharge of environmental pollutants

Sl. No.	Parameter	Standards			
		Inland surface water	Public Sewers	Land for irrigation	Marine coastal areas
1.	Suspended solids mg/l, Max.	100	600	200	(a) For process waste water- 100
					(b) For cooling water effluent 10 percent above total suspended matter of influent.
2.	pH Value	5.5 to 9.0	5.5 to 9.0	5.5 to 9.0	5.5 to 9.0
3	Temperature	shall not exceed 5°C above the receiving water temperature	-	-	shall not exceed 5°C above the receiving water temperature
4.	Oil and grease mg/l, Max	10	20	10	20
5	Total residual chlorin mg/l Max	1	-	-	1
6.	Ammoniacal nitrogen (as N), mg/l Max.	50	50	-	50
7	Total Kjeldahl Nitrogen (as NH_3) mg/l, Max.	100	-	-	100
8.	Biochemical oxygen demand [3 days at 27°C] mg/l, Max	30	350	100	100
9	Chemical oxygen demand, mg/l, Max	250	-	-	250
10.	Arsenic (as As), mg/l, Max.	0.2	0.2	0.2	0.2
11	Mercury (as Hg), mg/l, Max.	0.01	0.01	-	0.01

12.	Cadmium (as Cd) mg/l, Max.	2	1	-	2
13	Lead (as Pb) mg/l, Max	0.10	1.00	-	2.00
14.	Total chromium (as Cr.) mg/l, Max.	2	2	-	2
15	Copper (as Cu) mg/l, Max.	3	3	-	3
16.	Zinc (As Zn.) mg/l, Max.	5	15	-	15
17	Selenium (as Se.) mg/l, Max.	0.05	0.05	-	0.05
18.	Nickel (as Ni) mg/l, Max.	3	3	-	3
19	Cyanide (as CN) mg/l Max.	0.2	2.0	0.2	0.2
20.	Fluoride (as F) mg/l Max.	2	15	-	15
22.	Sulphide (as S) mg/l Max.	2	-	-	5
23	Phenoil compounds (as C_6H_5OH) mg/l, Max.	1	5	-	5
24.	Manganese (as Mn)	2	2	-	2
25	Iron (as Fe), mg/l, Max	3	3	-	3
26.	Vanadium (as V), mg/l, Max	0.2	0.2	-	0.2
27	Nitrate Nitrogen, mg/l, Max	10	-	-	20

3.3. Industrial Wastewater Treatment: current practices in paper mill

Identification of wastewaters containing components of high value for removal and recovery is an important aspect that needs attention prior to the treatment of the effluent. For industrial waste water treatment process engineering, typically the following formats are most popular.

Primary treatment (Basic clean-up/physical methods)

- Filtration (dual media, carbon, sand filters)
- Screening, grit removal, and sedimentation for sludge/solid removal

Secondary (removes 85–95% of BOD/COD and TSS; 20–40% of P; 0–50% of N)

- Neutralization/stabilization
- Coagulation/clarification
- Biological treatment (aerobic/anaerobic)
- Physico-chemical methods
- Hybrid separations

Tertiary/Polishing treatment (removes >99% of pollutants)

- Adsorption/ ion exchange/ membrane filtration
- Hybrid separations.

Paper mill effluent is conventionally treated in a multistage effluent treatment unit, integrating primary and secondary clarifiers with both aerobic and anaerobic digester units, effectively removing up to 80% of solids and bacteria. The treatment procedure begins with primary treatment, aiming to physically remove a significant portion of solid loading from the system swiftly and economically, without relying on high-tech equipment or excessive monitoring. In the primary clarifier unit, liquid effluent is subjected to aerobic bacteria within an aerobic chamber, facilitated by proper air supply through air diffusers. Microorganisms such as bacteria and protozoa utilize small particles and dissolved organic matter as nutrients, leading to the decomposition of pollutants in the wastewater. Following aerobic decomposition, the effluent undergoes secondary treatment in a secondary clarifier, also known as an activated sludge process (ASP). Here, the clarified water is separated from settling sludge, which accumulates at the bottom of the clarifier. The treated water from the secondary clarifier may undergo further purification in tertiary treatment units to eliminate remaining microbes and pathogens. The resulting effluent from the tertiary treatment units can then be safely discharged into water bodies. *Fig. 2* illustrates the overall treatment scheme, with further discussion of each treatment unit provided.

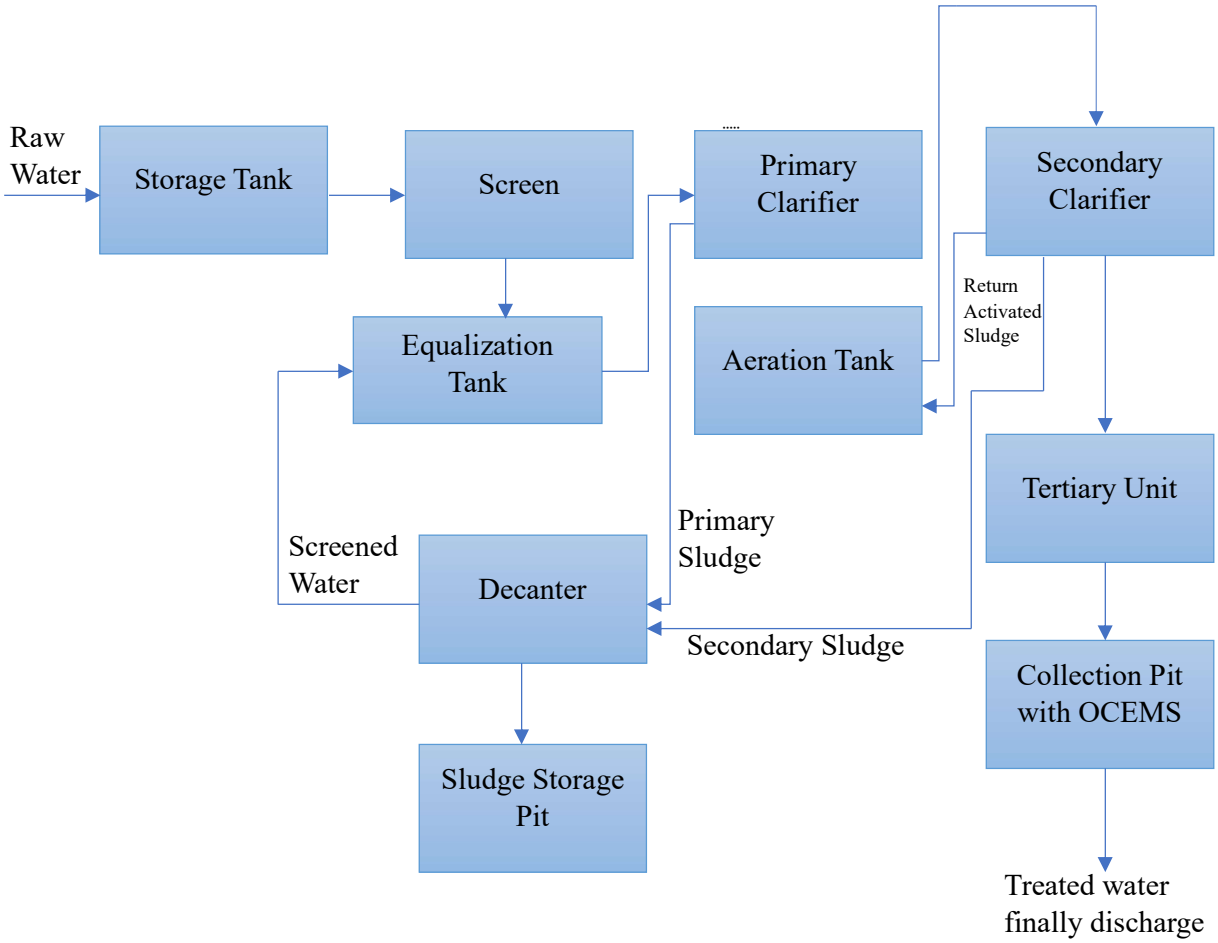


Figure 2 Flowchart of conventional pulp and paper-mill effluent treatment.

3.3.1. Primary Treatment

Wastewater contains a wide variety of solids of various shapes, sizes, and densities Effective removal of these solids may require a combination of unit operations such as screening, grinding, and settling are generally included in the primary system. Operations to eliminate large objects and grit, along with flow measurement, often referred to as preliminary treatment, are an integral part of primary treatment. Operations common to primary systems in most wastewater-treatment plants are described in the following paragraphs.

Screening

Screening devices are used to remove coarse solids from wastewater. Coarse solids consist of sticks, rags, and other large objects that often and, in- explicably, find their way into wastewater collection systems. Because the primary purpose of screens is to protect pumps and other mechanical equipment and to prevent clogging of valves and other appurtenances in the wastewater plant. screening is normally the first operation performed on the incoming wastewater

screens are classified as fine or coarse, depending on their construction. Coarse screens usually consist of vertical bars spaced 1 or more centi- meters apart and inclined away from the incoming flow whereas fine screens usually consist of woven-wire cloth or perforated plates mounted on a rotating disk or drum partially submerged in the flow, or on a traveling belt. Fine screens should be mechanically cleaned on a continual basis. Typical screening devices are shown in *photograph 1*.



Photograph 1 Screening unit in one the location

Hydraulically, flow velocity should not exceed 1.0 m/s (3.3 ft/s) in the channel, with 0.3 m/s (1 ft/s) considered good design. The quantity of solids removed by screening depends primarily on screen- opening size. Screened solids are coated with organic material of a very objectionable nature and should be promptly disposed of to prevent a health hazard and/or nuisance condition. Disposal in a sanitary landfill, grinding and returning to the wastewater flow, and incineration are the most common disposal practices.

Equalization

Variation in waste stream flows, constituents, and concentrations can significantly reduce the efficiency of unit processes and effluent quality. Most equations utilized for design assume steady-state conditions. Hence, variability reduction is critical to compliance with treatment and sustainability goals. Equalization therefore is a very important unit process typically preceding other pre- and primary treatment and subsequent treatment methods. The objective of equalization is to minimize or control fluctuations in wastewater characteristics in order to provide optimum conditions for subsequent treatment processes. The size and type of the equalization basin varies with the quantity of waste and the variability of the wastewater stream.

For design of equalization tank, the cumulative flow is plotted versus time over the equalization period (e.g., 24 h). The maximum volume with respect to the constant-discharge line is the equalization volume required.

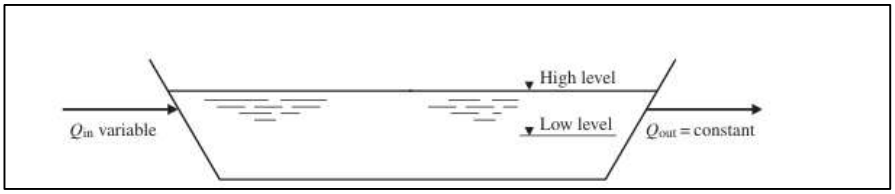


Figure 3 Equalization basin

Clarifier

Sedimentation is a unit operation designed to concentrate and remove suspended organic solids from the wastewater, within the clarifier unit. When primary treatment was considered sufficient as the total treatment, primary settling was the most important operation in the plant. Its design and operation were critical in reducing waste loads to receiving streams. Most of the suspended organic material is slightly heavier than water and settles slowly, usually in the range of from 1.0 to 2.5 m/h. Lighter materials, primarily oils and grease, float to the surface and must be skimmed off.

Primary sedimentation is accomplished in either long-rectangular tanks or circular tanks are shown in *Fig. 4*. In large plants, the use of several rectangular tanks with common wall reduces construction cost and space requirement. Whereas smaller plants tend to use circular tanks because of the simplicity of sludge removal.

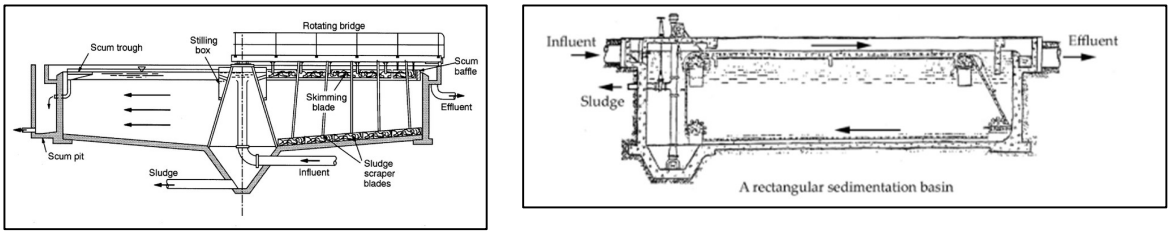


Figure 4 Typical cross-section of circular and rectangular clarifier



Photograph 2 Circular clarifier in one of the locations

Sludge should be removed from the primary sedimentation tank before anaerobic conditions develop. The quantity of sludge removed in primary sedimentation may depend on several variables, including the strength of the incoming waste, the efficiency of the clarifier, and the conditions of the sludge (i.e., specific gravity, water content, etc.). Furthermore, the removal efficiencies of well-designed primary tanks depend upon overflow rates (E.W.Steel, 1991).

3.3.2. Secondary Treatment

Secondary treatment techniques involve chemical or microbial unit processes performed on the primary treated wastewater. Chemical unit pro cesses may include advanced chemical oxidation, ion exchange, chemical neutralization, and stabilization. However, Pulp and paper mills prefer to treat the primary treated water using anaerobic or aerobic biological unit processes, which are efficient in removing soluble, colloidal, and particulate matters containing phosphorus, nitrites, and other organics. ASPs and aerated lagoons are the most commonly used aerobic, sus pended growth biological techniques where the hydraulic conditions, biomass concentration, and oxygen availability play significant roles in paper-mill effluent treatment.

Activated Sludge Process

The objective of the activated sludge process is to remove soluble and insoluble organics from a wastewater stream and to convert this material into a flocculent microbial suspension that is readily settleable and will permit the use of gravitational solid-liquid separation techniques. The process derives its names from the fact that settled sludge containing living, or active microorganism is returned to the reactor to increase the available biomass and speed up the reactions. It is one of the key processes for pulp and paper mill effluent and can degrade and is able to reduce BOD and COD by 85%-95% and 40%-80%, respectively from effluent. The activated sludge process is thus a suspended culture process with sludge return and may be either a completely mixed or a plug-flow process, as depicted in *Fig. 5.* The process is aerobic, with oxygen being supplied by dissolution from entrained air.

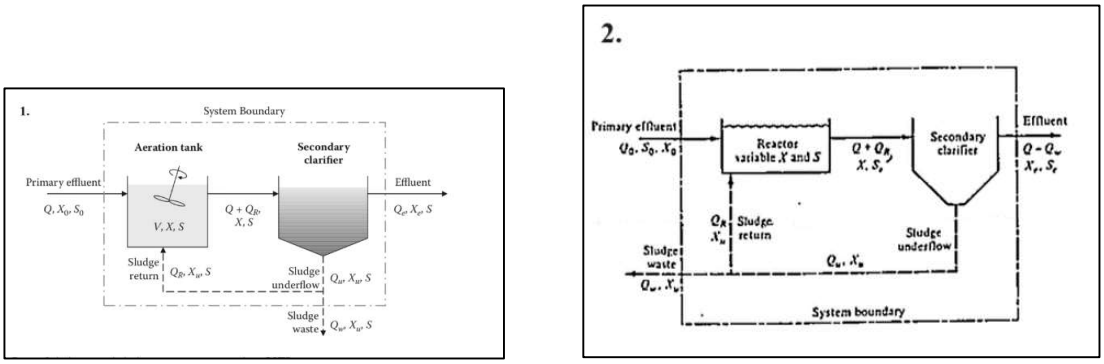


Figure 5 Typical activated sludge process: 1. completely mix reactor and 2. plug flow reactor

o Plug Flow Activated Sludge

The plug flow activated sludge process uses long, narrow aeration basins to provide a mixing regime that approaches plug flow. Waste water is mixed with a biological culture under aerobic conditions. The biomass is then separated from the liquid stream in a secondary clarifier. A portion of the biological sludge is wasted and the remain der returned to the head of the aeration tank with additional incoming waste. The rate and concentration of activated sludge returned to the basin determine the mixed liquor suspended solids concentration.

The dispersion number N_D can be used to express the degree of longitudinal mixing in an activated sludge plant. The dispersion number is a dimensionless number

$$N_D = \frac{D}{uL}$$

Where N_D = dispersion number
u = mean velocity of flow, m/s
L = total length of aeration tank, m
D = coefficient of axial compression, m^2/s

o Complete Mix Activated Sludge

To obtain complete mixing in the aeration tank, proper choices of tank geometry, feeding arrangement, and aeration equipment are required. Through the use of complete mixing, with either diffused or mechanical aeration, it is possible to establish a constant oxygen demand as well as a uniform mixed liquor suspended solids (MLSS) concentration throughout the basin volume. Hydraulic and organic load transients are dampened in these systems, giving a process that is very resistant to upset from shock loadings. Influent wastewater and recycled sludge are introduced to the aeration basin at different points.

Aeration in Activated Sludge

The rate at which oxygen is consumed by the micro-organism in the biological reactor is called the oxygen utilization rate. For the activated sludge processes, the oxygen utilization rate will always exceed the rate of natural replenishment, thus some artificial means of adding oxygen must be used. Oxygen addition should be sufficient to match the oxygen utilization rate which is a function of the characteristics of both the wastewater and the reactor to ensure aerobic metabolism.

Aeration techniques consists of using air diffuser to inject compressed air into the biological reactor and/or using mechanical mixer to stir the contents violently enough to entrain and distribute air through the liquid. It is common to practice to use diffused air in plug-flow systems and mechanical aerators in completely mixed systems.



Photograph 3 Aeration unit

Air Diffuser

Based on the size of air bubble diffused, diffuser is mainly of two types. Fine bubble diffuser produces many bubbles of approximately 2.0 to 2.5 mm in diameter, while coarse bubble diffuser injects fewer bubbles of a larger (up to 25 mm diameter) size. Both of these types have advantages and disadvantages. With respect to oxygen transfer, the fine bubble diffuser is more efficient because of the larger surface area per volume of air. However, head loss through the small pore requires greater compression of the air and thus greater energy requirement. Whereas coarse bubble diffusers offer less maintenance and lower head loss, but poorer oxygen transfer efficiencies.

Mechanical Aerator

This type of aerators produce turbulence at the air-liquid interface, and this turbulence entrains air into the liquid. Mechanical aerator may have high-speed impellers that add large quantities of air to relatively small quantities of water. This aerated water is then mixed with the reactor contents through velocity gradients. Large impellers driven at slow speeds agitate larger quantities of water less violently. Use of the smaller, high-speed units is common in extended aeration systems, while the slow-speed units are more common in conventional activated-sludge systems.

Design considerations of activated sludge

In general, following factors need to be considered during design of the activated sludge process, they are

- Aeration tank containing microorganisms in suspension in which the reaction takes place
- Activated sludge recirculation system
- Excess sludge wasting and disposal facilities
- Aeration systems to transfer oxygen and
- Secondary sedimentation tank to separate and thicken activated sludge.

The main variables of the activated sludge process are the loading rate, the mixing regime and the flow scheme.

Loading Rate

The loading rate expresses the rate at which the sewage is applied in the aeration tank. A loading parameter that has been developed empirically over the years is the hydraulic retention time (HRT), Θ, d.

$$\theta = \frac{V}{Q}$$

Where, V: Volume of aeration tank, m^3, and

Q: Sewage inflow, m^3/day

Another empirical loading parameter is volumetric organic loading which is defined as the BOD applied per unit volume of aeration tank, per day.

$$V_L = \frac{QS_0}{V}$$

A similar loading parameter is mean cell residence time or sludge retention time (SRT), θ_c, day:

$$\theta_c = \frac{VX}{Q_w X_s}$$

Where, S_0, S are influent and effluent organic matter concentrations respectively, conventionally measured as BOD_5, (g/m^3)

X and X_S are MLSS suspended solids concentration in the aeration tank liquor, also called mixed liquor suspended solids (MLSS), is generally taken as an index of the mass of active micro-organisms in the aeration tank. However, the MLSS will contain not only active micro- organisms but also non-biodegradable suspended solids derived from the influent sewage. But only the micro-organism part of the MLSS commonly termed as the mixed liquor volatile suspended solids (MLVSS) is actually taking part in decompositions of the organic matter, and it is one of the key parameters on which the effectiveness of the treatment is depending, (g/m^3)

Q_w waste activated sludge rate, (m^3/d)

Aeration tank

The volume of aeration tank is calculated for the selected value of θ_c by assuming a suitable value of MLSS concentration, X from the following equation

$$VX = \frac{YQ\theta_c(s_0 - s)}{1 + k_d\theta_c}$$

Alternately, the tank capacity may be designed from F/M ratio and MLSS concentration based on following equation,

$$F\ /\ M = \frac{QS_0}{VX}$$

It is seen that economy in reactor volume can be achieved by assuming a large value of X. However, it is seldom taken to be more than 5000 g/m^3. For typical domestic sewage, the MLSS value of 2000-3000 mg/l if conventional plug flow type aeration system is provided, or 3000-5000 mg/l for completely mixed types.

Oxygen requirements

Oxygen is required in the activated sludge process for the oxidation of a part of the influent organic matter and also for the endogenous respiration of the microorganisms in the system. The total oxygen requirement of the process may be formulated as follows:

$$O_2\ required\ (^{g}/_{d}) = \frac{Q(S_0 - S)}{f} - 142Q_wX_r$$

where, f = ratio of BOD_5 to ultimate BOD and 1.42 = oxygen demand of biomass (g/g)

The formula does not allow for nitrification but allows only for carbonaceous BOD removal. The extra theoretical oxygen requirement for nitrification is 4.56 Kg O_2/per kg NH_3 -N oxidized to NO_3 – N.

Aeration Facilities

The oxygen transfer capacity under field conditions can be calculated from the standard oxygen transfer capacity by the formula:

$$N = \frac{N_s(C_s - C_L)\ \times 1.024^{(T-20)}\alpha}{9.2}$$

Where, N: Oxygen transferred under field conditions, kg O_2/kW/hr.

Ns: Oxygen transfer capacity under standard conditions, kg O_2/kW/hr.

Cs: Dissolved oxygen saturation value for sewage at operating temperature, mg/l C_L: Operation

DO level in aeration tank usually 1 to 2 mg/1

T: Temperature, ℃

A: Correction factor for oxygen transfer for sewage, usually 0.8 to 0.85

Sludge recycles

The MLSS concentration in the aeration tank is controlled by the sludge recirculation rate and the sludge settle ability and thickening in the secondary sedimentation tank.

$$\frac{Q_R}{Q} = \frac{X}{X_s - X}$$

Where, Q_R = sludge recirculation rate, m^3/d.

3.3.3. Advanced Research of Treatment Mechanism

The primary and secondary treatments are unable to completely degrade organic recalcitrant along with color, which necessitates the use of tertiary treatment of wastewater through processes that include adsorption, precipitation, UV radiation, and oxidative disinfection by ozone or other oxidants (like hydrogen peroxide and halogens like chlorine, chlorine dioxide, bromine, and iodine) with a final step of dehalogination

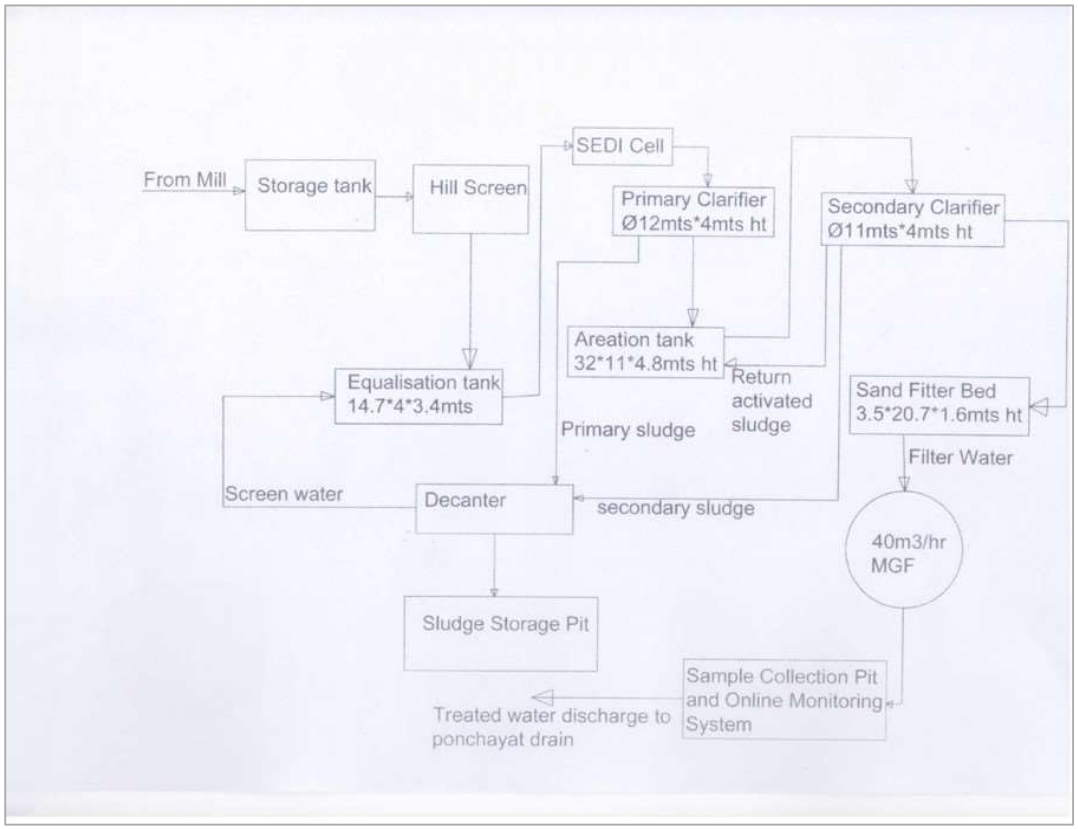
Adsorption

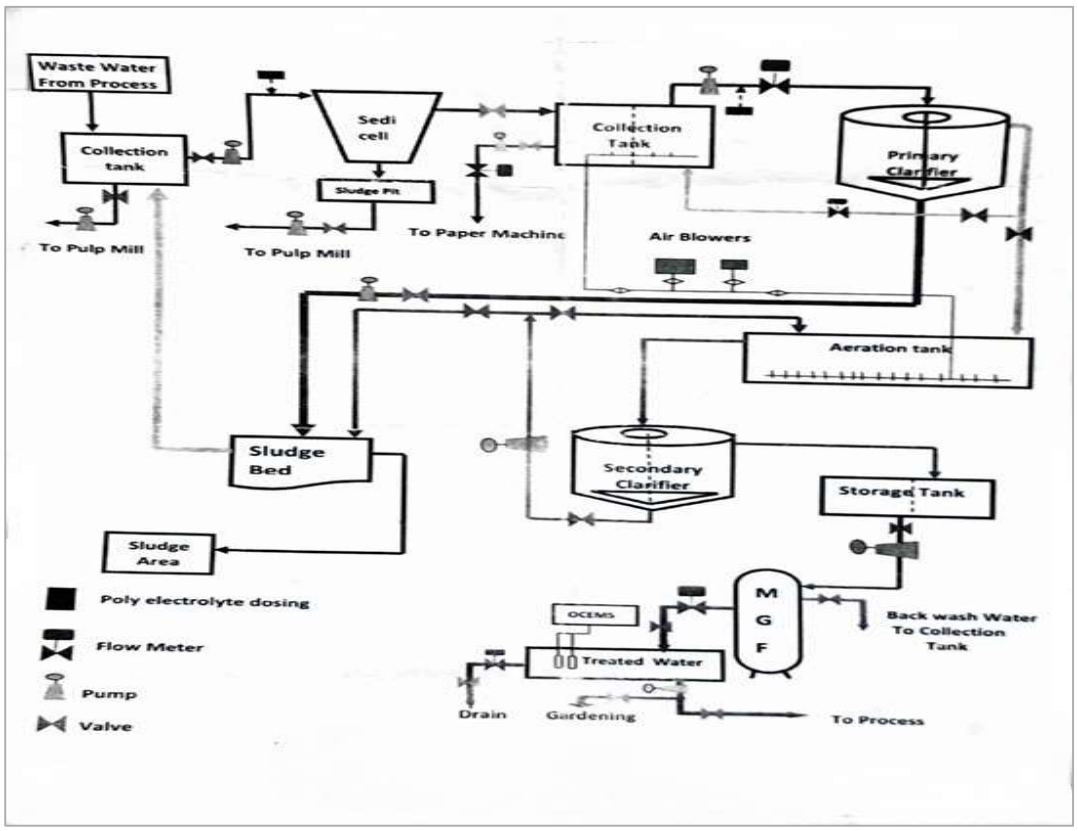
This process of adhesion leads to formation of a film of the adsorbate on the surface of the adsorbent (e.g., charcoal, silica gel, clay, metal oxides). Several processes (physical, chemical, and biological) occur at the surfaces between two phases, while others commence at the interface where the change in concentration of a given substance due to the accumulation of molecules at the interfacial layer as compared to that of neighbouring phases. As a result, the adsorbent (solid or liquid) surface achieves a state of tension due to the unbalanced or residual forces, which leads to the formation of bonds in between the surface molecules (adsorbent) and the molecules in the fluid phase. Adsorption with lignite (cost effective and easily disposable) can be efficiently integrated prior to biological treatment for efficient reduction of levels of BOD, COD, and colour.

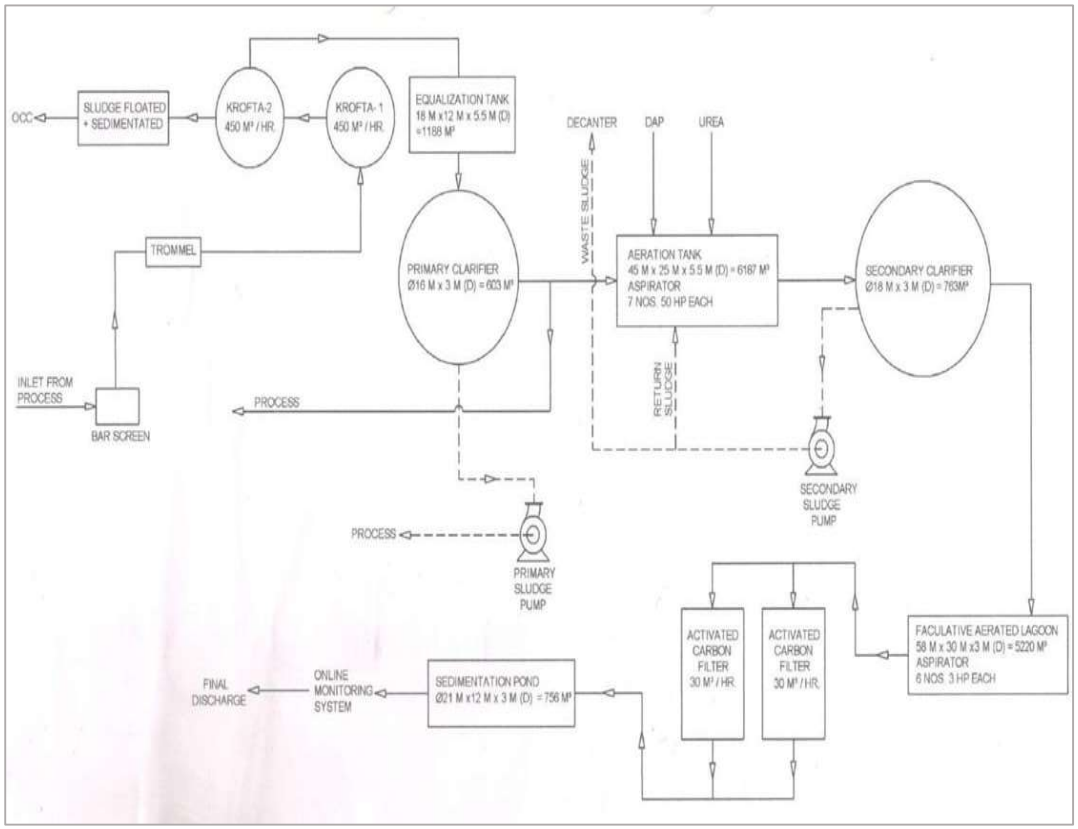
The high removal level of colour, COD, DOC, and AOX (.90%) is achieved by using activated coke for 4 hours with an adsorbent dosage of 15 g/L. A combination of adsorption (using Bentonite) and coagulation (using polyaluminium silicate chloride) treatment over biological treatment to increase the treatment performance of paper- and pulp-mill effluent has been found to be effective.

Membrane Technology

Membrane filtration is a separation process that employs semipermeable membrane to divide the supply wastewater stream into two parts: the first part is permeate that contains the material passing through the membranes and the second is retentate in which the species are being left behind (Mallevialle et al. 1996). Membrane filtration achieved the efficient recovery of waste materials, byproducts and several impurities discharged from wastewaters. Recently, various membrane technologies have been used for the treatment of pulp and paper mill wastewaters. Dube et al. (2000) reported that 88% and 89% removal of BOD and COD was attained by reverse osmosis. The most important applications of membrane filtration techniques are the recovery of lignosulfonate from spent sulphite liquor and lignin from kraft black liquor; it also saves energy and is beneficial for the environment.


From Mill
Storage tank
Hill Screen
SEDI Cell
Primary Clarifier
Ø12mts*4mts ht
Secondary Clarifier
Ø11mts*4mts ht
Areation tank
32*11*4.8mts ht
Return
activated
sludge
Equalisation tank
14.7*4*3.4mts
Primary sludge
Sand Fitter Bed
3.5*20.7*1.6mts ht
Filter Water
Screen water
Decanter
secondary sludge
40m3/hr
MGF
Sludge Storage Pit
Sample Collection Pit
and Online Monitoring
System
Treated water discharge to
ponchayat drain


Waste Water
From Process
Collection
tank
Sedi
cell
Collection
Tank
Primary
Clarifier
Sludge Pit
To Pulp Mill
To Pulp Mill
To Paper Machine
Air Blowers
Aeration tank
Sludge
Bed
Secondary
Clarifier
Storage Tank
Sludge
Area
Poly electrolyte dosing
Flow Meter
Pump
Valve
OCEMS
M
G
F
Back wash Water
To Collection
Tank
Treated Water
Drain
Gardening
To Process



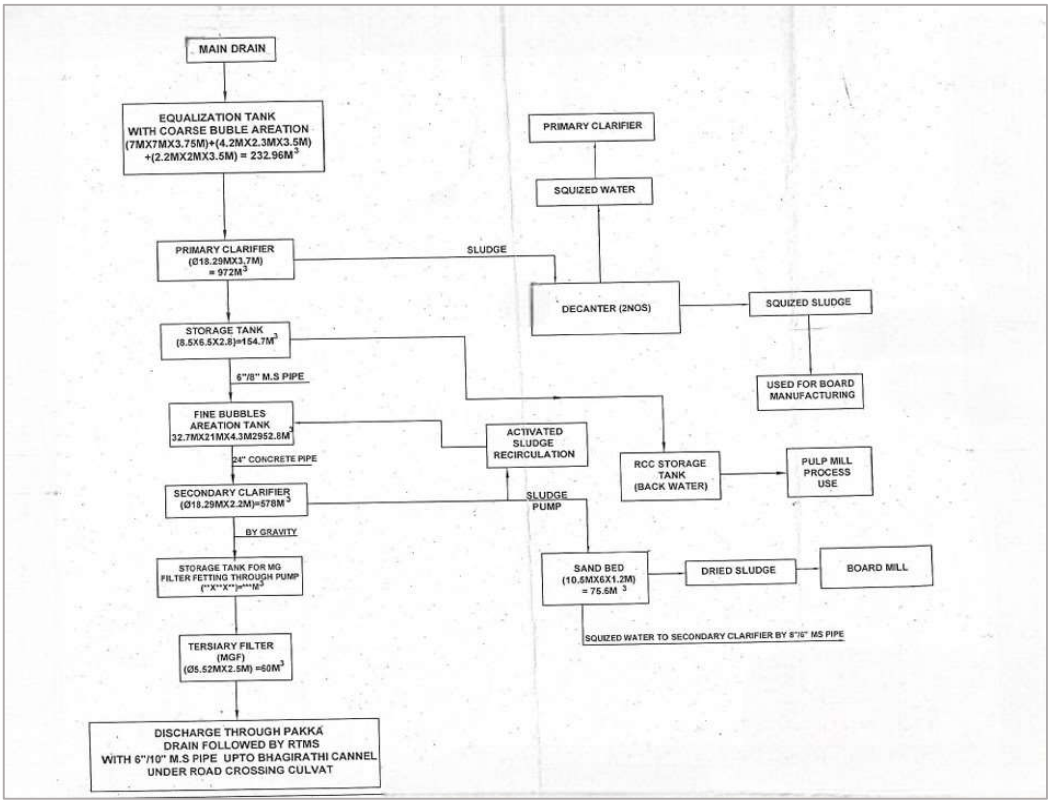


Figure 6 Operational layout of L1, L2, L4 & L6 respectively

3.4. Reliability

Evaluating the reliability of treatment processes and treatment facilities should be an important part of the planning and design process for water resource, wastewater treatment, and particularly wastewater reuse projects. Reliability evaluation for water and wastewater treatment has become more important, and more complex in recent years. This has occurred because there has been significant innovation in the range of available technologies and also, to strict regulatory standards by the governing body. Protection of the public health for that type of project depends to an unprecedented extent upon the consistent operation and effectiveness of the treatment processes and upon the overall reliability of the treatment facility. With the recent developments in technology, there is increasing need for a common methodology to evaluate the reliability of alternative processes and treatment facilities that utilize different combinations of those processes. Such evaluations are useful in planning and regulatory review, to compare the level of protection that would be provided by projects that utilize new technology versus levels that would have been considered acceptable with previous conventional technology.

(Benedetti, Keyser, Nopens, & Vanrolleghem, 2010) defined the reliability of a wastewater treatment plant (WWTP) as the probability of the effluent concentrations to comply with specified discharge standards or treatment objectives during a given period of time. Equation 1:

$$Reliability = 1 - P(effluent\ concentration > effluent\ requirement)$$

Where the probability (p) of the standard or a target being exceeded in the effluent depends on the distribution function describing the quality parameters concentrations. (Salar Niku, Edward D. Schroeder, Francisco J. Samaniego, 1979) defined the term "reliability of a wastewater treatment plant" as the ability to perform the specified requirements free from failure. (Graham B. Mcbride, 2001) and (Smith, 2001) defined reliability as the percentage of times a wastewater treatment plant remained in compliance to discharge standards. A WWTP will be completely reliable if the process performance response has no failure, that is, if the limits established by the targets or environmental legislations are not violated. Reliability analysis has been used to predict the performance of a technology over time and to determine the strategies that improve performance and reduce risks of failure (Johnstone, 2004).

Several methods have been used by others to evaluate and characterize the reliability of wastewater treatment. However, many of these methods are either limited in focus or are extremely theoretical. But in order to carry out a comprehensive and useful reliability evaluation for wastewater treatment plants and wastewater reuse facilities, a methodology was developed that relies on a range of measurements and observations to characterize treatment facility reliability with respect to: 1) variability of treatment effectiveness under normal operation, 2) probability of mechanical failures, 3) impacts of observed or projected mechanical failures upon effluent quality.

The method developed by Niku et al. (1979) has been recommended in regarded one of the best methods in evaluating the reliability of wastewater treatment unit. This method uses combination of analysis of the coefficient of reliability (COR) and the standard normal variate ($Z_{1-\alpha}$). COR is an index that relates the mean concentration of a parameter to the quality standards to be complied with a required reliability level. The COR was developed based on TSS and BOD data from activated sludge systems, wastewater treatment processes with high degree of mechanization and operational flexibility.

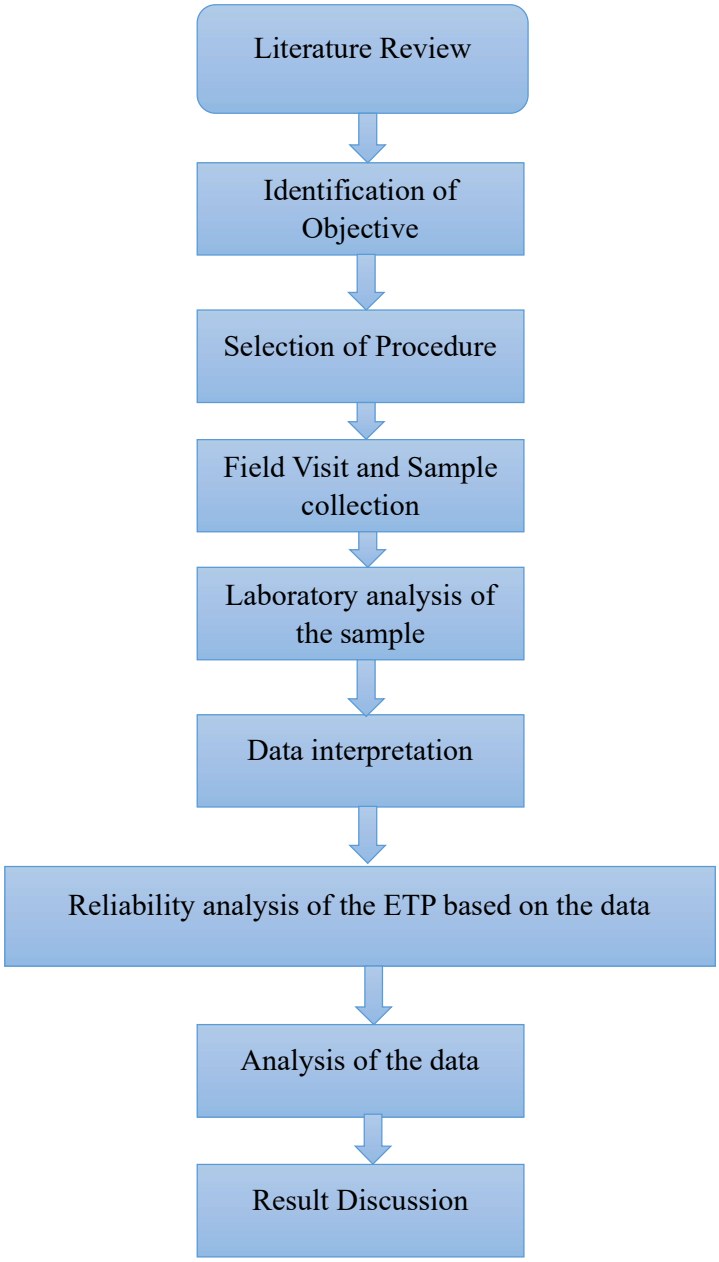
Later, comparative reliability studies by Oliveira and Von Sperling (2008) and Alderson et al. (2015) provided the COR of several wastewater treatment processes in Brazil. Still, few discussions were held on the practical applicability of COR results in natural systems with passive operation, such as Waste Stabilization Ponds (WSP), or consider different levels of restriction for discharge standards into water bodies. According to Weirich et al. (2011), the discharge standards are based on scientific criteria of water quality and the risk of significant adverse effects on the receiving water bodies. However, the imposition of regulatory limits that do not consider the regional socio-economic, institutional and climatic conditions may prevent the adoption of certain treatment technologies.

Based on the above, this study evaluated the performance and the coefficients of reliability (COR) for ETPs operating in few paper mills in West Bengal. It also analyses compliance with different criteria for effluent discharge and proposes an alternative approach for the design of WSPs based on the COR. We hope that the considerations of this study may contribute both in the design of new systems and in the definition of reasonable discharge standards by regulatory agencies.

Chapter 4: Methodology

Flow Chart

In this chapter, various activities of the study objectives are discussed. The various activities carried out in the study are shown through the flowchart.



4.1. Sample Collection

The wastewater collection process for this study involved meticulous sampling procedures conducted during field visits to the selected pulp and paper mills in West Bengal. Samples were systematically collected from both inlet and outlet points of Effluent Treatment Plants (ETPs), along with targeted specimens from specific treatment units such as aeration tanks and secondary clarifiers. Variably sized bottles ranging from 1000ml to 250ml were utilized to accommodate test procedure requirements. Each sample was assigned a unique identification code to ensure systematic organization and traceability. To preserve sample integrity, specimens were promptly stored in iceboxes as per standards to minimize potential degradation. Next the sample has been tested in laboratory to obtain the data required for the analysis. This detailed approach to collecting wastewater samples serves as the basis for further analysis, helping us better understand how wastewater treatment works and its impact on the environment. Photographs were taken during the sample collection process to document the methodology employed.



Photograph 4 Sample collection from the ETP inlet at location 5



Photograph 5 Sample collection from the AT at location 5

	
Photograph 6 Sample collection from the ETP outlet at location	*Photograph 7 Sample collection from the ETP at location 4*
	
Photograph 8 Sample collection from the ETP outlet at location 6	*Photograph 9 Sample collection from the ETP inlet at location 6*

	
Photograph 10 Sample collection from the ETP inlet at location 3	*Photograph 11 Sample collection from the ETP outlet at location 3*
	
Photograph 12 Sample collection from the ETP inlet at location 2	*Photograph 13 Sample collection from the AT at location 2*

	
Photograph 14 Sample collection from the ETP inlet at location 1	*Photograph 15 Sample collection from the ETP outlet at location 1*
	
Photograph 16 Sample collection from the AT at location 1	

4.2. Sample Analysis

Sample collected from the field analyse in the laboratory within 1 weeks such that quality is not degrade. Each sample is test for the parameters such as TSS, TDS, BOD and COD based on this parameter reliability analysis of the treatment unit is done for each of the paper mill.

All the parameters were measured according to the protocol mentioned in Standard Methods for Examination of Water and Wastewater (APHA, 1998). Test procedures carried out in lab for some of the parameters of concern has been discussed below.



Photograph 17 Laboratory setup, School of Water Resources Engineering, Jadavpur University

4.2.1. Total suspended solids

Materials used - Sample containers (preferably glass), Filtration apparatus (filtration flask, filter paper, vacuum pump or suction flask), Analytical balance, Drying oven, Desiccator, Weighing dishes, Graduated cylinder, Distilled water.

Test procedure:

- Set up the filtration apparatus. Place a pre-weighed filter paper in the filtration funnel.
- Pour the wastewater sample through the filter paper under gentle suction or vacuum. Filtration may take some time depending on the volume and turbidity of the sample.
- Ensure that all suspended solids are captured on the filter paper.
- After filtration, carefully remove the filter paper with the trapped solids. Place it in a pre-weighed dish.
- Record the weight of the dish with the filter paper and wet solids.
- Dry the filter paper with the trapped solids in an oven at a temperature between 103°C to 105°C for at least 1 hour, or until a constant weight is achieved.
- The vacuum pump was used to speed up the filtering effect.
- After drying, cool the dish with the dried solids in a desiccator to avoid moisture absorption.

- Weigh the dish with the dried solids and record the weight.

$$Total\ suspended\ solids = \frac{(W_f - W_i)\times 1000}{ml\ of\ smaple\ used}\text{, mg/l}$$

Where, W_f = Final dry weight of paper after filtration

W_i = Initial dry weight of paper before filtration



Photograph 18 Setup for TSS measurement

4.2.2. Total dissolved solids

Materials used - Multimeter with electrical conductivity measurement capability (HM-200), distilled water (for calibration), water sample, cleaning cloth.

Test procedure:

- Calibrate the multimeter according to the manufacturer's instructions using calibration standards with known conductivity values.
- Set the multimeter to measure electrical conductivity (typically in units of microsiemens per centimeter, µS/cm, or millisiemens per centimeter, mS/cm).
- Ensure the electrodes of the multimeter are clean and free from any residues that could affect the measurement.
- Immerse the electrodes of the multimeter into the water sample, ensuring they are fully submerged and not touching the sides or bottom of the container.
- Allow a stable reading to be obtained on the multimeter display. This may take a few seconds to stabilize.
- Record the TDS value displayed on the multimeter.

	
Photograph 19 HM- 200	*Photograph 20 During TDS determination*

4.2.3. Biochemical oxygen demand (BOD)

Materials used - BOD incubator, BOD bottles (300 ml.), dilution water (dechlorinated water), seed inoculum (activated sludge or other suitable microbial culture), dissolved oxygen meter (HACH HQ40d), measuring cylinder.

Test procedure:

- Prepare dilution water by dechlorinating tap water to remove any residual chlorine.
- Prepare a seed inoculum using activated sludge or other suitable microbial culture. The inoculum should be well-mixed and representative of the treatment plant's microbial community.
- Fill BOD bottles with appropriate volumes of sample water. Ensure that the bottles are filled completely to minimize headspace.
- Add a measured volume of seed inoculum to each BOD bottle. The inoculum volume should be sufficient to ensure a suitable microbial population for BOD degradation.
- Prepare a dilution water blank by filling a BOD bottle with dilution water only. This blank will serve as a control to account for any oxygen consumption by the seed inoculum or dilution water.
- Incubate the BOD bottles at a controlled temperature of 20 ± 1°C (or as specified) in a BOD incubator for a period of 5 days.
- Measure the initial dissolved oxygen (DO) concentration in each BOD bottle using a dissolved oxygen meter.
- Record the initial DO readings.
- After 5 days of incubation, measure the final dissolved oxygen (DO) concentration in each BOD bottle using the same method, record the final DO readings.
- Biochemical Oxygen Demand (BOD) of each sample calculated using the formula:

$BOD = \frac{(DO_i - D\ f)}{P}$ Where, DO_i = Initial dissolved oxygen concentration (mg/L)

DO_f = Final dissolved oxygen concentration (mg/L)

P = Dilution factor = volume of raw sample (ml.) / volume of total sample (ml.)



Photograph 21 BOD Incubator



Photograph 22 HACH HQ40d

4.2.4. Chemical oxygen demand (COD)

Materials used – COD reactor (DBR200), spectrophotometer (DR1900), COD digestion Reagent vials, micropipette, beaker, test tube rack.

Test procedure:

Reactor digestion procedure

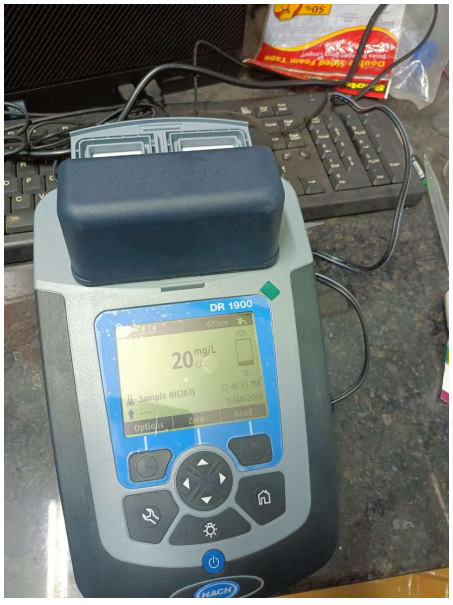
- Set the digestor power to on. Preheat to 150 °C.
- Use a clean pipet to add 2.00 mL of sample to the reagent vials.
- Prepare the blank sample by adding 2.00 mL of distilled water to the vial. Close the vials tightly. Rinse the vials with water and wipe with a clean paper towel.
- Invert the vials gently several times to mix and put it in the preheated digestor.
- Heat the vials for 2 hours.
- Set the reactor power to off. Let the vials cool in the reactor for approximately 20 minutes to 120 °C or less. Then put the vials in rack to cool to room temperature.

Colorimetric procedure

- Set the program for measuring COD in spectrophotometer.
- Clean the blank sample cell and insert it in the cell holder. Push ZERO to calibrate.
- Insert the prepared sample into the cell holder.
- Now push READ, COD value will display in mg/L.



Photograph 23 DRB200 Reactor



Photograph 24 DR1900 Spectrophotometer

	
Photograph 25 Sample preparation for COD test	*Photograph 26 During COD test*

4.3. Reliability Analysis and coefficient of reliability

The reliability of an Effluent Treatment Plant (ETP) is its capacity to consistently predict future treatment values (Garrido-Baserba, 2014). An ETP is considered more reliable when it frequently meets set discharge standards, unlike an ETP that often exceeds these standards (Alderson, 2015). Niku et al. (1979) developed a probabilistic analysis method to determine discharge thresholds that comply with standard values prescribed by governing bodies. The model by Niku et al. (1979) is as follows:

$$r = 1 - P_f$$

Where r is the reliability of the plant and P_f is the probability of failure. This probability is sensitive to the probabilistic distribution functions (PDFs) of pollutant parameters. Knowing the PDF helps predict exceedances of set standards and the future behaviour of an ETP, aiding in setting mean design effluent concentrations (Messaoud, 2013). Niku et al. (1979) introduced the term *Coefficient of Reliability (COR)* to assess system performance under varying conditions. The COR quantifies the probability that a wastewater treatment process consistently meets specified effluent quality standards, accounting for fluctuations in input loads and environmental conditions. This approach aids in designing resilient and efficient treatment plants by considering the inherent variability in biological processes.

The calculation of the COR parameter, as developed by Niku et al., is shown in the following *Fig. 7*.

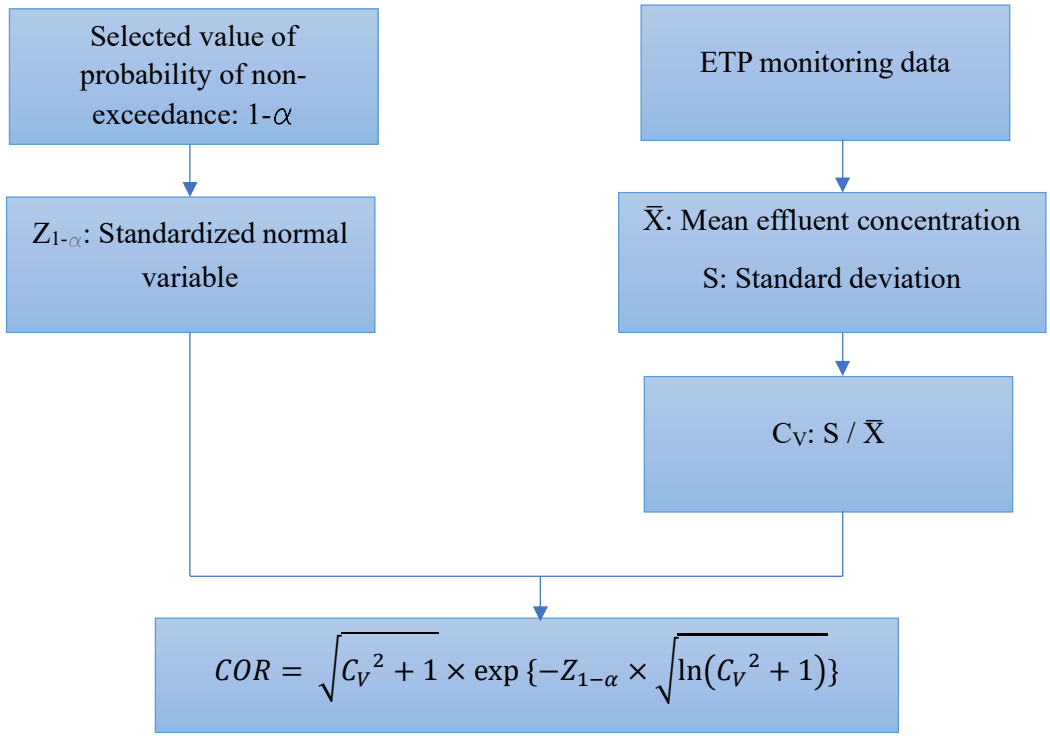


Figure 7 Calculation procedure for coefficients of reliability (COR)

The COR relates the values of the mean design concentration to the standard to be achieved, on a probability basis:

$$m_x = (COR) \times X_s \tag{4.1}$$

Where m_x is the mean effluent concentration (design value) (mg/L), X_S is the effluent concentration as specified by the discharge standards (mg/L) and COR is the coefficient of reliability.

The COR is calculated from the following equation (Salar Niku, Edward D. Schroeder, Francisco J. Samaniego, 1979):

$$COR = \sqrt{{C_V}^2 + 1} \times \exp\left\{-Z_{1-\alpha} \times \sqrt{\ln\left({C_V}^2 + 1\right)}\right\} \tag{4.2}$$

where $Z_{1-\alpha}$ is the standardized normal variate corresponding to the value of no exceedance probability of 1-α, where α is the probability of failure of meeting the standards.

The probability of no exceedance (1-α) with their corresponding $Z_{1-\alpha}$ distribution values are given in *Table 4* for ease of understanding of the concept of COR. These values are common for all treatment plants in general.

Table 4 Values of standardized normal distribution (Niku et al. 1979)

Cumulative Probability (1-α)	**$Z_{1-\alpha}$**
99	2.326
98	2.054
95	1.645
92	1.405
90	1.282
80	0.842
70	0.523
60	0.253
50	0

From the COR obtained, it was possible to determine the design concentrations that would be required to achieve the discharge standards.

4.4. Design and operational concentrations to achieve the discharge standards

The design concentrations that would lead to the achievement of the specified discharge standards were calculated from the COR by means of Eq. (4.1), for all the ETPs. The pollutant discharge standards for this point are: 30 mg/L of BOD, 250 mg/L of COD, 100 mg/L of TSS, and 1600 mg/L of TDS.

The application of COR for setting effluent values can be demonstrated using an example: for a CETP discharging effluent into a river, if the COR value for BOD is 0.36, then to achieve 95% compliance of the effluent quality with the standard discharge values, the mean BOD concentration of the effluent should be, according to Eq. (4.1),

$$m_x = 0.36 \times X_S$$

Chapter 5: Result and Discussion

5.1. Monitoring data from the treatment plants

The data evaluated in this work were obtained directly from the operational records of effluent water treatment unit installed in 6 pulp and paper industry located in the state of West Bengal. These ETPs in each of the plants evaluated taking into consideration the monitoring of TSS, TDS, BOD and COD effluent concentration.

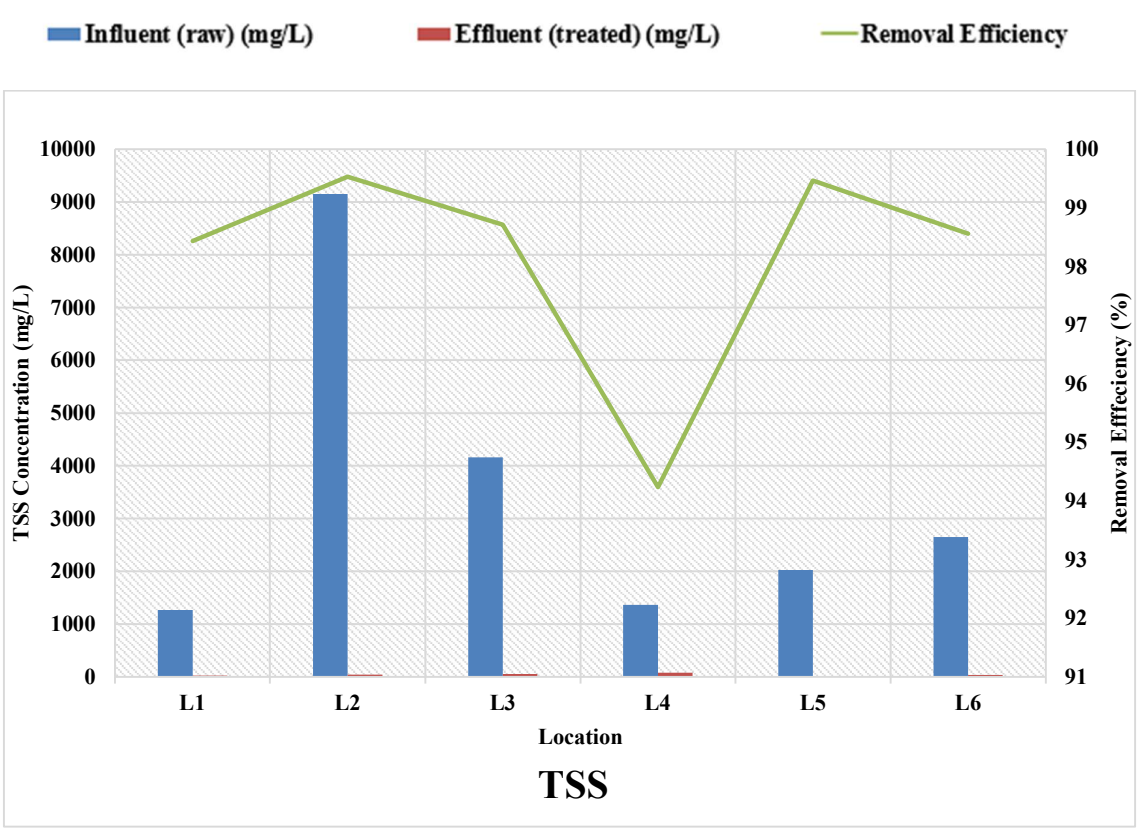
The mean concentrations of raw and treated wastewater, and the mean removal efficiencies associated with the six treatment units are presented in *table 5*.

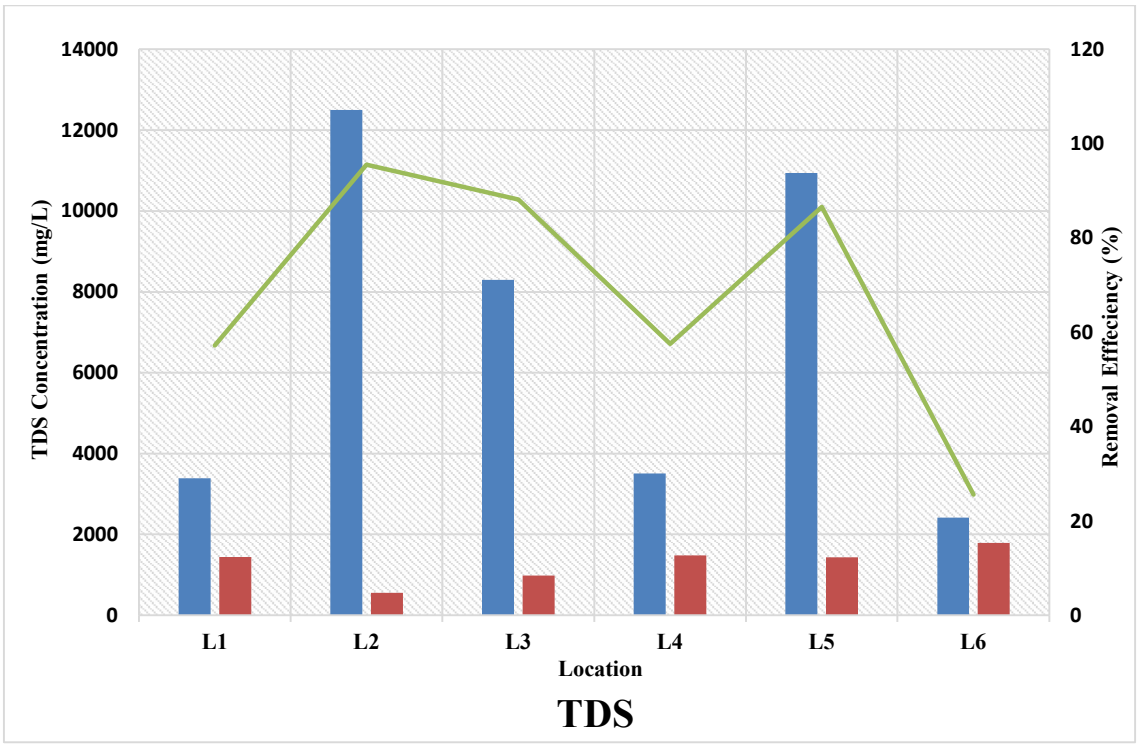
Table 5 Mean concentrations and mean removal efficiencies in the six ETPs

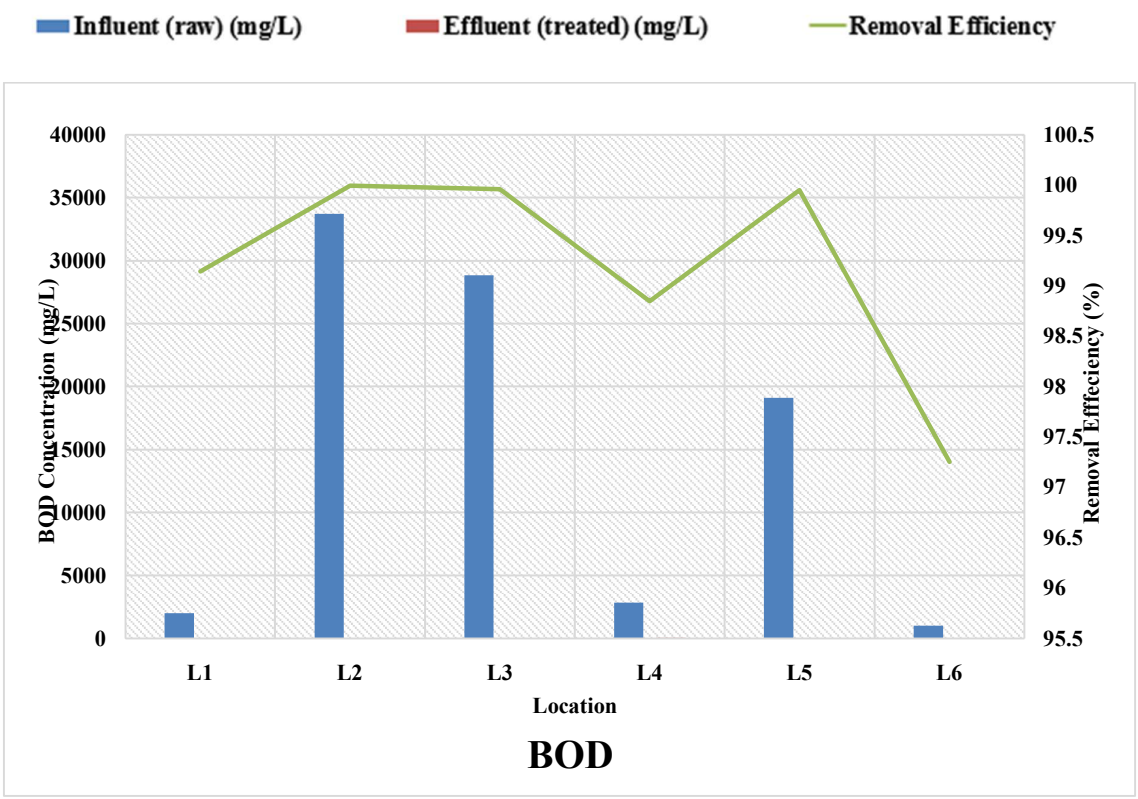
Parameter	Location	L1	L2	L3	L4	L5	L6
	Influent (raw) (mg/L)	1266.73	9148.67	4161.37	1358.07	2022.77	2648.53
TSS	Effluent (treated) (mg/L)	19.4	42.7333	53.6667	76.4	10.7	37.9333
	Removal Efficiency (%)	98.4354	99.5328	98.7091	94.2365	99.4673	98.5588
	Influent (raw) (mg/L)	3385	12500.2	8297.5	3504.13	10938.8	2422.9
TDS	Effluent (treated) (mg/L)	1445.53	562.133	984.467	1480.3	1441.4	1791.87
	Removal Efficiency (%)	57.2189	95.5028	88.1067	57.5445	86.5325	25.5761
	Influent (raw) (mg/L)	1995.63	33728.5	28840.1	2832.27	19111.5	1028.77
BOD	Effluent (treated) (mg/L)	17.0667	1.95	11.2667	32.3667	9.36667	28.0333
	Removal Efficiency (%)	99.1407	99.9942	99.9609	98.847	99.951	97.2521
	Influent (raw) (mg/L)	3860.93	42257	37342.8	6408.33	27563.8	2084.1
COD	Effluent (treated) (mg/L)	55.8667	10.6	40.5333	82.5	36.8333	43.1
	Removal Efficiency (%)	97.1911	99.9748	99.8913	98.7105	99.8664	97.91

In general, a great variability was noticed in the effluent concentrations and in the removal efficiencies as depict in *Fig. 38*, considering all the analysed parameters. Effluent concentrations in the ETPs are inherently variable due to the dynamic nature of the influent loads (inflow and concentrations) and environmental characteristics (such as temperature, pH and dissolved oxygen in the reactors). These influencing factors may follow a certain pattern, but they are frequently affected by other factors of a stochastic nature.

The extent of effluent variability depends on the behavioural the influent loads and environmental factors, but also on the treatment process itself. Reactors with long hydraulic retention times usually have a higher buffering capacity, whereas compact treatment units are more subject to instability due to variation of influent characteristics. Plant behaviour is also influenced by operational control. Some processes, such as Activated Sludge Process, have manipulated variables (return sludge flow, waste sludge flow, aeration capacity), which can be used in order to reduce effluent concentrations and their variability. These aspects and the plants performance are discussed in more detail by Oliveira and von Sperling (2006) and Oliveira (2006).


Influent (raw) (mg/L)
Effluent (treated) (mg/L)
Removal Efficiency
TSS Concentration (mg/L)
Removal Efffeciency (%)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
100
99
98
97
96
95
94
93
92
91
L1
L2
L3
L4
L5
L6
Location
TSS


TDS Concentration (mg/L)
Removal Efffeciency (%)
14000
12000
10000
8000
6000
4000
2000
0
120
100
80
60
40
20
0
L1
L2
L3
L4
L5
L6
Location
TDS



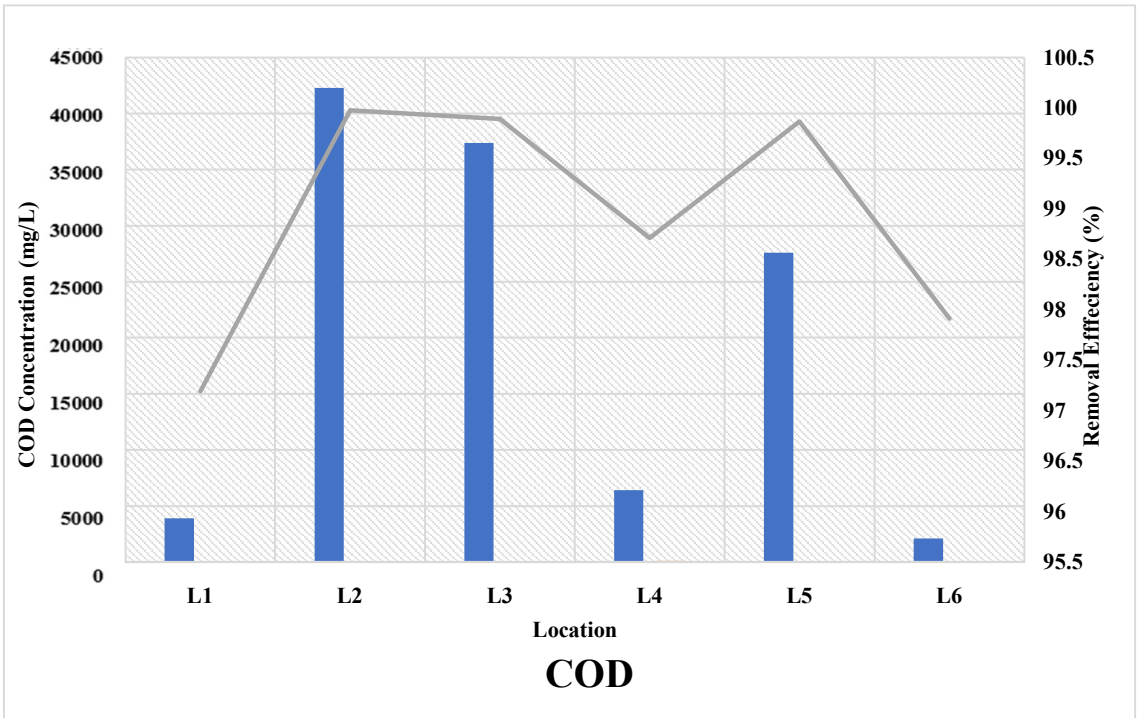


Figure 8 Variation of average influent and effluent concentration with mean removal efficiency in different plant location for the parameters e.g. TSS, TDS, BOD and COD respectively

5.2. Interpretation of the coefficient of reliability (COR)

In order to assist in the interpretation of the concept of the COR, Table have been prepared for selected levels of reliability and for a wide range of CV values, many effectively observed in the investigated plants. The determination and interpretation of the COR values in Table areas described below.

Table 6 Coefficient of reliability as a function of C_V and Reliability level

Reliability Level (%)	Cv								
	0.5	1	1.5	2	2.5	3	3.5	4	4.5
99	0.372624	0.203936	0.144292	0.116936	0.101947	0.092713	0.086553	0.082204	0.079006
98	0.423713	0.255766	0.193861	0.165124	0.149499	0.140085	0.13402	0.129935	0.127108
95	0.514019	0.359522	0.302226	0.27743	0.265855	0.260572	0.258642	0.258649	0.259842
90	0.610168	0.486382	0.448213	0.439696	0.443131	0.452011	0.463572	0.476506	0.490137
80	0.751133	0.701568	0.722674	0.768379	0.823166	0.881279	0.940352	0.99934	1.057764
70	0.872469	0.913458	1.019545	1.148762	1.286047	1.425672	1.56529	1.703898	1.841076
60	0.992091	1.14561	1.369788	1.622153	1.885906	2.154123	2.423726	2.693262	2.962024

For instance, for effluent concentrations with mean C_V values of 0.5, and adopting a reliability level of 95% ($\alpha = 0.05$) and the percentile $Z_{1-\alpha}$ obtained from standard normal variate tables (see *table 5* for selected values of $Z_{1-\alpha}$; for $1-\alpha = 0.95 \rightarrow Z_{1-\alpha} = 1.645$), the resulting value of COR is 0.514019, which can also be obtained from Table for $C_V = 0.5$ and a reliability level of 95% using Eq.

$$\text{COR} = \sqrt{0.5^2 + 1} \times exp\{-1.645\sqrt{\ln(0.5^2 + 1)}\} = 0.514019$$

This means that, in order to comply with the standards 95% of the time, the mean effluent concentration should be, according to Eq. $m_x = \text{COR} \times X_S$. For a standard of 100 mg/L, this means that the design effluent concentration ((assumed equal to the mean value) should be $m_x = 0.51 \times 100 = 51$ mg/L. For a lower reliability level of 80% and the same C_V of 0.50, from Table one obtains COR = 0.75. Therefore, in order to comply with the standards 80% of the time, a mean effluent concentration of $0.75 \times 100 = 75$ mg/L is required (naturally higher, that is, less stringent than the value required for a 95% reliability level). However, for the reliability level of 95%, if the C_V value were higher, say, $C_V = 1.5$, COR would be 0.30, indicating that the mean effluent concentration should be $0.30 \times 100 = 30$ mg/L. Similar calculations can be done for different C_V values and reliability levels.

From *table 6* it is seen that, for the reliability levels frequently adopted (80% or higher) and CV values frequently found in practice (lower than 1.0), there is a general trend of decreasing COR with the increase of CV and the reliability level. The interpretation is that, the higher the desired reliability and the effluent variability, the lower the COR should be, or, in other words, the lower the mean value of the effluent concentration should be, but it is also interesting to observe that the reliability level curves start to show an increasing trend after the C_V reaches a certain value. On first thoughts, this would not be expected, but a detailed analysis of the behaviour of the lognormal distribution helps to explain this apparent inconsistency. Because

the distribution is not symmetrical, being skewed to the right (i.e., the data are clustered more to the left of the mean, with most of the extreme values to the right), the arithmetic mean will be shifted to the right, since it is strongly influenced by the relatively small quantity of large values obtained. As a result, a plant with a large CV value fora particular constituent, even if having a high arithmetic mean value (close to the standard), may have most of the values well below the standard, thus possibly characterizing a high reliability level.

5.3. COR values obtained in the study

The COR of the components of interest, taking into consideration the C_V of the ETPs in operation, have been calculated for a level of reliability of 95%. The mean values of C_V and COR of the six locations, considering all constituents are presented in *table 7*.

It should be noted that low C_V values and, consequently, high COR values do not necessarily imply a good performance (since the effluent concentrations of the components have not been taken into consideration), but simply a more stable operating condition. Low COR values imply the need for lower design effluent concentrations, since these will be obtained by multiplying the COR by the discharge standard value to be achieved.

Table 7 C_V and COR for the treatment unit in different location

Location	Coefficient of variation (CV)				Coefficient of reliability (COR)			
	TSS	TDS	BOD	COD	TSS	TDS	BOD	COD
L1	0.167221	0.087308	0.157625	0.056552	0.771518	0.869748	0.782366	0.912692
L2	0.067581	0.047209	0.438206	0.165454	0.896941	0.92635	0.547929	0.773497
L3	0.068391	0.181503	0.213544	0.142939	0.895799	0.825461	0.722473	0.799448
L4	0.159701	0.14609	0.34997	0.126799	0.779998	0.795733	0.605692	0.818912
L5	0.552169	0.187427	0.372463	0.237228	0.488927	0.749464	0.589809	0.699398
L6	0.190469	0.122272	0.399591	0.213984	0.746234	0.824505	0.571741	0.722032

Table 7 provides a quantitative basis for understanding the operational reliability of each ETP in terms of specific parameters. It has been found that L2 stands out with exceptional reliability for TSS (0.896941) and TDS (0.92635), indicating highly stable operations for these parameters. However, it shows significant variability in BOD management with a COR of 0.547929, suggesting potential issues in maintaining consistent BOD levels. In contrast, L1 consistently perform well across all parameters, with COR values of 0.771518 for TSS, 0.869748 for TDS, 0.782366 for BOD, and an outstanding 0.912692 for COD. This indicates particularly excellent reliability in COD management, reflecting stable and effective operations.

L3 also demonstrates high reliability for TSS (0.895799) and TDS (0.825461), but exhibits moderate variability in BOD (0.722473) and COD (0.799448). This suggests reasonably stable operations, with some room for improvement in managing organic and chemical pollutants. Similarly, L4 shows moderate reliability with COR values of 0.779998 for TSS, 0.795733 for TDS, 0.605692 for BOD, and 0.818912 for COD. While it manages COD effectively, the lower COR for BOD indicates a need for improved operational control to enhance stability.

L6 displays moderate reliability across all parameters, with COR values of 0.746234 for TSS, 0.824505 for TDS, 0.571741 for BOD, and 0.722032 for COD. This suggests a stable operation overall, but with specific emphasis required for enhancing BOD consistency. Lastly, L5 shows the lowest reliability values among the six ETPs, with COR values of 0.488927 for TSS, 0.749464 for TDS, 0.589809 for BOD, and 0.699398 for COD. These figures indicate the highest variability, suggesting significant operational challenges and the greatest need for improvements in effluent treatment processes.

Overall, while some ETPs demonstrate high reliability for specific parameters, others exhibit variability that necessitates targeted improvements. ETPs with higher COR values for certain parameters, such as L1 and L2 for TSS and TDS, indicate more consistent performance. In contrast, ETPs with lower COR values, like L5 for TSS and COD, highlight areas requiring enhanced operational controls to achieve more consistent and effective effluent treatment performance. The detailed COR values for each parameter provide a clear understanding of the operational stability and areas needing improvement for each ETP.

5.4. Design and operation concentrations required to achieve the discharge standards

Table 8 and Fig. 9 show the mean design concentrations, which would lead to the achievement of the discharge standards: TSS = 100 mg/L; TDS = 1600 mg/L; BOD = 30 mg/L; COD = 250 mg/L, as well as the actual concentrations observed for each treatment technology. As discussed in Section 4.4., these standards correspond, in some cases, to hypothetical targets based on intermediate standards as per CPCB in India and also in other developing regions in the world. Design concentrations were calculated by means of Eq. (4.1) for each system, using their C_V and $\alpha = 0.05$.

Table 8 Mean design effluent concentrations to achieve 95% compliance with the standards and observed actual effluent concentrations

Location	Mean design concentrations				Observed actual mean concentrations			
	TSS	TDS	BOD	COD	TSS	TDS	BOD	COD
L1	77.15182	1391.596	23.47099	228.173	19.4	1445.533	17.06667	55.86667
L2	89.6941	1482.161	16.43788	193.374	42.73333	562.1333	1.95	10.6
L3	89.57993	1320.737	21.67418	199.862	53.66667	984.4667	11.26667	40.53333
L4	77.99978	1273.173	18.17075	204.728	76.4	1480.3	32.36667	82.5
L5	48.8927	1199.142	17.69426	174.85	10.7	1441.4	9.366667	36.83333
L6	74.6234	1319.209	17.15222	180.508	37.93333	1791.867	28.03333	43.1

Discharge standards considered: TSS = 100 mg/L; TDS = 1600 mg/L; BOD = 30 mg/L; COD = 250 mg/L

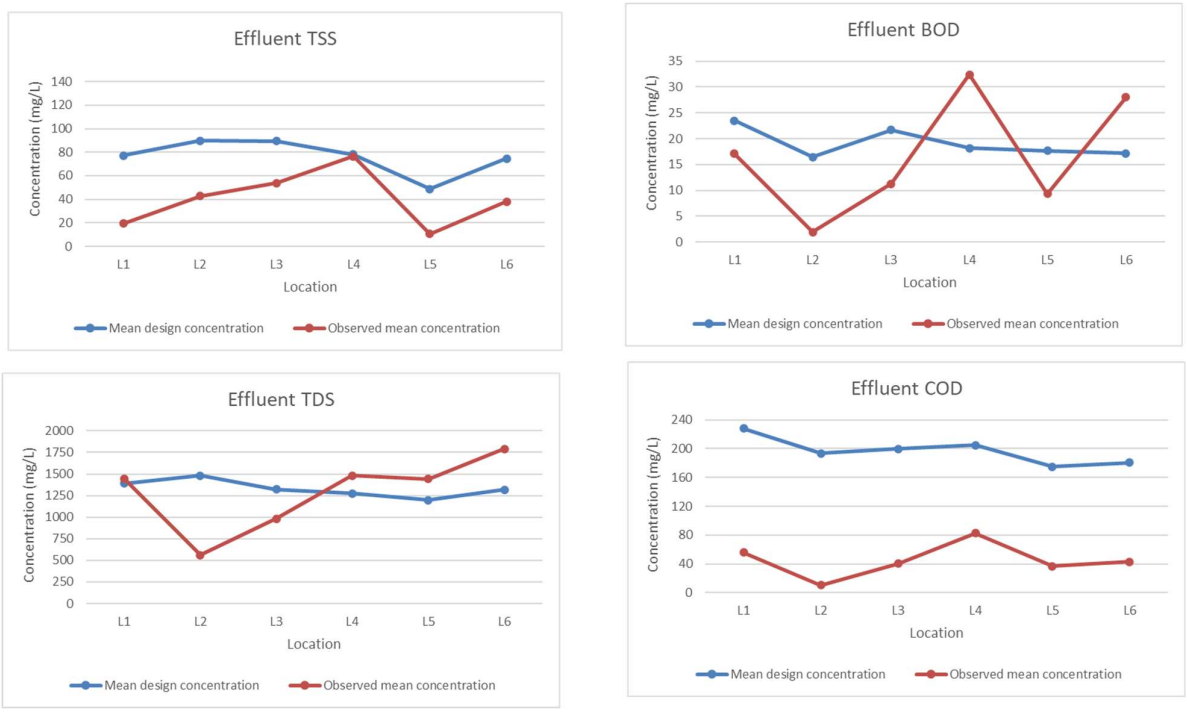


Figure 9 Mean (design) effluent concentrations to achieve 95% compliance with the standards and the observed actual concentrations

This analysis of mean design concentrations versus observed mean concentrations reveals critical insights into the performance and reliability of the Effluent Treatment Plants (ETPs). Mean design concentrations, calculated to ensure a 95% compliance with discharge standards, represent the ideal effluent quality the treatment systems should achieve under normal operations. These values are set to prevent exceedances of TSS TDS, BOD and COD, with thresholds of 100 mg/L, 1600 mg/L, 30 mg/L, and 250 mg/L respectively. Observed mean concentrations, however, reflect the actual performance of the ETPs during regular operations. Discrepancies between these values and the design concentrations as shown in *Fig. 9* also indicate operational challenges, such as inefficiencies in solid removal, difficulties in controlling dissolved solids, problems in biological treatment stages, and inefficiencies in removing chemical pollutants. For instance, in one of the ETPs, the observed mean concentration of BOD was significantly higher than the design mean concentration, indicating that the biological treatment process was not performing as expected, potentially due to inadequate microbial activity or insufficient retention time. These differences highlight the gap between theoretical standards and real-world performance, which can be attributed to factors like operational variability, maintenance issues, lack of process optimization, and technological limitations.

5.5. Some statistical concepts in the assessment of COR and design mean concentration

Several studies have addressed the application of statistical concepts to setting standards for wastewater discharges (Wheatland, 1972; Porter, 1975; Dean, 1976a). However, legal requirements have generally not included statistical considerations. If a plant's performance follows lognormal statistics (as demonstrated by Niku and Schroeder, 1981; Niku et al., 1979, 1981, 1982; P. M. Berthouex, 1983; Metcalf and Eddy, 2003; Oliveira, 2006), there is always a definite probability of exceeding any finite upper limit, even if this probability is very small. Use of probabilistic methods in setting discharge standards is a realistic and practical approach from an operational point of view. By knowing or assuming the variability of plant performance, it should be possible to determine what average effluent quality must be maintained to meet a standard with some predetermined probability. As discussed in Section 5.4., depending on the desired reliability level, the plant should be designed for higher or lower effluent concentrations.

while performing the reliability analysis and obtaining the COR values it is also important to discuss the following point:

5.5.1. Value of COR closer to 1.0

The Coefficient of Reliability (COR) is a crucial metric for evaluating the performance consistency of wastewater treatment units. In general, COR value close to 1 indicates higher reliability, meaning the treatment process consistently meets performance standards with minimal variability. For example, in the *table 7*, L1 have a COR of 0.912692 for COD, signifying excellent reliability in removing Chemical Oxygen Demand. Conversely, lower COR values, such as 0.488927 for TSS for L5, suggest significant variability and less dependable performance. These results align with the theoretical expectations based on reliability engineering principles, as outlined in Elsayed's (2012) 'Reliability Engineering'.

High COR values typically result from stable operational conditions, effective maintenance, and advanced treatment technologies (Eddy, Metcalf &, 2014). In contrast, low COR values may arise from fluctuating influent quality, poor maintenance, or outdated technologies (Journal of Environmental Management, "Reliability Analysis of Wastewater Treatment Plants: Case Studies and Methodological Insights," 2020). Understanding these values helps identify areas needing improvement to enhance the overall reliability of wastewater treatment processes. By striving for COR values close to 1, treatment facilities can ensure more consistent and efficient operations, ultimately leading to better compliance with environmental standards (Water Research, "Influence of Operational and Influent Factors on the Reliability of Wastewater Treatment Processes," 2019).

5.5.2. COR values greater than 1.0

An important observation is related to the behaviour of the 50% level of reliability, for which all COR values are greater that 1.0 (see *table 6*). This means that, in order to comply with the standards during 50% of the time, the mean effluent concentration can be equal to or greater than the standard, according to Eq. (4.1). This particular case arises from the fact that, for the lognormal distribution, as mentioned above, the arithmetic mean is greater than the median. If the median is taken to be the value of the discharge standard, thus being a direct interpretation of the 50% reliability level, then the arithmetic mean will be higher than the discharge standard, which justifies the COR greater than 1.0. COR values greater than 1.0 can be found for other reliability levels, and the interpretation remains that a certain desired percentage of compliance with the standards may be achieved, even though the arithmetic mean is, in this particular case, greater than the discharge standard. Once again, this is associated with the non-symmetrical pattern of the lognormal distribution.

Chapter 6: Conclusions

6.1. Conclusion

In conclusion, this study highlights the critical role of reliability analysis in the effective management of industrial wastewater treatment. The research conducted a comparative reliability analysis of effluent treatment plants (ETPs) in the pulp and paper industry in West Bengal, focusing on key water quality parameters such as Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD), and Chemical Oxygen Demand (COD). The analysis revealed significant variability in the reliability of different ETPs.

High reliability was observed in some locations, such as Location 1 (L1), which demonstrated Coefficient of Reliability (COR) values of 0.771518 for TSS, 0.869748 for TDS, 0.782366 for BOD, and 0.912692 for COD, indicating stable and effective operations. Conversely, other locations, such as Location 5 (L5), showed lower reliability with COR values of 0.488927 for TSS, 0.749464 for TDS, 0.589809 for BOD, and 0.699398 for COD, highlighting significant operational challenges. Among the six ETPs analysed, the ETP at L1 emerged as the most efficient, consistently showing high COR values across all parameters (TSS, TDS, BOD, and COD). L1's superior performance can be attributed to its effective operational practices and design features that ensure stable and reliable effluent treatment. Specifically, L1 has a design flow of 288 m^3/day, a bar screen measuring 3.5m x 3m, an equalization tank of 14.7m x 4m x 3.4m, a sedi-cell with a capacity of 100 m^3/hr, an aeration tank measuring 32.1m x 11m x 4.8m, and a clarifier with an 11m diameter and a height of 4m. These design specifications contribute significantly to its high reliability and consistent performance.

The COR values provide a clear indication of the areas where improvements are needed and underscore the importance of maintaining consistent and reliable performance in effluent treatment processes. This analysis can serve as a valuable reference for designing and optimizing ETPs to achieve better environmental outcomes. Moreover, the research establishes performance benchmarks for ETPs, providing valuable insights for future design and operational practices. These recommendations aim to improve environmental management and sustainability practices within the industry, ensuring that ETPs can consistently achieve the necessary discharge standards.

By focusing on key performance indicators and employing robust statistical methods, the research provides a pathway for enhancing the efficiency and reliability of ETPs, thereby contributing to improved environmental outcomes and sustainable industrial practices

6.2. Limitation of the study

The limitations of this study on the comparative reliability analysis of effluent treatment plants (ETPs) in the pulp and paper industry of West Bengal include:

- Differences in data collection methods and the availability of comprehensive datasets could affect the consistency and reliability of the study's findings.
- The study focused on key parameters such as TSS, TDS, BOD and COD, while excluding other important factors like heavy metals and nutrients.
- The findings may not be generalizable to other regions or industries with different environmental regulations and operational practices due to geographical and technological limitations.
- The study did not extensively document the influence of operational practices and human factors, such as operator expertise and maintenance schedules, on the performance of effluent treatment plants (ETPs).
- Assumptions of normality and potential sampling biases could affect the accuracy of the statistical results.
- Variations in temperature and rainfall, which can significantly impact treatment efficiency, were not explicitly accounted for in the study.
- Finally, the study did not evaluate economic aspects such as cost-effectiveness and financial sustainability, which are crucial for a comprehensive assessment of ETPs.

Addressing these limitations in future research will enhance the understanding and optimization of ETPs for better environmental management and sustainability.

6.3. Future scope of the study

This study's analysis of effluent treatment plants (ETPs) in the pulp and paper industry in West Bengal highlights several avenues for future research to enhance environmental management and sustainability. Future studies should focus on expanding the scope by including additional parameters such as heavy metals, nutrients, and emerging contaminants for a more comprehensive assessment of ETP performance. Investigating advanced treatment technologies like membrane bioreactors, moving-bed biofilm reactors, and hybrid systems could improve treatment efficiency and resource recovery. Integrating eco-friendly and energy-efficient methods will be crucial in addressing the high energy demands and ecological impacts of traditional treatments. Additionally, thorough investigation into the economic aspects of ETP operations, including cost-effectiveness and financial sustainability, is needed to ensure proposed improvements are viable for widespread adoption. Considering the impact of varying environmental and seasonal conditions on treatment performance will help develop robust solutions for diverse scenarios. Developing predictive models to forecast treatment plant performance and reliability based on different influent characteristics and operational practices could enhance decision-making and operational efficiency. Collaboration with regulatory bodies and industry stakeholders will be vital in establishing standardized protocols and benchmarks for ETP performance, ensuring consistent compliance with environmental regulations. Addressing these areas in future research will significantly contribute to the optimization of effluent treatment processes, promoting sustainable industrial practices and better environmental stewardship in the pulp and paper sector.

References

International Water Association. (2018). *Wastewater Report 2018.*

Silva, C., & Rosa, M. J. (2022). A treatment reliability-based method for supporting infrastructure asset management of wastewater treatment plants. *Water, 14*(7). Retrieved from https://doi.org/10.3390/w14071106

A. Padalkar, S. K. (2019). Reliability analysis and removal efficiency relationship of common effluent treatment plants of industrial clusters. *International Journal of Environmental Science and Technology, 16*(3), 1379-1394. Retrieved from https://doi.org/10.1007/s13762-018-1740-9

Acumen Research and Consulting. (2019). *Industrial Wastewater Treatment Market (By Process: Primary Treatment, Secondary Treatment, Tertiary Treatment; By Type: Coagulants, Biocides & Disinfectants, Flocculants; By End-Use Industry: Mining, Power Generation, Chemical) - Global Industry Analysis*. Retrieved from https://www.acumenresearchandconsulting.com/industrial-wastewater-treatment-market

Alderson, M. a. (2015). Reliability analysis of low-cost, full-scale domestic wastewater treatment plants for reuse in aquaculture and agriculture. *Ecological Engineering*.

Arya Vijayanandan, A. A. (2023). Domestic and industrial wastewater treatment: current status and challenges in India. *IWA Publishing*.

Ashwini V. Padalkar, R. K. (2018). Common effluent treatment plant (CETP): Reliability analysis and performance. *Water Science and Engineering, 11*(3), 205-213. doi:https://doi.org/10.1016/j.wse.2018.10.002

Benedetti, L., Keyser, W. D., Nopens, I., & Vanrolleghem, P. A. (2010). Probabilistic modelling and evaluation of wastewater treatment plant upgrades in a water quality based evaluation context. *Journal of Hydroinformatics*.

Bharagava RN, M. S. (2018). Hexavalent chromium reduction potential of Cellulosimicrobium sp. isolated from common effluent treatment plant of tannery industries. *Ecotoxicol Environ Saf*, 102-109. doi:https://doi.org/10.1016/j.ecoenv.2017.08.040

Biermann, C. J. (1993). *Essentials of pulping and papermaking.* San Diego: Academic Press.

Choudhury, S., & Saha, A. K. (2018). Prediction of operation efficiency of water treatment plant with the help of multi-criteria decision-making. *Water Conserv Sci Eng*, 79-90. doi:https://doi.org/10.1007/s41101-017-0034-2

CPCB. (2019). *General Standards for Discharge of Environmental Pollutants*. Retrieved from https://cpcb.nic.in/displaypdf.php?id=R2VuZXJhbFN0YW5kYXJkcy5wZGY=

CPCB. (n.d.). *Designated Best Use Water Quality Criteria*. Retrieved from https://cpcb.nic.in/wqm/Designated_Best_Use_Water_Quality_Criteria.pdf

D.V. Savant a, R. A.-R. (2006). Anaerobic degradation of adsorbable organic halides (AOX) from pulp and paper industry wastewater. *Bioresource Technology*, 1092-1104.

Dean, R. A. (1976a). Estimating the reliability of advanced waste treatment. 87-89.

Deblina Dutta, S. A. (2021). Industrial wastewater treatment: current trends, bottlenecks, and best practices. *Chemosphere*.

E.W.Steel, T. J. (1991). Water Supply and Sewerage. McGraw-Hill Education.

Eddy, Metcalf &. (2014). *Wastewater Engineering: Treatment and Resource Recovery.* McGraw-Hill Education.

Eisenberg, D., Soller, J., Sakaji, R., & Olivieri, A. (2001). A methodology to evaluate water and wastewater treatment plant reliability. *Water Science & Technology*, 91–99.

Elsayed, E. A. (2020). *Reliability Engineering* (3rd ed.). Wiley.

Garrido-Baserba, M. a. (2014). Including the Environmental Criteria When Selecting a Wastewater Treatment Plant. *Environmental Modelling & Software*, 74-82.

Graham B. Mcbride, J. C. (2001). Confidence of Compliance: A Bayesian Approach for Percentile Standards. *Water Research*.

Howard Peavy, Donald Rowe, George Tchobanoglous. (1985). *Environmental Engineering.* McGraw-Hill.

Johnstone, C. E. (2004). Decentralized wastewater treatment system reliability analysis. *Environmental Science Engineering*.

Joshua T. Bunce, D. W. (2019). A simple approach to predicting the reliability of small wastewater treatment plants. *Water*. Retrieved from https://doi.org/10.3390/w11112397

Matheus Sales Alves, F. J. (2021). Performance evaluation and coefficients of reliability for waste stabilization ponds in northeast Brazil. *Ambiente & Água - An Interdisciplinary Journal of Applied Science (AMBIAGUA) , 16*(1). Retrieved from https://doi.org/10.4136/ambi-agua.2571

Messaoud. (2013). Determination and analysis of daily reliability level of municipal wastewater treatment plant. 39-46.

P. M. Berthouex, W. G. (1983). How to construct reference distributions to evaluate treatment plant effluent quality. *Water Pollution Control Federation*, 1417-1424.

P.K. Tewari, P., Batra, V., & Balakrishnan, M. (2008). Efficient water use in industries: Cases from the Indian agro-based pulp and paper mills. *Journal of environmental management*, 265-273.

Padalkar, A., & Kumar, R. (2018). Common effluent treatment plant (CETP): Reliability analysis and performance evaluation. *Water Science and Engineering*.

Pal, P. (2017). Industrial Water Treatment Process Technology. In P. Pal, *Industrial Water Treatment Process Technology* (pp. 243-511). Durgapur: Butterworth-Heinemann.

Porter, K. S. (1975). Percentile mean relation for effluent assessment. *Journal of the Environmental Engineering Division*, 473-478.

Rajaram, T., & Das, A. (2008). Water pollution by industrial effluents in india: discharge scenarios and case for participatory ecosystem specific local regulation. *Futures*, 56-69.

Salar Niku, Edward D. Schroeder, Francisco J. Samaniego. (1979). Performance of activated sludge processes and reliability-based design. *Journal Water Pollution Control Association*, 2841-2857.

Sílvia C. Oliveira, M. V. (2008). Reliability analysis of wastewater treatment plants. *Water Research*, 1182-1194.

Smith, E. Y. (2001). Statistical Assessment of Violations of Water Quality Standards Under Section 303(d) of the Clean Water Act. *Environmental Science and Technology*, 606-12.

Sumit Dagar, S. K. (2022). Economics of advanced technologies for wastewater treatment: evidence from pulp and paper industry. *Frontiers in Environmental Science*.

Tripathi, U. S. (2020). Characteristics and treatment of pulp and paper mill effluents – a review. *International Journal of Engineering and Technical Research (IJETR)*, 2454-4698.

UN Water, UNESCO . (2017). *2017 UN World Water Development Report, Wastewater: The Untapped Resource*. Retrieved from https://reliefweb.int/report/world/2017-un-world-water-development-report-wastewater-untapped-resource

Vivek V. Ranade, Vinay M Bhandari. (2014). *Industrial Wastewater Treatment, Recycling and Reuse.* Netherlands: Butterworth-Heinemann Limited.

W. Wesley Eckenfelder, Davis L. Ford, Andrew J. Englande. (2009). *Industrial Water Quality* (4th ed.). New York: McGraw-Hil.

Wheatland, A. (1972). Discussion statistical expression of effluent quality standards. *Water Research, 6*, 339-340. doi:https://doi.org/10.1016/0043-1354(72)90102-9

Annexure 1

Sampling results for L1

Sl. No.	TSS			TDS			BOD			COD		
	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency
	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)
1	1242	20	98.38969	3496	1520	56.52174	1997	16	99.1988	3883	57	98.53206
2	1459	22	98.49212	3601	1342	62.73257	1811	15	99.17173	3896	56	98.56263
3	1405	25	98.22064	3618	1394	61.47043	1912	16	99.16318	3667	59	98.39106
4	1441	23	98.40389	3453	1655	52.07066	1796	15	99.16481	3798	57	98.49921
5	1042	20	98.08061	3304	1354	59.01937	2019	15	99.25706	3824	54	98.58787
6	1509	17	98.87343	3138	1273	59.43276	2100	17	99.19048	3979	55	98.61774
7	1547	20	98.70718	3437	1644	52.16759	1861	16	99.14025	3726	60	98.38969
8	999	25	97.4975	3519	1642	53.33902	1988	16	99.19517	3876	57	98.52941
9	1319	15	98.86277	3307	1388	58.02842	1859	21	98.87036	3880	59	98.47938
10	1324	16	98.79154	3341	1551	53.57677	1993	18	99.09684	3733	58	98.44629
11	1371	21	98.46827	3351	1382	58.75858	1811	19	98.95086	4143	52	98.74487
12	1326	20	98.4917	3189	1613	49.41988	1951	21	98.92363	3950	59	98.50633
13	1532	19	98.75979	3452	1317	61.8482	2029	20	99.01429	3858	52	98.65215
14	1274	18	98.58713	3560	1238	65.22472	2023	14	99.30796	4025	51	98.73292
15	1214	20	98.35255	3372	1297	61.53618	2042	16	99.21645	4090	51	98.75306
16	1321	18	98.6374	3254	1342	58.75845	1939	21	98.91697	3657	55	98.49604
17	1272	16	98.74214	3171	1407	55.62914	1825	18	99.0137	3994	56	98.5979
18	1109	22	98.01623	3647	1448	60.29613	2039	21	98.97008	3938	58	98.52717
19	996	15	98.49398	3462	1656	52.16638	2118	19	99.10293	3689	60	98.37354
20	1171	15	98.71904	3234	1546	52.19542	1992	21	98.94578	3872	55	98.57955
21	989	25	97.47219	3650	1424	60.9863	2187	18	99.17695	3739	57	98.47553
22	1113	21	98.11321	3356	1282	61.79976	1911	21	98.9011	3665	59	98.39018
23	1401	16	98.85796	3354	1458	56.52952	2145	17	99.20746	3844	55	98.5692
24	1102	22	98.00363	3553	1575	55.67126	2035	13	99.36118	3629	59	98.37421
25	974	15	98.45996	3212	1353	57.87671	2146	14	99.34762	4024	60	98.50895
26	1325	23	98.26415	3182	1594	49.90572	1998	18	99.0991	3892	53	98.63823
27	1520	16	98.94737	3194	1450	54.60238	2087	14	99.32918	3682	57	98.45193
28	1185	17	98.5654	3507	1390	60.36498	2087	16	99.23335	3801	56	98.5267
29	1329	17	98.72084	3346	1350	59.65332	2107	13	99.38301	4134	50	98.79052
30	1191	23	98.06885	3290	1481	54.9848	2061	13	99.36924	3940	49	98.75635

Annexure 2

Sampling results for L2

Sl. No.	TSS			TDS			BOD			COD		
	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency
	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)
1	9132	44	99.51818	12462	540	95.66683	33373	1.5	99.99551	42695	10	99.97658
2	9134	39	99.57302	12574	581	95.37935	33357	1	99.997	45067	8	99.98225
3	9237	40	99.56696	12358	545	95.5899	31200	3	99.99038	40075	12	99.97006
4	9121	43	99.52856	12402	573	95.37978	36136	1	99.99723	44876	12	99.97326
5	9244	47	99.49156	12351	542	95.61169	35093	2	99.9943	41691	11	99.97362
6	9107	42	99.53882	12609	556	95.59045	32637	2	99.99387	41843	12	99.97132
7	9191	39	99.57567	12551	558	95.55414	30978	3	99.99032	40316	13	99.96775
8	9229	42	99.54491	12437	590	95.25609	35888	1	99.99721	41568	12	99.97113
9	9202	46	99.50011	12510	587	95.30775	36114	1	99.99723	41506	13	99.96868
10	9086	42	99.53775	12381	595	95.19425	33559	3	99.99106	43923	12	99.97268
11	9230	47	99.49079	12474	592	95.25413	33836	2	99.99409	42993	8	99.98139
12	9123	42	99.53963	12453	580	95.34249	33369	2	99.99401	41507	9	99.97832
13	9218	42	99.54437	12673	557	95.60483	30477	2	99.99344	40092	11	99.97256
14	9121	39	99.57242	12485	559	95.52263	32692	2	99.99388	40028	13	99.96752
15	9191	45	99.51039	12465	567	95.45126	34265	1	99.99708	42888	12	99.97202
16	9061	39	99.56958	12367	557	95.49608	30530	1	99.99672	43617	10	99.97707
17	9010	45	99.50055	12402	507	95.91195	36195	1	99.99724	42060	8	99.98098
18	9129	45	99.50707	12684	581	95.41943	30445	3	99.99015	41831	11	99.9737
19	9019	47	99.47888	12584	527	95.81214	30530	1	99.99672	44758	11	99.97542
20	9221	42	99.54452	12588	502	96.01207	34128	1	99.99707	42023	8	99.98096
21	9049	47	99.48061	12505	589	95.28988	34487	3	99.9913	40869	12	99.97064
22	9185	45	99.51007	12400	588	95.25806	34910	3	99.99141	40360	10	99.97522
23	9239	38	99.5887	12609	578	95.41597	34970	3	99.99142	40605	10	99.97537
24	9129	39	99.57279	12488	515	95.87604	35273	3	99.99149	41965	8	99.98094
25	9098	44	99.51638	12525	584	95.33733	35847	1	99.99721	42298	9	99.97872
26	9160	43	99.53057	12598	556	95.5866	33584	1	99.99702	44135	11	99.97508
27	9187	40	99.5646	12516	599	95.21413	32885	2	99.99392	44447	9	99.97975
28	9158	39	99.57414	12565	556	95.57501	35121	3	99.99146	44150	8	99.98188
29	9081	45	99.50446	12493	533	95.73361	36289	3	99.99173	41599	12	99.97115
30	9168	45	99.50916	12498	570	95.43927	33687	2	99.99406	41924	13	99.96899

Annexure 3

Sampling results for L3

Sl. No.	TSS			TDS			BOD			COD		
	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency
	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)
1	4248	52	98.77589	8510	990	88.36663	29590	10	99.9662	38808	42	99.89177
2	4231	51	98.79461	8718	1007	88.44919	29284	11	99.96244	37010	32	99.91354
3	4066	49	98.79488	7637	1173	84.64057	29510	11	99.96272	37681	49	99.86996
4	4047	54	98.66568	8398	1161	86.17528	27391	15	99.94524	36788	41	99.88855
5	4220	58	98.62559	8222	985	88.01995	30025	10	99.96669	38198	43	99.88743
6	4093	52	98.72954	8040	829	89.68905	28065	7	99.97506	38069	42	99.88967
7	4165	54	98.70348	7790	823	89.43517	29313	12	99.95906	37337	48	99.87144
8	4183	57	98.63734	8730	1053	87.93814	30770	9	99.97075	39224	33	99.91587
9	4253	59	98.61274	8127	887	89.08576	27382	7	99.97444	37373	47	99.87424
10	4125	52	98.73939	8173	1101	86.52881	28389	10	99.96478	37666	38	99.89911
11	4103	49	98.80575	8355	930	88.86894	28127	11	99.96089	37804	42	99.8889
12	4298	56	98.69707	7749	1103	85.76591	28305	12	99.9576	37428	36	99.90382
13	4381	50	98.85871	8400	948	88.71429	29230	15	99.94868	37626	37	99.90166
14	4040	50	98.76238	8357	844	89.90068	30694	9	99.97068	38565	34	99.91184
15	4247	48	98.86979	7722	835	89.18674	27318	11	99.95973	38735	38	99.9019
16	4364	53	98.78552	8557	1113	86.99311	30069	14	99.95344	35991	45	99.87497
17	4076	51	98.74877	8472	1000	88.19641	26852	9	99.96648	36905	37	99.89974
18	4214	55	98.69483	8735	873	90.00572	29481	11	99.96269	35763	35	99.90213
19	4062	49	98.7937	8471	842	90.06021	28726	14	99.95126	36266	37	99.89798
20	4371	49	98.87898	8282	1056	87.24946	28748	10	99.96521	38100	50	99.86877
21	4066	58	98.57354	8427	829	90.16257	28964	15	99.94821	36167	31	99.91429
22	4008	57	98.57784	8592	801	90.67737	28487	11	99.96139	37986	36	99.90523
23	4032	58	98.56151	7880	1117	85.82487	30046	13	99.95673	35226	47	99.86658
24	4030	54	98.66005	7777	1063	86.33149	30712	13	99.95767	39821	43	99.89202
25	4194	60	98.56938	8943	892	90.02572	27481	11	99.95997	35171	47	99.86637
26	4038	52	98.71223	8858	1097	87.61571	27476	12	99.95633	35894	48	99.86627
27	4274	57	98.66635	8129	1134	86.04994	30012	15	99.95002	39103	47	99.8798
28	4150	57	98.62651	8531	1096	87.15274	28089	7	99.97508	35693	43	99.87953
29	4258	50	98.82574	8244	884	89.27705	28256	14	99.95045	36869	31	99.91592
30	4004	59	98.52647	8099	1068	86.81319	28411	9	99.96832	37018	37	99.90005

Annexure 4

Sampling results for L4

Sl. No.	TSS			TDS			BOD			COD		
	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency
	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)
1	1280	73	94.29688	3422	1346	60.66628	2800	19	99.32143	6300	83	98.68254
2	1204	61	94.93355	3841	1397	63.62926	2642	42	98.4103	6636	89	98.65883
3	1539	91	94.08707	2986	1132	62.08975	2463	41	98.33536	6185	96	98.44786
4	1595	87	94.54545	3679	1820	50.53004	3267	38	98.83685	6495	72	98.89145
5	1283	89	93.06313	3424	1743	49.09463	2966	21	99.29198	6585	79	98.8003
6	1674	54	96.77419	3501	1219	65.18138	2993	18	99.3986	6702	98	98.53775
7	1233	67	94.5661	3695	1692	54.20839	3008	46	98.47074	6317	82	98.70192
8	1407	73	94.81166	3796	1820	52.05479	2510	30	98.80478	6140	96	98.43648
9	1152	66	94.27083	3057	1359	55.54465	2807	45	98.39686	6364	62	99.02577
10	1461	76	94.79808	3804	1606	57.78128	2740	46	98.32117	6497	87	98.66092
11	1136	69	93.92606	3443	1634	52.54139	3183	45	98.58624	6343	80	98.73877
12	1616	83	94.86386	3704	1510	59.23326	3177	20	99.37048	6495	70	98.92225
13	1088	64	94.11765	3575	1656	53.67832	2548	15	99.4113	6742	71	98.9469
14	1302	84	93.54839	3693	1705	53.83157	2565	17	99.33723	6306	92	98.54107
15	1410	57	95.95745	3406	1425	58.16207	2622	43	98.36003	6402	81	98.73477
16	1375	93	93.23636	3143	1461	53.51575	2546	21	99.17518	6476	65	98.99629
17	1626	67	95.87946	3180	1637	48.52201	2796	21	99.24893	6602	79	98.80339
18	1336	66	95.05988	3512	1399	60.16515	2711	41	98.48764	6197	93	98.49927
19	1651	92	94.42762	3459	1254	63.74675	2494	18	99.27827	6521	98	98.49716
20	1391	84	93.96118	3296	1801	45.35801	2935	39	98.67121	6107	83	98.6409
21	1154	90	92.20104	3298	1630	50.57611	3184	22	99.30905	6752	73	98.91884
22	1026	89	91.32554	3680	1196	67.5	2450	44	98.20408	6358	90	98.58446
23	1006	94	90.65606	3698	1334	63.92645	3073	28	99.08884	6057	90	98.51412
24	1105	83	92.48869	3713	1601	56.88123	3266	41	98.74464	6320	64	98.98734
25	1312	71	94.58841	3006	1714	42.98071	3211	40	98.75428	6371	79	98.76001
26	1332	93	93.01802	3342	1233	63.10592	2570	27	98.94942	6049	78	98.71053
27	1506	78	94.82072	3857	1293	66.47654	3213	43	98.66169	6223	91	98.53768
28	1299	60	95.38106	3839	1144	70.20057	3126	18	99.42418	6640	90	98.64458
29	1615	65	95.97523	3542	1424	59.79673	2408	45	98.13123	6567	92	98.59906
30	1628	73	95.51597	3533	1224	65.35522	2694	37	98.62658	6501	72	98.89248

Annexure 5

Sampling results for L5

Sl. No.	TSS			TDS			BOD			COD		
	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency
	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)
1	1972	4	99.79716	10978	1428	86.99217	18200	5	99.97253	27066	24	99.91133
2	2053	16	99.22065	11362	1007	91.13712	16075	7	99.95645	27033	44	99.83724
3	1998	5	99.74975	12905	1426	88.95002	18908	13	99.93125	27650	31	99.88788
4	1853	4	99.78413	9434	1625	82.77507	17571	7	99.96016	29479	45	99.84735
5	2228	10	99.55117	10280	1467	85.72957	20378	14	99.9313	28863	34	99.8822
6	2101	15	99.28605	9232	1987	78.47704	17263	4	99.97683	27026	37	99.86309
7	2026	8	99.60513	10515	1246	88.15026	17408	13	99.92532	29822	48	99.83905
8	2047	13	99.36492	11218	1547	86.20966	20195	12	99.94058	27596	23	99.91665
9	2209	18	99.18515	12040	1078	91.04651	17935	11	99.93867	24985	28	99.88793
10	2103	19	99.09653	11147	1657	85.13501	21136	12	99.94322	25135	29	99.88462
11	1763	18	98.97901	12250	1161	90.52245	21125	6	99.9716	27632	40	99.85524
12	2051	16	99.21989	10294	1814	82.37808	20705	12	99.94204	30109	32	99.89372
13	1998	17	99.14915	9176	1736	81.08108	20771	14	99.9326	29283	47	99.8395
14	2216	17	99.23285	12139	1753	85.55894	17011	11	99.93534	26186	43	99.83579
15	1926	4	99.79232	11980	1409	88.23873	19596	3	99.98469	26235	42	99.83991
16	1703	18	98.94304	9140	1983	78.30416	20088	7	99.96515	29054	32	99.88986
17	2215	20	99.09707	11964	1501	87.45403	17718	9	99.9492	26532	35	99.86808
18	2158	4	99.81464	10111	1689	83.29542	20430	8	99.96084	26084	46	99.82365
19	1957	4	99.79561	11449	988	91.37043	21398	9	99.95794	25851	42	99.83753
20	2086	8	99.61649	12225	1454	88.10634	18269	12	99.93431	25339	33	99.86977
21	1898	3	99.84194	12007	1131	90.58049	21296	11	99.94835	28620	33	99.8847
22	2076	9	99.56647	12230	1098	91.02208	19233	7	99.9636	27924	28	99.89973
23	2194	10	99.54421	9054	1245	86.24917	18016	7	99.96115	28676	48	99.83261
24	2250	7	99.68889	9888	1208	87.78317	20219	14	99.93076	29907	34	99.88631
25	1970	4	99.79695	12513	1591	87.28522	18396	11	99.9402	28073	41	99.85395
26	1996	5	99.7495	10660	1448	86.41651	20181	14	99.93063	25149	20	99.92047
27	2015	6	99.70223	10906	1300	88.07996	17421	13	99.92538	29923	45	99.84961
28	2133	9	99.57806	12473	1275	89.77792	19889	4	99.97989	27635	49	99.82269
29	1719	20	98.83653	9639	1590	83.50451	16050	5	99.96885	26636	49	99.81604
30	1769	10	99.43471	8954	1400	84.36453	20465	6	99.97068	27410	23	99.91609

Annexure 6

Sampling results for L6

Sl. No.	TSS			TDS			BOD			COD		
	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency	ETP Inlet	ETP Outlet	Removal Efficiency
	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)	mg/l	mg/l	(%)
1	2664	27	98.98649	2314	1884	18.58254	936	9	99.03846	2071	45	97.82714
2	2908	40	98.62448	2039	1581	22.46199	1003	44	95.61316	2308	36	98.44021
3	2621	50	98.09233	2502	2017	19.38449	1036	22	97.87645	1873	34	98.18473
4	2795	41	98.53309	2622	1580	39.74066	1009	36	96.43211	2094	45	97.851
5	2598	41	98.42186	2643	1961	25.80401	1191	36	96.97733	1854	50	97.30313
6	2957	46	98.44437	2076	1748	15.79961	887	40	95.49042	2264	33	98.5424
7	2878	26	99.09659	2617	1700	35.04012	1170	25	97.86325	2240	44	98.03571
8	2440	34	98.60656	2459	1983	19.35746	1088	24	97.79412	1945	57	97.06941
9	2447	37	98.48794	2294	2144	6.538797	977	39	96.00819	2105	35	98.33729
10	2867	48	98.32578	2417	1432	40.753	1039	32	96.92012	2233	31	98.61173
11	2512	33	98.68631	2575	1562	39.33981	994	17	98.28974	2061	33	98.39884
12	2503	50	98.0024	2030	1610	20.68966	1166	33	97.16981	2153	36	98.32791
13	2690	50	98.14126	2343	1876	19.93171	864	22	97.4537	1829	58	96.82887
14	2480	44	98.22581	2121	1492	29.65582	1137	22	98.06508	1966	30	98.47406
15	2894	33	98.85971	2453	1626	33.71382	896	27	96.98661	2333	42	98.19974
16	2754	36	98.69281	2743	2182	20.45206	909	27	97.0297	1829	55	96.99289
17	2481	31	98.7505	2660	1533	42.36842	1118	9	99.19499	2078	60	97.11261
18	2763	27	99.0228	2357	2139	9.249045	1068	45	95.78652	1899	36	98.10427
19	2426	36	98.51608	2076	1712	17.53372	993	9	99.09366	2352	34	98.55442
20	2909	25	99.1406	2428	2086	14.08567	1244	23	98.15113	2272	58	97.44718
21	2415	36	98.50932	2794	2065	26.09162	1026	37	96.39376	1938	54	97.21362
22	2754	37	98.6565	2834	1847	34.8271	1103	40	96.37353	2213	52	97.65025
23	2920	32	98.90411	2336	1848	20.89041	926	22	97.62419	2195	34	98.45103
24	2544	39	98.46698	2357	1594	32.37166	1109	14	98.7376	1841	41	97.77295
25	2436	39	98.39901	2742	1663	39.35084	994	35	96.47887	2343	46	98.03671
26	2617	32	98.77723	2386	1791	24.93713	969	39	95.97523	1973	47	97.61784
27	2540	42	98.34646	2244	1980	11.76471	1114	44	96.05027	2158	40	98.14643
28	2575	39	98.48544	2517	1531	39.17362	879	36	95.90444	2032	36	98.22835
29	2501	47	98.12075	2327	1920	17.49033	954	10	98.95178	1828	40	97.81182
30	2567	40	98.44176	2381	1669	29.9034	1064	23	97.83835	2243	51	97.72626