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Energy Conservation Potential of Wastewater Treatment Systems in Kathmandu Valley:

A Comparison of Activated Sludge System and Constructed Wetland System

by

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079MSEEB006

A THESIS SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENERGY EFFICIENT BUILDINGS

DEPARTMENT OF ARCHITECTURE,

LALITPUR, NEPAL

APRIL, 2025

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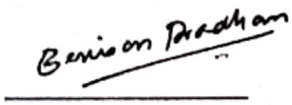

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ABSTRACT

Wastewater treatment is energy-intensive, and in regions like Kathmandu Valley—where energy availability and costs are pressing concerns—optimizing energy use in treatment systems is crucial. This study evaluates the energy conservation potential of decentralized wastewater treatment systems (DEWATS), comparing the centralized activated sludge system with decentralized constructed wetland (CW) systems. It examines energy consumption, treatment efficiency, and suitability for Nepal. The activated sludge system consumes approximately 3.2 kWh/m³ of treated wastewater, with aeration alone accounting for 60–70% of total energy use. In contrast, CW systems use only 0.01–0.02 kWh/m³, primarily for water pumping, representing an 80–90% reduction in energy use.

While CW systems require larger land areas—posing challenges in dense urban settings—their low operational costs and minimal maintenance needs make them especially viable for peri-urban and rural contexts. The study concludes that CW systems offer a more energy-efficient alternative in energy-constrained areas. However, many decentralized systems in Nepal are underperforming. To enhance their effectiveness and longevity, the study recommends hybrid approaches or system modifications. These insights support more energy-efficient wastewater strategies for urban planners, policymakers, and engineers in the Kathmandu Valley.

Keywords: Energy efficiency, wastewater treatment, decentralized systems, constructed wetlands, energy conservation, sustainable sanitation.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my thesis supervisor, **Dr. Nawraj Bhattarai**, for his invaluable guidance, encouragement, and insightful feedback throughout this research. His expertise and unwavering support have been instrumental in shaping the direction of this study.

I would also like to thank **Dr. Sanjay Uprety** for his continuous help, guidance, and invaluable suggestions throughout the research. Additionally, I would like to extend my gratitude to our program coordinator, **Dr. Bijay Singh**, for his valuable suggestions and guidance as the Program Coordinator of the MSc in Energy Efficient Buildings (EEB).

My sincere appreciation to the different stakeholders, especially **Er. Prabhat K.C.,** Project Engineer, Project Implementation Directorate (PID), Guheshwori Wastewater Treatment Plant, **Er. Raja Ram Parajuli**, Engineer at the Dhulikhel Hospital, and Er. **Rajendra Shrestha,** Program Director at ENPHO, Kathmandu, for their valuable time and coordination in providing the relevant information and data and for providing the necessary resources and a conducive research environment. My heartfelt thanks also go to the technical team and staff at **Guheshwori Wastewater Treatment Plant** and **Dhulikhel Hospital**, whose cooperation in data collection significantly contributed to this study.

Finally, I am also grateful to my colleagues and friends for their continuous motivation, constructive discussions, and support during this journey. A special mention to my family for their unwavering patience, encouragement, and belief in me throughout this process.

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ABBREVIATIONS

ASP	Activated Sludge Process
ASP	Activated Sludge Process
ASTS	Activated Sludge Treatment System
CW	Constructed Wetland
DEWAT	Decentralized Wastewater Treatment System
ENPHO	Environment and Public Health Organization
GON	Government of Nepal
HFCW	Horizontal Flow Constructed Wetlands
LCA	Life Cycle Assessment
MLD	Million Litres per Day
NPC	National Planning Commission
QGIS	Quantum Geographic Information System
SSF	Subsurface Flow
VFCW	Vertical Flow Constructed Wetlands
WWTP	Waste Water Treatment Plant

CHAPTER 1: INTRODUCTION

1.1. Introduction

The process of wastewater treatment is characterized by its significant energy demands, as traditional centralized treatment facilities frequently utilize substantial quantities of electricity for functions such as aeration, pumping, and the management of sludge. In rapidly urbanizing areas like Kathmandu Valley, the unreliability and high cost of energy supply create substantial operational and financial challenges due to the elevated energy demands associated with centralized wastewater treatment systems. Nepal is actively working to enhance its wastewater treatment capacity while simultaneously aiming to decrease reliance on energy-intensive infrastructure. In this context, decentralized wastewater treatment systems (DEWATS) have surfaced as a viable alternative.

The activated sludge system and the constructed wetland system exemplify two distinct methodologies in wastewater treatment, particularly regarding their energy consumption profiles. The activated sludge system, frequently employed in urban wastewater treatment, depends on aeration to enhance the microbial degradation of organic matter. Nonetheless, aeration represents the most energy-demanding aspect of the process, frequently constituting over fifty percent of the overall energy usage in wastewater treatment facilities. Conversely, constructed wetlands employ natural processes, including microbial activity, sedimentation, and plant uptake, to effectively treat wastewater while requiring minimal energy input. This nature-based solution presents a low-energy alternative, rendering it especially appropriate for areas where energy efficiency is of paramount importance.

This investigation seeks to evaluate the energy conservation potential inherent in these two decentralized wastewater treatment systems. Investigating the energy implications associated with various treatment systems is essential for formulating cost-effective and sustainable wastewater management strategies in Nepal, where the challenge of reconciling environmental protection with energy efficiency persists.

1.2. Importance of the Research

The energy crisis in developing countries is exemplified by Nepal, which, similar to numerous other nations in this category, experiences considerable energy shortages. The significant energy requirements of traditional wastewater treatment plants (WWTPs) intensify this crisis, highlighting the necessity for energy-efficient alternatives like constructed wetlands (CWs). Constructed wetlands serve a dual purpose by treating wastewater while simultaneously offering ecological advantages, including carbon sequestration, enhancement of biodiversity, and mitigation of flooding (Zhang et al., 2016). Community wind systems exhibit reduced capital and operational expenditures in comparison to traditional systems, thereby enhancing accessibility for communities that face financial constraints (Rousseau, 2013). Through the reduction of energy consumption and greenhouse gas emissions, constructed wetlands play a significant role in the global initiatives aimed at addressing climate change.

This study seeks to measure the energy conservation potential of constructed wetlands (CWs) and juxtapose it with traditional wastewater treatment plants (WWTPs), thereby offering significant insights for policymakers and planners in the field of wastewater treatment.

1.3. Research Gap

Although a variety of studies have underscored the treatment efficiency and environmental advantages of constructed wetlands (CWs), there remains a scarcity of research focused on their potential for energy conservation, especially within the framework of developing nations such as Nepal. The majority of current research primarily concentrates on the efficacy of treatments or their cost-effectiveness, while there is a notable lack of attention given to energy savings. Furthermore, there exists an absence of direct comparisons regarding energy consumption between constructed wetlands and traditional wastewater treatment plants. This study aims to fill these gaps through a comprehensive energy analysis of both systems.

1.4. Objectives

The primary objective of this research is to evaluate the energy conservation potential of decentralized wastewater treatment systems, specifically constructed wetlands, compared to conventional activated sludge systems in the Kathmandu Valley. The specific objectives are:

- To compare the energy consumption and treatment efficiency of a constructed wetland system and a conventional activated sludge wastewater treatment plant (WWTP) in Kathmandu Valley.
- To evaluate the operational costs, environmental impacts, and feasibility of constructed wetlands as an alternative wastewater treatment solution.

CHAPTER 2: LITERATURE REVIEW

2.1. Background

The Kathmandu Valley encompasses an area of 933.73 km² and had a recorded population of 2,996,341 in the year 2021, according to the Government of Nepal. The valley has recorded a total of 105,649 households, with an average of 3.75 individuals per household in Kathmandu. The anticipated wastewater generation per capita in the urban region is roughly 60 liters, derived from the daily water consumption of each individual. (NPC, 1997). Consequently, the overall wastewater generation is estimated to be around 180 MLD.

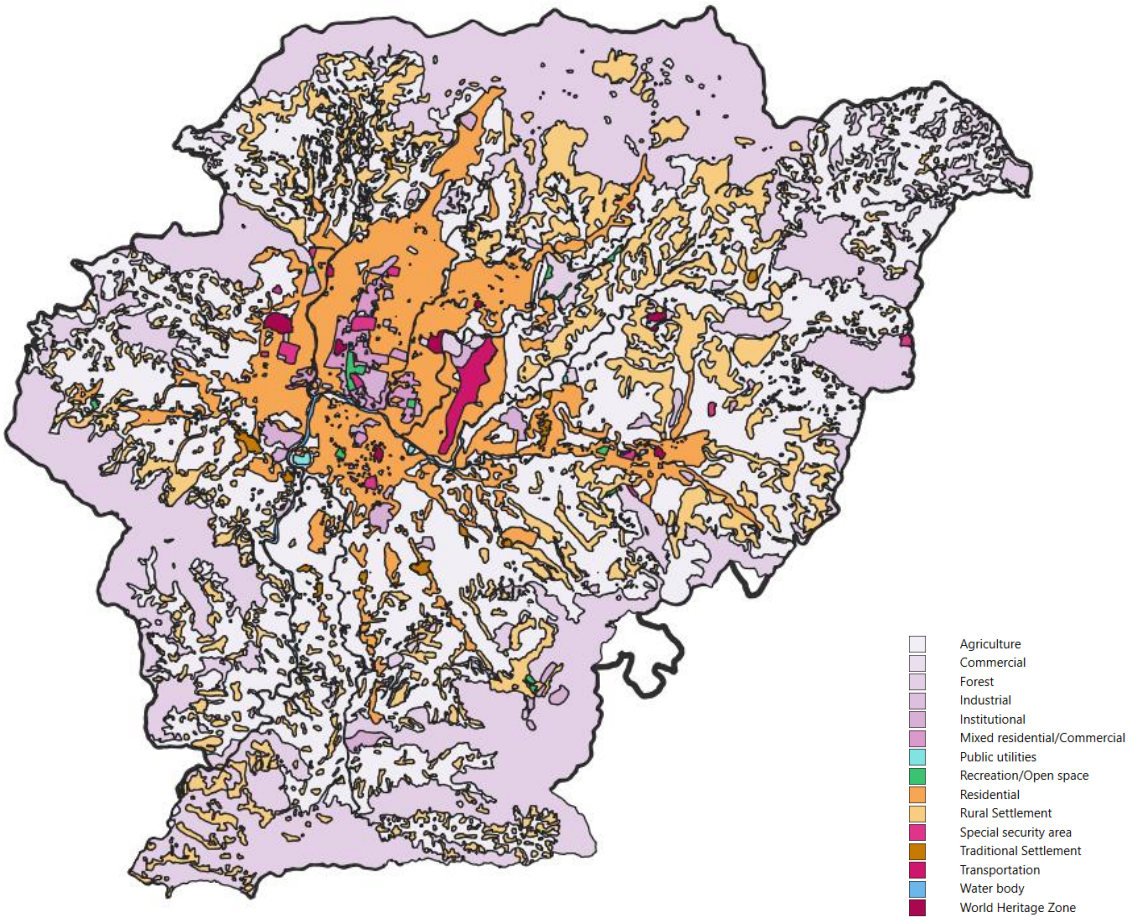

Figure 1.1: Land use illustration of Kathmandu Valley (Source: Generated from QGIS Software)

The Kathmandu Valley's 153% population expansion over the past ten years is expected to have a significant impact on wastewater generation. The generation of wastewater treatment is predominantly achieved through two methodologies: centralized wastewater treatment systems and decentralized treatment systems. The centralized system of wastewater treatment engages in the active treatment of wastewater via multiple processes; nonetheless, it exhibits a high energy intensity. The Kathmandu Valley represents a highly urbanized area, demonstrating a level of development that surpasses that of the rest of the country, and displays notable variability in energy consumption patterns along with corresponding emissions(Pankaj Sadavarte, March 2019).

The treatment of wastewater represents an essential element of urban infrastructure, playing a vital role in safeguarding public health and preserving environmental integrity. Traditional wastewater treatment facilities, exemplified by the Guheshwori plant in Kathmandu, Nepal, depend significantly on processes that require substantial energy, including aeration, pumping, and sludge management. The contribution of these systems to greenhouse gas emissions and operational costs is substantial, rendering them unsustainable over the long term, particularly in areas with constrained energy resources (Seyring and Kuschk, 2005).

In contrast, constructed wetlands (CWs) present a decentralized and energy-efficient option for the treatment of wastewater. Constructed wetlands utilize natural processes that involve vegetation, soil, and microbial interactions to treat wastewater, requiring limited mechanical intervention and energy use (Vymazal, 2010). Given the increasing apprehensions surrounding energy scarcity and climate change, it is imperative to investigate sustainable wastewater treatment methodologies that minimize energy usage while ensuring effective treatment outcomes.

2.2. Wastewater and energy consumption scenario

The Kathmandu Valley, which encompasses Nepal's capital, Kathmandu, as well as Bhaktapur and Lalitpur, has undergone rapid urbanization and population growth in recent decades. The increase has considerably burdened the current wastewater management infrastructure, resulting in serious environmental and public health issues.

In recent decades, the Kathmandu Valley—which includes Kathmandu, the capital of Nepal, as well as Bhaktapur and Lalitpur—has experienced a sharp increase in both population and urbanization. The observed increase has significantly strained the existing wastewater management infrastructure, leading to notable environmental and public health challenges. An important aspect of this situation is the energy-intensive nature of current wastewater treatment and disposal methods, which often demonstrate inadequacy and lack sustainability.

The Kathmandu Valley represents a significant urbanized area, exhibiting a higher level of development relative to the rest of the country, characterized by notable differences in energy consumption patterns and corresponding emissions. The examination of energy consumption patterns in the Kathmandu Valley (KTM) and Nepal (NPL) for the year 2011, encompassing all industries and fuel types, reveals that the total energy consumption in KTM amounts to 30 PJ, representing 8% of the national energy consumption, which is recorded at 374 PJ (Pankaj Sadavarte, March 2019). Within the Kathmandu Valley, the residential sector represents 41% of overall energy consumption, which includes a significant portion of wastewater generation.

2.2.1. Historical Context of Wastewater Management and Energy Use

The management of wastewater in Nepal, especially within the Kathmandu Valley, has experienced significant transformation, influenced by changes in demographics, urban development, and advancements in technology. The valley has a historically advanced indigenous water management system that employed natural and low-energy techniques. Despite this, the increasing rate of urbanization and modern infrastructure advancements have amplified the necessity for wastewater treatment. This has led to the adoption of energy-intensive techniques that frequently struggle to match the rapidly growing quantities of wastewater.

2.2.2. Traditional Wastewater Management Practices

Before the establishment of modern piped water systems, traditional water management practices played a crucial role in maintaining sanitation and managing wastewater in Nepal. Indigenous systems, such as dhunge dharas (stone spouts), wells, and ponds, played a crucial role in the delivery of water. Meanwhile, effluent was either absorbed organically into the soil or released into nearby rivers. The operation of these systems

required little to no energy, relying instead on gravitational forces and natural filtration processes.

In the Kathmandu Valley, one can observe the presence of quintessential Newari communities that maintain traditional perspectives on life and exhibit distinctive lifestyles. The villages, which trace their origins to the 6th century, display a limited impact from contemporary developments and are located within the valley. Upon examination of the sustainable management practices concerning wastewater at both the household and community levels in a typical Newari settlement, it becomes apparent that there is a historical precedent for wastewater management, characterized by the use of traditional methods. A systematic approach exists for the collection, transportation, storage, and disposal of wastewater generated at the household level. This is also utilized in both agricultural and non-agricultural contexts.

In traditional Newar dwellings, the kitchen features a sink made from burnt clay, strategically located in one corner of the kitchen space. One end exhibits a bowl-like morphology, characterized by an average diameter of 300 mm, designated as 'Dhow Pwo' in Newari. Conversely, the opposing end features a slender, open channel constructed from burnt clay, referred to as 'Chee Dha'. The wastewater produced from activities such as vegetable washing, food preparation, hand washing, mouth rinsing, and utensil cleaning in the kitchen is directed through Chee Dha to the collection pit located in the courtyard of the residence. The collection pit is referred to as 'Saagaa'—in Newari, 'Saa' translates to manure while 'gaa' means pit. Therefore, Saagaa pertains to the collection of wastewaters and the production of compost manure. The nutrient components present in wastewater are extracted and processed into compost manure, which is subsequently employed in agricultural production. The excavation of this multifunctional wastewater collection pit is commonly conducted in the courtyard area of a residential property. The pit can exhibit various geometric configurations, including circular, square, or rectangular forms, and its dimensions may fluctuate based on the volume of household waste generated. Household-generated solid and liquid waste is systematically disposed of in Saagaa, where it undergoes a composting process to be transformed into manure. Newar dwellings are generally built in close proximity, often surrounding a shared communal courtyard. In this scenario, a shared pit located in the courtyard serves as a collection point for wastewater, biodegradable solid waste,

and animal excreta generated by each household. In the base of the pit, dense materials have accumulated, while water is expelled through a minor outlet referred to as 'Byeku Pwo'. The flow of water from Byeku Pwo is directed to a common collector drain via an earthen conduit referred to as 'Nali'. The collector drain accumulates water, which is subsequently stored within the pond system. The pond operates as a waste stabilization pond. The water is employed for agricultural applications. The management of Nali ponds is a collective obligation of the community (Shrestha, 2011).

In the early Newari settlements, firewood was utilized for both cooking and heating the living spaces. Each household produces ash as a byproduct. Newari communities establish sustainable solid waste management systems at the household level. Ash collection pits, known as 'Naugah,' are situated on the lower level, directly beneath the wooden stairs, in traditional residential structures. Throughout the night, family members urinate over the collected ash. This combination of ash and urine is allowed to mature in a pit for approximately three months before being extracted for use as a fertilizer on agricultural land. The composition of this fertilizer includes Magnesium, Potassium, Calcium, and Phosphorus. This substance may be regarded as an effective fertilizer for tomatoes and other types of nightshade vegetables . (Shrestha, 2011)

Figure 1.2: Traditional Kitchen in Newari House (Dhow Pow or Wastewater Sink is located at the corner of the kitchen) (Source: Shrestha, 2011)

Figure 1.3: Bowl shaped sink in Chee Dha (Source: Shrestha, 2011)

The historical drainage infrastructure of Kathmandu consisted of exposed stone channels and ditches designed to redirect effluent away from populated regions. Some residences utilized soak pits or small-scale decentralized wastewater treatment systems, such as reed beds or sedimentation ponds, to manage domestic wastewater effectively. While these systems demonstrate efficacy for limited populations, they were not designed to handle the substantial wastewater generation typical of modern urban environments.

Figure 1.4 Tapwater system Dhungedhara in Licchavi Dynasty (300AD-879AD) (Source: Shrestha, 2011)

2.3. Introduction of Modern Sewerage Systems

With the increase in population density and urbanization, traditional methods became insufficient, leading to the adoption of modern sewerage systems during the Rana era (1846–1951). The first piped water delivery system was established in 1895, resulting in notable alterations in water consumption and wastewater generation trends. During that period, there was a diminished focus on wastewater treatment, resulting in the majority of sewage being discharged into rivers without treatment. (Arata, March 2003).

2.4. Introduction to the Activated Sludge Treatment System and Constructed Wetlands for Wastewater Treatment

The treatment of wastewater plays a critical role in ensuring public health, protecting ecosystems, and fostering sustainable practices in water management. Activated Sludge Treatment Systems (ASTS) and Constructed Wetlands (CWs) represent two prominent methodologies employed in the treatment of municipal and industrial wastewater. The operational mechanisms of these treatment technologies are complemented by their environmental impacts, efficiency, and appropriateness for various contexts.

The Activated Sludge Treatment System (ASTS) represents a widely utilized approach for the treatment of wastewater on a global scale. The system functions based on the principle of biological treatment, employing microorganisms, chiefly bacteria, that decompose organic matter present in the wastewater. The system employs mechanical aeration to deliver oxygen to these microorganisms, facilitating the breakdown of organic pollutants by aerobic bacteria. Furthermore, the system incorporates the sedimentation process of treated water to facilitate the separation of biomass (sludge) from the effluent. While ASTS is commonly recognized as a viable approach for large-scale treatment, it demands considerable energy and substantial infrastructure investment (Eddy, 2014).

The late 20th century saw the establishment of Kathmandu's first official wastewater treatment plant (WWTP) to address the city's escalating sanitary issues. The first

centralized wastewater treatment project was the Dhobighat Wastewater Treatment Plant, which opened its doors in 1978. The system utilized conventional activated sludge technology, which required significant energy for both aeration and pumping processes. Despite this, due to operational challenges, including power shortages and maintenance issues, the plant faced obstacles in attaining optimal performance.

The growth of Nepal's urban population has led to a significant increase in wastewater production, which in turn requires more energy-intensive treatment processes. Conventional wastewater treatment techniques, such as the activated sludge process, necessitate continuous aeration, leading to considerable energy consumption. The persistent electricity outages in Nepal, coupled with a heavy dependence on hydropower, present a considerable obstacle to maintaining a dependable energy supply for wastewater treatment processes. A significant number of wastewater treatment facilities have been developed over the years, such as those located in Guheshwori, Sallaghari, and Kodku. However, many of these facilities have faced operational challenges due to a lack of adequate financial support, technical knowledge, and a dependable energy supply. The reliance on grid electricity made them vulnerable to power interruptions, leading to inconsistent treatment processes and the discharge of untreated sewage into water bodies.

Recognizing the limitations associated with energy-intensive centralized wastewater treatment systems, there is a growing focus on decentralized wastewater treatment systems (DEWATS), which encompass constructed wetlands and anaerobic digesters. These systems leverage natural processes, resulting in a significant reduction in energy requirements. Constructed wetlands employ reed plants (narkat) to improve wastewater treatment through natural microbiological processes, thereby eliminating the need for mechanical aeration.

The Constructed Wetlands (CWs) represent an innovative methodology for wastewater treatment, leveraging the inherent filtration properties of plants, soil, and microorganisms to effectively process wastewater. The systems in question replicate the processes observed in natural wetlands and can be categorized into two primary types: Free Water Surface (FWS) wetlands and Subsurface Flow (SSF) wetlands.

Constructed wetlands function by facilitating the passage of wastewater through a substrate, such as gravel or sand, which is integrated with vegetation. This setup aids in the filtration of contaminants via mechanisms including adsorption, filtration, and absorption. The microbial communities present in the system are integral to the degradation of organic pollutants. (Vymazal, 2011). Because of their minimal energy needs and capacity to offer ecological advantages like wildlife habitat, CWs are typically regarded as a more sustainable option.

Comparing ASTS with CWs is done to assess their relative advantages and disadvantages in various situations. For example, because ASTS can efficiently handle large-scale wastewater treatment, it is frequently chosen in urban areas with significant wastewater volumes. However, it is expensive to run and repair due to its high energy consumption and intricate mechanical components. However, CWs provide a more environmentally friendly option that uses less energy and has extra advantages like supporting biodiversity and aesthetic appeal. They might not work well, though, in places with high wastewater flow rates or where there is a shortage of available land (Tchobanoglous et al., 2014).

Interest in CWs has grown as a result of the rising focus on sustainable practices, especially in small communities, rural areas, and locations where energy efficiency and environmental impact are top priorities. However, a number of variables, including climate, land availability, wastewater qualities, and economic concerns, affect how well both systems perform. Therefore, choosing the best treatment approach for a given site requires an understanding of the advantages and disadvantages of both ASTS and CWs.

2.5. Typical Wastewater Treatment Process

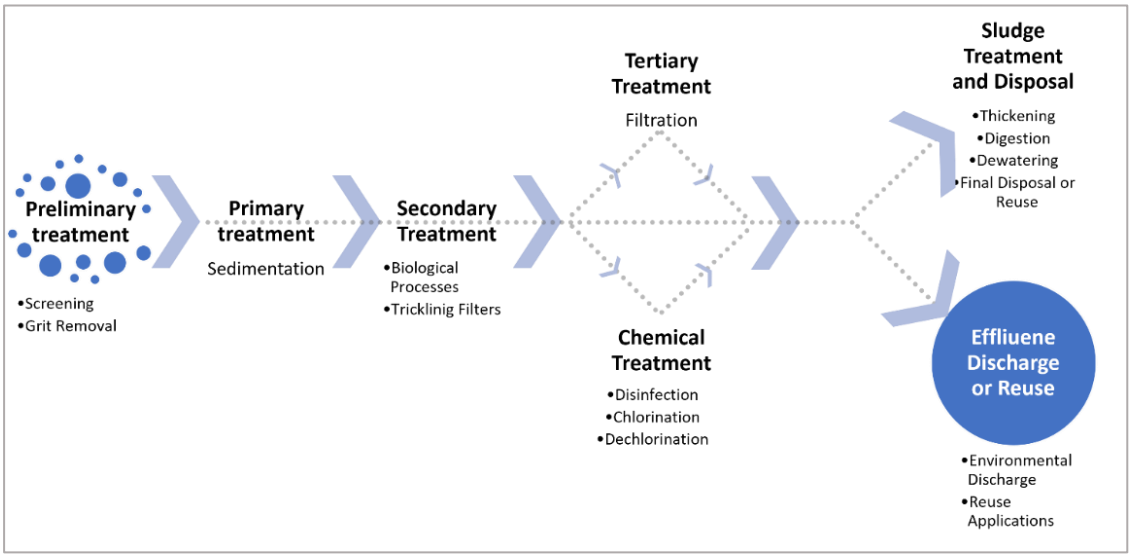

Figure 1.5: Typical process of treatment of wastewater

- **Collection and Conveyance**

Wastewater is first collected and then transported from different sources to treatment facilities via a system of pipes and channels. In order to stop leaks and guarantee that all wastewater is sent to the treatment facility for processing, effective collecting systems are essential.

- **Preliminary Treatment**

Wastewater is first treated at the treatment facility to get rid of big particles and silt that can harm machinery or obstruct later procedures. While grit removal focuses on heavier materials like sand and gravel, screening entails sifting out contaminants like plastics, rags, and other solids. These actions are essential for safeguarding equipment and guaranteeing the effectiveness of the therapy procedure.

- **Primary Treatment**

Wastewater is sent to sedimentation tanks for first treatment, where lighter materials, such oils and grease, float to the top for removal while heavier solids sink to the bottom and produce sludge. The amount of suspended particles in wastewater is successfully decreased at this stage.

- **Secondary Treatment**

Secondary treatment breaks down dissolved organic materials by using biological processes. By adding air to aeration tanks, methods like the activated sludge process encourage the growth of microorganisms that break down organic contaminants. The amount of biodegradable material in wastewater is greatly reduced at this stage.

- **Secondary Sedimentation**

After biological treatment, the wastewater moves into secondary sedimentation tanks, where activated sludge—a freshly created biomass—sets. To preserve microbial populations, some of this sludge is recycled back into the aeration tanks, while the remainder is taken out for additional processing.

- **Tertiary Treatment**

This stage, also known as advanced treatment, attempts to purify the effluent by eliminating any last pollutants, such as microorganisms and nutrients like phosphate and nitrogen. To make sure the water satisfies quality criteria appropriate for discharge or reuse, techniques may include filtration, chemical treatments, and disinfection procedures.

- **Disinfection**

The treated wastewater is disinfected to get rid of any remaining harmful microbes. Ozonation, ultraviolet (UV) irradiation, and chlorination are common techniques. Prior to the water being discharged into the environment or used for other purposes, this procedure is essential for protecting public health.

- **Sludge Treatment and Disposal**

In order to eliminate potential pathogens and minimize volume, the sludge collected during primary and secondary treatments undergoes additional processing. The sludge is converted into stable biosolids via thickening, aerobic or anaerobic digestion, and dewatering. These biosolids can be recycled into fertilizer for farming or disposed of responsibly.

2.6. Treatment Mechanisms in Activated Sludge Treatment Systems and Constructed Wetlands

In order to remove toxins from wastewater, Constructed Wetlands (CWs) and Activated Sludge Treatment Systems (ASTS) use different biological and physical processes. Comparing the effectiveness, performance, and suitability of each treatment approach in many contexts requires an understanding of these mechanisms. Although the goals of both systems are to eliminate nutrients and break down organic contaminants, there are substantial differences in their working theories and the part that biological processes play.

2.6.1. Treatment Mechanisms in Activated Sludge Treatment Systems (ASTS)

In order to treat wastewater, the Activated Sludge Treatment System (ASTS) mostly uses aerobic biological processes. The fundamental process entails the activation of microorganisms that break down organic materials in wastewater when oxygen is present. The secondary clarifier, which separates solid particles (biomass) from the treated water, and the aeration tank, which pumps air or oxygen into the wastewater to promote microbial growth, are the two main parts of ASTS.

In the aeration tank, dissolved organic materials like proteins, lipids, and carbohydrates are broken down by microorganisms, especially bacteria, into simpler substances like carbon dioxide, water, and cell biomass. When oxygen is added during aeration, aerobic bacteria are more active and organic materials break down into non-toxic byproducts. The biomass, sometimes referred to as activated sludge, sinks to the bottom of the secondary clarifier after the treated water has passed through it. To satisfy discharge requirements, the cleared water is usually sent for additional treatment, including disinfection.

To keep a sufficient number of microorganisms in the aeration tank, the leftover activated sludge is either recycled back into the tank or transferred to a sludge treatment facility for additional processing (Eddy, 2014). Aeration and sedimentation, two crucial phases in the treatment process, enable the removal of suspended solids (SS), biological oxygen demand (BOD), and nutrients, especially nitrogen and phosphorus, which are eliminated via nitrification and denitrification.

2.6.2. Treatment Mechanisms in Constructed Wetlands (CWs)

Constructed wetlands (CWs), on the other hand, use a more organic treatment process, treating wastewater by utilizing the combined activity of microbes, plants, and soil. Through physico-chemical processes, the system's substrate—typically sand or gravel—is covered with flora like cattail and reed, which aid in filtering and adsorbing pollutants. In addition to providing surfaces for microbial activity and oxygenating the substrate, these plants' roots aid in the wastewater's nutrient removal.

Filtration, adsorption, and plant uptake of nutrients are the main treatment processes in CWs. Wastewater flows through the substrate, where organic pollutants are broken down by microbes affixed to the plant roots and particle matter is filtered away. Furthermore, marsh plants absorb nutrients such as phosphorus and nitrogen, which considerably lowers the levels of these contaminants in the effluent. (Vymazal, 2010)

Subsurface flow wetlands (SSF) reduce odor and mosquito breeding by allowing wastewater to flow beneath the substrate's surface, decreasing the amount of water exposed to the atmosphere. The majority of the treatment in SSF wetlands is anaerobic, meaning that organic matter is broken down by bacteria without oxygen. On the other hand, both aerobic and anaerobic processes have an impact on the treatment methods of free water surface wetlands (FWS), which are more exposed to the atmosphere. By encouraging aerobic bacterial activity and improving the breakdown of organic contaminants, plants in FWS wetlands help to stabilize the oxygen levels in the water.

The capacity of CWs to eliminate organic pollutants, pathogens, and heavy metals by adsorption to soil particles and plant roots is a key benefit. Furthermore, the wetland ecology provides wider ecological advantages like better biodiversity and habitat for wildlife, therefore CWs are not only useful for treating wastewater but also good for the environment (Vymazal, 2010).

2.6.3. Comparison of Treatment Mechanisms

In large-scale, high-load wastewater treatment, where mechanical aeration and biomass separation are crucial for treating substantial volumes of water, ASTS is quite effective when comparing the treatment processes. Although it produces dependable, high-

quality wastewater, it comes at a high energy cost and requires constant maintenance of intricate mechanical machinery.

CWs, on the other hand, use the processes of filtration, adsorption, and plant absorption to provide a low-energy, natural treatment method. In comparison to ASTS, CWs can be less efficient in managing high-flow wastewater volumes, even though they are frequently better suited for small-scale or decentralized systems (Tchobanoglous, 2014). However, CWs are more sustainable which can be credited to their natural treatment processes, especially in regions that prioritize lowering energy consumption and promoting environmental biodiversity.

2.7. Current Situation of Wastewater and wastewater treatment plants in Kathmandu valley

The Kathmandu Valley's main wastewater sources are stormwater contributions, commercial, industrial, residential, and agricultural. Untreated wastewater from communities is thought to be appropriate for dumping in the Valley Rivers. They are converting the city's rivers into a sewer trunk line. Wastewater with high oxygen demand is produced by a number of industries located in the valley, such as brick kilns, cement, clothing, hospitals, pharmaceuticals, breweries and distilleries, soap and chemical solvents, oil and vegetables, and iron and steel. It has been found that industries are randomly dumping industrial wastewater into rivers. The valley is home to over 50.9% of the country's industry (KVDA, 2014), and the wastewater from these areas greatly contributes to river pollution.

By outlawing the direct discharge of solid and liquid waste into the Bagmati River and protecting the river system within the valley, the High Powered Committee for Integrated Development of Bagmati Civilization (HPCIDBC) is presently working to keep the Bagmati River and its tributaries clean. The committee plans to build wastewater treatment facilities, river training projects, secondary sewer pipelines, and trunk sewer pipelines along both banks of the river (ISO, 2006).

International organizations and local governments have pushed for sustainable and energy-efficient wastewater treatment systems in recent years. Dhulikhel Hospital has demonstrated an alternative to conventional treatment facilities by managing

wastewater using a constructed wetland system. Such systems offer a workable answer for Nepal's growing wastewater management problems by reducing energy dependency and improving wastewater treatment effectiveness.

Energy-efficient wastewater treatment technology will be crucial for sustainable development, preventing environmental degradation, and guaranteeing long-term energy conservation as Nepal becomes more urbanized.

2.8. Energy considerations in Wastewater Management

An essential part of urban infrastructure is wastewater management, which involves significant energy inputs for treatment, transportation, and disposal. The energy need for wastewater treatment presents major issues in developing nations like Nepal, where infrastructure is generally lacking and energy supplies are frequently scarce. Aeration, pumping, and sludge processing in traditional wastewater treatment systems, such the activated sludge process (ASP), are mostly dependent on energy. Optimizing energy use in wastewater treatment is essential for environmental and economic sustainability in Nepal, given the country's high energy costs and frequent power outages. The most used wastewater treatment method in the world, including in Nepal, is the activated sludge process (ASP). The most energy-intensive part of wastewater treatment, constant aeration, is necessary for this approach. According to studies, aeration uses between 50 and 60 percent of the energy used in a typical wastewater treatment plant (WWTP) (Zhang, 2006). One of the biggest treatment facilities in Kathmandu, Nepal's Guheshwori WWTP, depends on mechanical aeration and pumping, which raises operating energy costs dramatically. Other energy-intensive procedures besides aeration include chemical treatments, pumping, and sludge treatment and disposal. It takes continuous pumping to move wastewater from homes and businesses to treatment facilities via vast sewage networks. Since there aren't many gravity-fed sewer systems in Kathmandu, more pumping stations result in higher energy usage. Sewage sludge, which is produced by wastewater treatment, needs additional processing before it can be disposed of or used again. High energy demands are a result of combustion, digestion, and mechanical dewatering. (Tchobanoglous et al., 2014). Certain WWTPs

employ chemical disinfectants and coagulants, which need energy to produce, store, and dose.

2.9. Challenges of Energy Use in Nepal's Wastewater Management

Due to its heavy reliance on hydropower, which fluctuates periodically, Nepal's energy infrastructure produces an unstable supply of electricity. Hydropower output declines during dry seasons, leading to electricity shortages that negatively impact wastewater treatment operations. Costs and carbon emissions are increased when diesel generators are used for backup. Due to energy shortages, many wastewater treatment facilities, such as Dhobighat and Sallaghari, operate sporadically or at reduced capacity, allowing untreated sewage to flow into rivers.

Energy-efficient device adoption is also hampered by financial constraints. Municipal wastewater management expenditures are often inadequate, prioritizing basic sewage disposal over energy efficiency. Furthermore, energy inefficiency is made worse by outdated machinery and decaying infrastructure, which calls for quick improvements to improve performance.

2.10. Context of wastewater and its treatment plants

Gray water and black water are two general categories for urban wastewater. Black water comprises wastewater from toilets and urinals, whereas gray water comes from non-toilet sources such bathtubs, showers, washing machines, and kitchen sinks. (ElZein. Z, 2016). There are several advantages to treating and reusing gray water, such as agricultural irrigation, freshwater conservation, and lower fertilizer needs because treated gray water is nutrient-rich (Zhang, 2006). Decentralized wastewater treatment systems, or DEWATS, are becoming more popular as a sustainable option in Nepal, where waterborne illnesses continue to be a major cause of childhood death. In Nepal, just 5% of wastewater is now adequately treated, and only 12% of urban households are connected to sewer networks. In Kathmandu, a city of almost a million people, the only centralized wastewater treatment plant in the nation is unable to keep up with the increasing demand. The majority of wastewater is released into rivers or treatment

facilities that aren't operating, which exacerbates environmental and public health issues (NEWS, 2012).

2.10.1. Context of Conventional Wastewater treatment plants

Due to rapid urbanization, population growth, and inadequate sanitary infrastructure, Nepal faces significant challenges in managing wastewater. In cities like Kathmandu, Lalitpur, and Bhaktapur, most municipal wastewater is dumped into rivers and other bodies of water without being properly treated, posing serious risks to the environment and human health. The Guheshwori Wastewater Treatment Plant (WWTP) in Kathmandu is the largest facility using the Conventional Activated Sludge (CAS) technology. Conventional wastewater treatment facilities (WWTPs) have been established in major urban centers to address this (Darnal, 2002). The goal of this plant is to reduce organic pollutants and enhance water quality by treating wastewater from the Bagmati River basin.

However, the effectiveness of these devices is often limited by operational inefficiencies, high energy use, and poor maintenance. Many wastewater treatment facilities struggle with intermittent power supplies, a lack of trained personnel, and budgetary constraints, which lead to less than ideal performance. Decentralized alternatives, such artificial wetlands and anaerobic treatment systems, are becoming more and more important because peri-urban areas and informal settlements lack access to centralized wastewater treatment. As awareness of sustainable wastewater management grows, Nepal is looking into low-energy alternative wastewater treatment techniques to enhance traditional systems, increase treatment effectiveness, and lessen environmental impact.

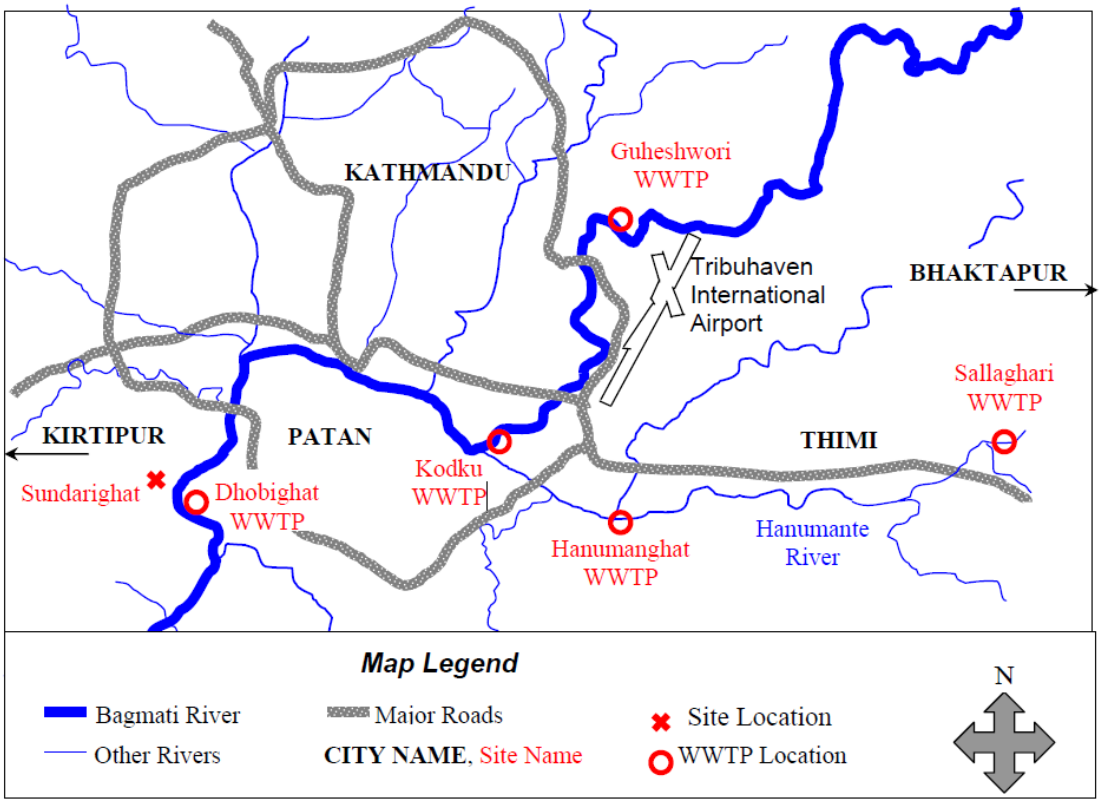

Figure 1.6: Planning of Wastewater Treatment Plants in Kathmandu Valley (Source: ADB, 2000)

2.10.2. Context of Constructed Wetland system of wastewater treatment

DEWATS, which use natural, low-maintenance technology to treat wastewater near its source, have become a competitive alternative to centralized, energy-intensive systems. The Sunga neighborhood, which is close to Kathmandu, is one of the communities where DEWATS have been implemented since they were first introduced in Nepal fifteen years ago by the local NGO ENPHO. An approximately $27,000 community-based treatment plant was built in Sunga in 2005 with assistance from the Asian Development Bank, WaterAid, and the United Nations. ((BASP)., 2002). Anaerobic baffle reactors and subsurface CWs, including horizontal and vertical flow systems, are used in this system to treat wastewater from more than 80 homes. The community has established a committee to supervise the system's upkeep and functioning, and the treated water is securely released into a nearby river (NEWS, 2012).

In 1997, the Environment and Public Health Organization (ENPHO) created the first wetland system with a capacity of 10 m^3 per day at Dhulikhel Hospital to treat hospital wastewater.

SN	Location	Type	Year Built
1	Dhulikhel Hospital	Hospital	1997
2	Dallu, Private House	Domestic	1998
3	Kathmandu University	Institutional	2001
4	ENPHO	Institutional	2002
5	Malpi International School	Institutional	2002
6	Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital	Hospital	2002
7	Kapan Monastry	Institutional	2002
8	Private House at Dallu	Domestic	2002
9	Septage Treatment, Pokhara	Community	2003
10	Shuvatara School, Lamatar	Institutional	2004
11	Surya Tobacco	Industrial	2005
12	Private House, Bishal Nagar	Domestic	2005
13	Sunga, Thimi	Municipal	2006
14	Kirtipur Housing Community	Community	2006
15	Kusunti Housing Community	Community	2007
16	Ilam Polyclinic	Hospital	2007
17	Sano Khokana Community	Community	2008
18	Srikhandapur	Community	2008
19	Monastry in Pharping, Dakshinkali	Institutional	2009
20	Private House at Kirtipur	Domestic	2010
21	ICIMOD, Khumaltar	Institutional	2010
22	Ama Ghar, Bishankhu Narayan VDC, Godawari	Institutional	2011
23	Central Horticulture Centre, Kirtipur	Institutional	2011
24	Hotel Park Village, Pokhara	Institutional	2011
25	Nala, Ugrachandi VDC	Community	2011
26	Shree Satya Sai School, Tokha	Institutional	2014
27	Lumbini Medical College, Butwal	Institutional	2012
28	Shiddhartha Children & Women Hospital , Butwal	Institutional	2012
29	Gokarna Deshe village-1, Kathmandu	Community	2014
30	Gokarna Deshe village-2, Kathmandu	Community	2015

Figure 1.7: Constructed DEWATs (Constructed Wetlands) in Nepal (Source: ENPHO, 2010)

In Nepal, thirty additional wetland systems have been built and placed in various locations over the past 15 years, including hospitals, schools, universities, and private homes, as a result of its effective operation. Nepal is the primary user of the two-staged subsurface flow technology (Reed Bed Treatment System) kind of artificial wetland with a medium depth of 0.3–0.6 m. (ENPHO, 2003).

In order to manage septic wastewater, the Kathmandu Metropolitan City built a wetlands wastewater treatment facility in 1998 that can treat about 50 m3 of wastewater per day. It uses a 200 m3 settling tank, three 75 m3 gravel-sand filter beds, and a 362 m3 vertical reed bed. In Dallu, Kathmandu, a wetland technology built by a household is effectively treating and recycling grey wastewater from the home. Water that has been treated is utilized for flushing, gardening, and washing.

Despite these developments, managing wastewater remains a major concern for Nepal. Basic sanitation is only available to 27% of the population, and the situation is made more difficult by the high operating expenses of traditional systems like the Activated Sludge System (ASS). ASS mostly uses energy-intensive aeration techniques, which are expensive in a nation with few fossil fuel resources and a lackluster hydroelectric system. For example, 1.7 kg of oxygen are needed to mineralize 1 kilogram of organic matter in municipal sewage, which has a biochemical oxygen demand (BOD) of about 250 mg/l (Ellingsen, 2010). In many situations, the high oxygen demand of the activated sludge system results in significant energy consumption, rendering it unsustainable from an economic and environmental standpoint.

However, by using natural processes to clean wastewater, CWs provide a more sustainable option. Hydraulic retention time (HRT), influent nutrient concentration, water depth, hydraulic loading rate, vegetation type, water chemistry, soil composition, and alternating dry (aerobic) and wet (anaerobic) conditions all affect how well they retain nutrients (Chavan, 2008). These systems offer further ecological advantages including habitat building and flood prevention in addition to lowering energy use.

Centralized desalination and wastewater treatment facilities, which are frequently suggested for urban areas, provide a unique set of difficulties (ADB, 2000). These include the requirement for expensive and extensive piping infrastructure that is prone to leaks, high energy usage, noise and gas emissions, and environmental disruption

during construction (World Energy Outlook, 2012). Decentralized systems, such as CWs, on the other hand, provide a more community-driven and sustainable method of managing wastewater, especially in areas with limited infrastructure and resources like Nepal.

2.11. Wastewater treatment plants and their types

2.11.1. Centralised system of wastewater treatment: Conventional Activated Sludge (CAS) Wastewater treatment system

The system's multi-stage operation guarantees effective wastewater treatment while preserving ideal microbial activity.

- **Preliminary and Primary Treatment**

To safeguard downstream equipment, screens and grit chambers are used to remove big debris and grit during the preliminary treatment stage. After that, the wastewater passes through a primary clarifier, where settleable materials are permitted to produce primary sludge. The organic load entering the biological treatment step is decreased by this procedure. (Engineering, 2013).

- **Biological Treatment in the Aeration Tank**

The fundamental component of the CAS system is the aeration tank, where organic matter is broken down by microorganisms suspended in activated sludge. To maintain aerobic conditions and ensure effective microbial metabolism, air is supplied by diffused aeration systems or mechanical aerators. (Ellingsen, 2010). By using organic contaminants as a source of energy, the bacteria create biological flocs.

- **Secondary Clarification and Sludge Recycling**

Following aeration, the combined liquid enters a secondary clarifier, where the gravity causes the microbiological flocs to settle. Return Activated Sludge (RAS), a portion of the settled sludge, is recycled back into the aeration tank to sustain microbial populations after the treated water has been separated from the sludge. Waste Activated Sludge (WAS), the leftover surplus sludge, is taken out for disposal or additional treatment (BAA & TRB, 1998).

- **Disinfection and Effluent Discharge**

In order to eliminate microorganisms, the treated water may be disinfected with ozone, ultraviolet (UV) light, or chlorine before being released into the environment. Tertiary treatment is occasionally used to improve the quality of the water even more before it is released (Bertolini, 2005).

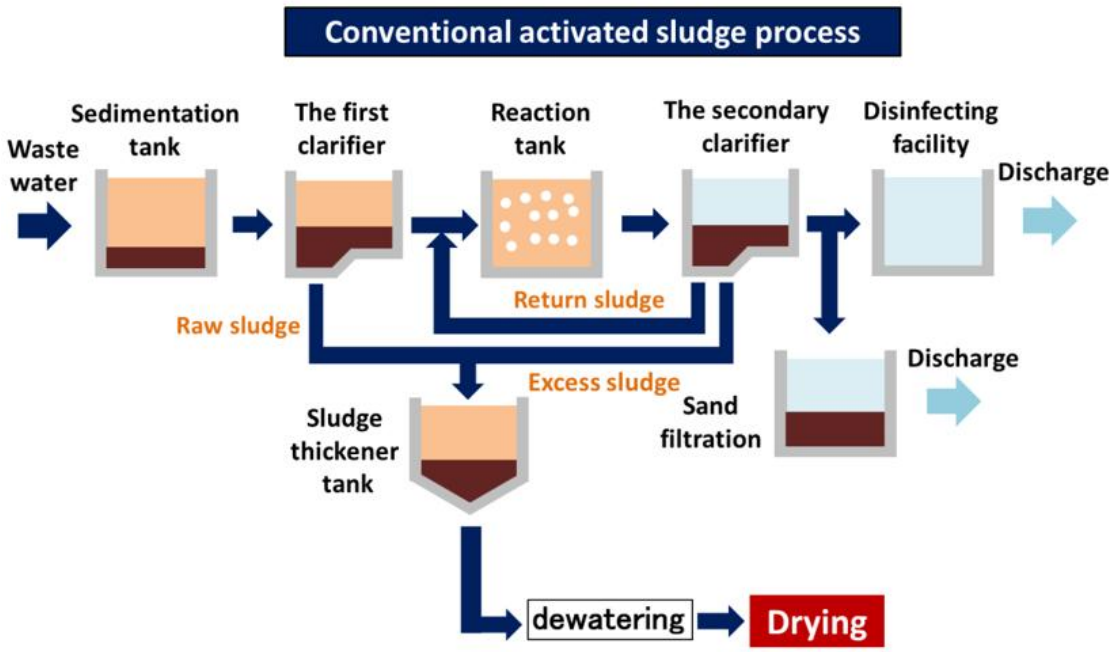

Figure 1.8: Conventional Activated Sludge (CAS) Wastewater Treatment Process (Source: Kenki, 2020)

2.11.2. Decentralized System of Wastewater treatment plant: Constructed wetlands (CW) Wastewater treatment system

Constructed wetlands are designed systems that mimic the natural wetlands' processes to treat wastewater by utilizing the combined effects of soil, plant, and microorganisms. Water flow and vegetation type are the main factors used to characterize these systems. Free water surface (FWS) created wetlands, subsurface flow (SSF) constructed wetlands, and hybrid systems that incorporate aspects of both are the primary types. (Wateraid, 2008).

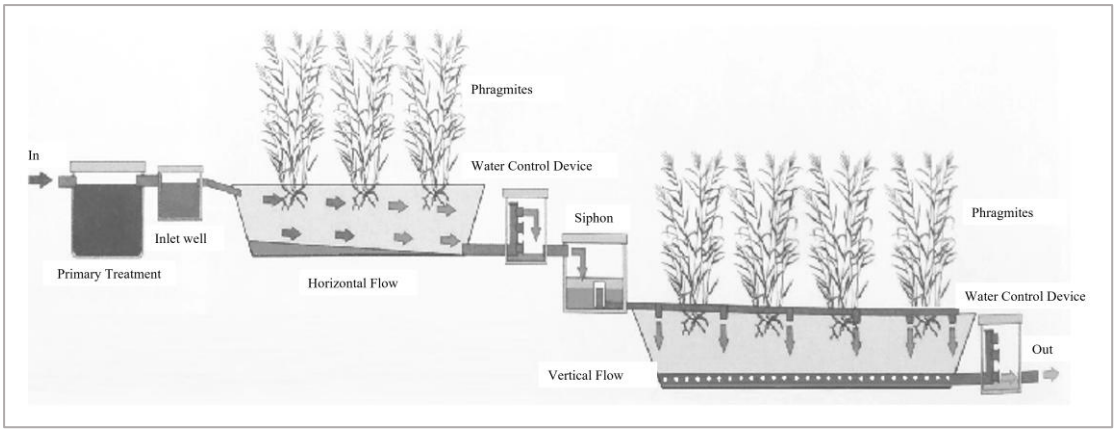

Figure 1.9: Constructed Wetland System Working Mechanism (Source: Gujar, 2024)

- **Free Water Surface (FWS) Constructed Wetlands**

Wetlands built by FWS are intended to resemble natural marshes, in which water runs over the soil or substrate's surface. These systems are made up of shallow basins where emergent plants, including cattails and reeds, have roots in the soil. Wastewater enters at one end and travels to the outlet horizontally across the vegetated surface. The interaction of water, plants, and microbial communities in FWS wetlands facilitates the treatment processes of sedimentation, filtration, and biological uptake. These wetlands are very good in eliminating fertilizers, organic debris, and suspended particulates from wastewater. They need a sizable amount of land, though, and their performance varies seasonally as a result of temperature changes. Furthermore, if not adequately managed, the open water surface may draw wildlife and present issues with mosquitoes and odors.

- **Subsurface Flow (SSF) Constructed Wetlands**

Water flow is intended to occur beneath the surface of the substrate, which is usually made of sand or gravel in SSF-constructed wetlands. This design lessens the amount of wastewater that humans and wildlife are exposed to, as well as problems with odors and insects. (Engineering, 2013). There are two primary configurations of SSF wetlands: horizontal flow and vertical flow.

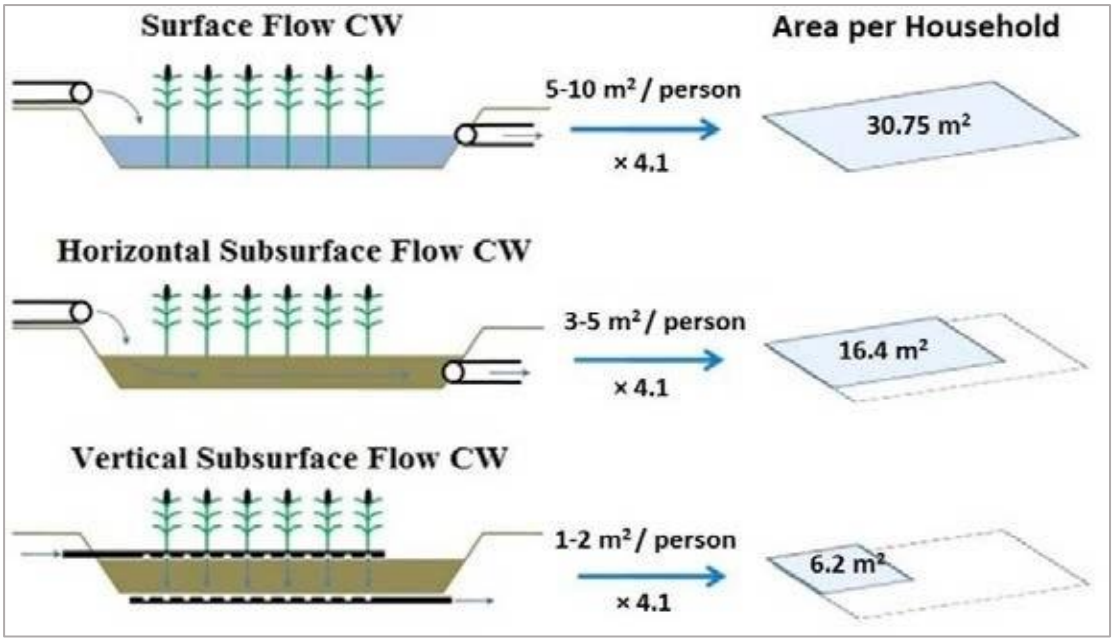

Figure 1.10: Different Types of Constructed Wetland Systems (Source: Gujar, 2024)

- **Horizontal Flow Constructed Wetlands (HFCW):**

Wastewater enters HFCW systems from the entrance and passes horizontally through the porous substrate, where it interacts with microbial biofilms and vegetation roots. Through microbial breakdown and plant uptake, this environment encourages the removal of nutrients and organic materials. Domestic and agricultural effluents are among the wastewaters that HSSF wetlands are good at treating. They offer constant treatment performance and typically take up less land area than FWS systems. However, to guarantee even flow distribution and avoid clogging, careful design is required.

- **Vertical Flow Constructed Wetlands (VFCW):**

Wastewater is applied sporadically to the substrate's surface in VFCW systems, where it percolates vertically through the media before being collected at the bottom. By improving oxygen transport, this vertical movement aids aerobic microbial processes, which effectively eliminate nitrogen compounds and organic contaminants. Because of their compact design, VFCW are well-suited for spaces with limited space and are renowned for their great treatment efficiency. To control the dosage and avoid blockage, they could need more advanced distribution systems and routine upkeep.

2.11.3. Hybrid Constructed Wetlands

Different kinds of artificial wetlands are combined in hybrid systems to maximize treatment efficiency and address particular wastewater properties. By mixing different layouts, such as vertical and horizontal subsurface flow systems, hybrid wetlands can benefit from each type's advantages to remove toxins more effectively. To achieve thorough nitrogen removal, a hybrid system might, for example, employ a VSSF wetland for efficient nitrification and an HSSF wetland for denitrification. Hybrid systems are appropriate for complex waste streams or scenarios with varying space and environmental circumstances because of their adaptable design, which can be customized to fulfill particular treatment goals.

Free surface flow and subsurface flow are the two primary categories into which CWs are divided. Although they are less expensive, free surface flow CWs are less appropriate for highly populated metropolitan areas since they require bigger land areas (5–10 m^2 per person). Subsurface flow CWs, on the other hand, are more compact (1–5 m^2 per person) and more appropriate for urban environments since they channel wastewater through a layer of filter material. Depending on the application, subsurface flow systems are further separated into horizontal flow and vertical flow CWs, each of which has unique benefits.

2.12. Environmental Impact of Concrete Construction in Conventional Wastewater Treatment Systems Compared to Constructed Wetland Systems

In order to maintain environmental sustainability and public health, wastewater treatment is a necessary procedure. Conventional wastewater treatment plants (WWTPs) usually use intricate concrete infrastructure to house different treatment units, including sludge digestion chambers, aeration basins, and sedimentation tanks. (Eddy, 2014). Because concrete has a large embodied energy and carbon footprint, its usage in these facilities greatly contributes to environmental degradation. By using natural processes to clean wastewater, built wetland systems (CWS) provide an alternate strategy that uses a lot less concrete (Vymazal, 2010). This study examines

the environmental effects of traditional WWTPs that use a lot of concrete and contrasts them with more environmentally friendly wetland systems.

2.13. Operational Considerations in Activated Sludge Treatment Systems and Constructed Wetlands

The effectiveness, sustainability, and performance of wastewater treatment systems are all greatly influenced by operational factors. Constructed wetlands (CWs) and activated sludge treatment systems (ASTS) both have unique operating features that need to be considered in order to guarantee the systems operate as efficiently as possible. Maintenance needs, energy usage, land area, system complexity, and environmental condition adaptability are some of these factors.

2.13.1. Operational Considerations in Activated Sludge Treatment Systems (ASTS)

Activated Sludge Treatment Systems (ASTS) are intricately designed systems that need a lot of upkeep and supervision. The energy used for aeration is one of the most important operating factors for ASTS. In addition to being necessary to supply oxygen for microbial activity, the constant pumping of air or oxygen into the aeration tank uses a large amount of energy. Energy expenses can be a significant operating expense in large-scale ASTS (Eddy, 2014).

Sludge management is another crucial operational component. It is necessary to periodically remove and treat the surplus sludge generated during the biological treatment process, either by dewatering, digesting, or other sludge management techniques. Sludge handled improperly can result in contamination or odor, as well as operational inefficiencies. The system must also keep the influent and recycled activated sludge in balance, which calls for constant observation and modification to maximize system performance.

Because of the intricacy of the ASTS system, it also requires skilled workers for upkeep and operation. Key parameters like temperature, pH, biological activity, and dissolved oxygen levels must be monitored in order to preserve treatment effectiveness and avoid malfunctions. To guarantee the system runs well, equipment including pumps, aerators, and clarifiers also need to be maintained on a regular basis (Tchobanoglous, 2014).

2.13.2. Operational Considerations in Constructed Wetlands (CWs)

Constructed Wetlands (CWs) are easier and less expensive to maintain than ASTS because they use less energy and have fewer mechanical parts. Since CWs mostly rely on natural processes like plant growth and microbial activity, one of their main operating advantages is their low energy usage. The plants in the wetland system aid in microbial breakdown of organic materials, oxygenation of the substrate, and nutrient uptake. Consequently, CWs are especially appealing for decentralized or small-scale systems when energy expenses are an issue (Vymazal, 2010).

Nevertheless, CWs also need some upkeep, especially in the area of plant management. To keep the system functioning, wetland plants need to be harvested or replanted on a regular basis. Over time, the substrate may also need to be refilled since organic material might clog it and lessen its ability to filter pollutants. This is especially crucial in subsurface flow wetlands (SSF) since blocked substrates can reduce treatment effectiveness and impede wastewater flow (Vymazal, 2010).

The land acreage requirements in CWs are one of the difficulties. Even though CWs are frequently low-maintenance and more sustainable, the treatment procedure necessitates a sizable amount of land. This may restrict their use in urban settings or in places with limited land supply. Since free water surface wetlands (FWS) rely on open water surfaces for treatment, they might need even more area than subsurface flow systems (Vymazal, 2010).

Compared to ASTS, CWs are typically more equipped to adjust to changing environmental conditions. For instance, seasonal temperature changes have an impact on their effectiveness because plants thrive in warmer climates while microbial activity may be less productive in colder climates. CWs are a more robust choice for wastewater treatment in some situations, nevertheless, because of their inherent ability to continue treating wastewater even in the face of changing conditions.

2.13.3. Comparison of Operational Considerations

In terms of operational considerations, ASTS systems are more complicated and energy-intensive than CWs, necessitating more frequent maintenance of mechanical components and active management. Conversely, CWs provide a low-energy and more

sustainable option, but they may have drawbacks including the need for plant and substrate upkeep and acreage needs. CWs are better suitable for smaller, decentralized systems where low operating costs and environmental sustainability are top priorities, whereas ASTS is best suited for large-scale, highly efficient treatment in metropolitan contexts.

2.14. Cost Analysis and Economic Feasibility of Activated Sludge Treatment Systems and Constructed Wetlands

When choosing a wastewater treatment system, cost and economic viability are important factors, particularly for large-scale projects or areas with limited funding. Constructed wetlands (CWs) and activated sludge treatment systems (ASTS) both have distinct economic profiles and cost structures. Although ASTS is frequently seen to be more effective in terms of treatment capacity, CWs offer a more affordable, sustainable, and low-maintenance option, particularly for decentralized or smaller-scale applications.

2.14.1. Cost of Activated Sludge Treatment Systems (ASTS)

Constructed wetlands (CWs) require less capital than activated sludge treatment systems (ASTS). Installing an ASTS requires a large upfront investment in mechanical equipment and infrastructure, such as sludge handling systems, pumps, clarifiers, and aeration tanks. Depending on the system design, technology, and location, the capital expenses for ASTS might vary from $1 to $5 million per million gallons per day (MGD) of treatment capacity (Eddy, 2014).

ASTS's energy requirements can result in high operating costs. Over 50% of the overall operating costs of ASTS can be attributed to aeration, the process that uses the greatest energy (Tchobanoglous, 2014). These energy expenses can be substantial for large-scale ASTS systems, particularly in regions with high energy prices or where the grid is largely dependent on non-renewable energy sources. Sludge disposal and routine maintenance are additional operational expenses that might raise the system's total cost.

Nevertheless, ASTS systems are typically more effective at handling higher wastewater volumes, which makes them a financially feasible option for industrial or urban settings requiring a high treatment capacity. They are appropriate for densely populated areas with considerable wastewater generation because of their capacity to handle big volumes of wastewater.

2.14.2. Cost of Constructed Wetlands (CWs)

For smaller-scale or dispersed systems, Constructed Wetlands (CWs) provide a more economical option than ASTS. Compared to ASTS, CWs typically require less capital input. The building of the wetland basin, substrate materials, and site acquisition are the main expenses related to CWs. Depending on the design and location, CWs can cost anywhere from $100,000 to $500,000 per MGD of treatment capacity (Vymazal, 2010). Because of this, CWs are a more cost-effective choice, particularly in rural or underdeveloped areas where financial limitations are an issue.

When it comes to operating costs, CWs are far less costly than ASTS. Plant maintenance and sporadic substrate replenishment are the main operational costs for CWs. Because CWs run on natural processes like plant growth, microbial activity, and sun energy, they use less energy than ASTS. CWs are therefore a more sustainable choice in terms of both financial and environmental factors because the energy expenses are essentially zero (Vymazal, 2010).

Because CWs don't need complicated mechanical equipment and their systems often have fewer moving parts than ASTS, they also have lower maintenance expenses. Because of its ease of use, low energy consumption, and minimal requirement for frequent intervention, CWs offer substantial cost savings over the long run.

2.15. Economic Feasibility and Long-Term Considerations

ASTS may be more appropriate for high-capacity treatment requirements in urban or industrial contexts, even though CWs are more economical in the short run. However, CWs provide a cost-effective and sustainable option for rural or dispersed locations with available land and little room for major infrastructure.

The long-term viability of both regimes' economies is another important factor. ASTS is economically feasible for large-scale applications due to its ability to handle massive amounts of wastewater, despite the fact that it requires significant initial and ongoing investments. Since CWs have lower lifetime costs than ASTS, especially in places with smaller wastewater volumes or where energy consumption is a major concern, their low operating and maintenance costs make them an appealing long-term solution.

2.16. Applicability and Suitability of Activated Sludge Treatment Systems and Constructed Wetlands

A wastewater treatment system's applicability and acceptability are determined by a number of criteria, such as site-specific circumstances, treatment capacity, land availability, climate, and regulatory requirements. Constructed wetlands (CWs) and activated sludge treatment systems (ASTS) each have unique benefits and drawbacks that make them appropriate for various wastewater treatment applications. In order to choose the best treatment approach for the community, business, or environment, it is essential to comprehend the distinctive features of these systems.

2.16.1. Applicability of Activated Sludge Treatment Systems (ASTS)

Large-scale wastewater treatment facilities where effective pollutant removal and high treatment capacity are crucial might benefit greatly from the use of activated sludge treatment systems (ASTS). ASTS systems are appropriate for municipal wastewater treatment, industrial facilities, and urban locations where significant wastewater volumes must be treated on a daily basis. They are a dependable option for such high-demand scenarios because to their capacity to manage high organic loading and significant variations in influent features (Eddy, 2014).

ASTS is especially appropriate for areas with stringent wastewater discharge quality regulations. By eliminating pollutants including organic matter, nitrogen, and phosphorus to extremely low quantities, these systems can be made to satisfy the strictest discharge regulations. According to Tchobanoglous et al. (2014), this makes

them perfect for locations where good effluent water quality is necessary to avoid eutrophication or to satisfy recycled water use requirements.

The versatility of ASTS in managing huge, fluctuating wastewater flows is one of the main factors contributing to its widespread use, which makes it suitable for use in commercial complexes, industries, and municipalities with substantial wastewater volumes. Additionally, it may be modified to treat various wastewater types, including stormwater runoff, industrial wastewater, and household wastewater. Additionally, ASTS is easily scalable, enabling greater capacity to accommodate future industrial expansion or population growth.

2.16.2. Suitability of Activated Sludge Treatment Systems (ASTS)

Despite their great efficiency, ASTS systems are less appropriate for places with limited energy resources or land. The energy and area requirements of the infrastructure needed for ASTS can be high. ASTS may not be as appropriate for rural areas or places with high energy expenditures because of the aeration process's significant energy consumption. Furthermore, ASTS systems are less suitable for dispersed applications or locations with restricted access to technical expertise since they require trained staff to manage the technology (Tchobanoglous et al., 2014).

2.17. Applicability of Constructed Wetlands (CWs)

Conversely, Constructed Wetlands (CWs) are especially well-suited for low-energy, decentralized, and smaller-scale applications. When land availability is less of a concern and wastewater flow is relatively modest, they are frequently utilized in residential subdivisions, small towns, and rural locations. According to Vymazal (2011), CWs are particularly well-suited to areas with a lot of land and climates that allow for substantial vegetation growth, such temperate or tropical regions.

In places with little infrastructure and funding, CWs can be an affordable and environmentally friendly wastewater treatment option. They are also a desirable choice for environmentally conscious neighborhoods or areas that place a high value on sustainable development and green infrastructure. CWs are appropriate for locations

with restricted access to electricity or where energy costs are exorbitant due to their small energy usage and comparatively low operating costs (Vymazal, 2010).

2.17.1. Suitability of Constructed Wetlands (CWs)

CWs, however, are not appropriate for large-scale applications in areas with heavy wastewater flow and human density. Due to their huge land area requirements, CWs may not be feasible in urban or densely populated locations with limited space. Additionally, CWs might not work well in areas with extremely cold temperatures since low temperatures can limit microbial and plant activity, which lowers treatment effectiveness (Vymazal, 2011).

When compared to more mechanically demanding systems like ASTS, CWs are also less successful at eliminating specific pollutants like heavy metals or viruses. Therefore, unless additional treatment stages are included, CWs are less appropriate for treating wastewater with high concentrations of these contaminants (Vymazal, 2011).

2.18. Introduction to Life Cycle Assessment (LCA) in Wastewater Treatment

An environmental management method called life cycle assessment (LCA) is used to assess how a system, process, or product will affect the environment overall during the course of its whole life cycle, from the extraction of raw materials to disposal. Finding and measuring the environmental consequences of each stage of a product's life cycle is the main goal of life cycle assessment (LCA), which aims to reduce negative effects and maximize sustainability (ISO, 2006). By taking into account variables like energy use, greenhouse gas emissions, resource utilization, and other environmental burdens throughout the treatment, operation, and disposal phases, life cycle assessment (LCA) is used to evaluate and compare the sustainability of various treatment technologies in the wastewater treatment context.

2.18.1. Application of LCA in Wastewater Treatment

The growing demand for sustainable water management techniques has made life cycle assessment (LCA) a crucial tool in wastewater treatment plant evaluation. Depending on the technology employed, wastewater treatment systems can have a variety of environmental effects. Although they are frequently energy-intensive, traditional techniques such as Activated Sludge Treatment Systems (ASTS) are renowned for their excellent efficiency in treating vast amounts of wastewater. Conversely, Constructed Wetlands (CWs) use natural processes to clean wastewater and use less energy, although they may need a large amount of land. Through a thorough comparison of various systems made possible by LCA, stakeholders can evaluate trade-offs between long-term sustainability, energy usage, and operating expenses (Tchobanoglous, 2014). LCA has shown that one of the biggest environmental burdens associated with ASTS is energy usage, especially for aeration. According to studies, aeration uses roughly 60% of the operational energy in activated sludge systems (Metcalf & Eddy, 2014). As a result, LCA evaluations of ASTS usually find ways to cut energy use by optimizing processes or using alternative energy sources. On the other hand, because CWs use passive treatment methods, they have a smaller energy footprint. Although considerations like land acreage and maintenance are still necessary, life cycle assessment (LCA) has shown that CWs have a lower carbon footprint and less resource depletion than mechanical systems like ASTS.

Furthermore, LCA looks at the sustainability of wastewater treatment by taking into account not only treatment effectiveness but also wider environmental effects like ecosystem services, biodiversity preservation, and the possibility of developing circular economies. For instance, by establishing habitats for water plants and fauna, CWs have the extra advantage of promoting local biodiversity, which increases their long-term sustainability.

2.18.2. Importance of LCA in Decision-Making

LCA offers crucial information to help with well-informed wastewater treatment system design and implementation decisions. Policymakers, engineers, and local authorities are among the stakeholders that can choose the best technology that supports

sustainability objectives by calculating the environmental effects of each treatment option. Additionally, LCA can assist in determining methods for mitigating environmental effects, like improving nutrient removal procedures, integrating renewable energy sources, or optimizing energy use (Vymazal, 2011).

To sum up, Life Cycle Assessment is an essential instrument for assessing wastewater treatment facilities' environmental sustainability. LCA facilitates the adoption of more environmentally friendly wastewater treatment techniques by offering a thorough examination of energy use, emissions, resource use, and ecological effects. LCA offers the information required to make ecologically conscious decisions that limit harm and maximize the long-term benefits of wastewater treatment, whether comparing traditional systems like activated sludge with cutting-edge techniques like built wetlands.

2.19. Environmental Impact of Concrete Construction in Conventional Wastewater Treatment Systems Compared to Constructed Wetland Systems

In order to maintain environmental sustainability and public health, wastewater treatment is a necessary procedure. Conventional wastewater treatment plants (WWTPs) usually use intricate concrete infrastructure to house different treatment units, including sludge digestion chambers, aeration basins, and sedimentation tanks (Metcalf & Eddy, 2014). Because concrete has a large embodied energy and carbon footprint, its usage in these facilities greatly contributes to environmental degradation. By using natural processes to clean wastewater, built wetland systems (CWS) provide an alternate strategy that uses a lot less concrete (Vymazal, 2010).

2.19.1. Case of Conventional Waste Water Treatment plants

2.19.1.1 Carbon Footprint of Concrete in WWTPs

Because of its longevity and resistance to chemical corrosion, concrete is one of the most commonly utilized building materials in wastewater treatment facilities. But its creation requires a lot of energy; the production of cement alone is responsible for

around 8% of the world's CO2 emissions (Andrew, 2018). The main cause of this large carbon footprint is the cement-making process of calcination, which releases CO_2 by heating limestone ($CaCO_3$) (Ellingsen, 2010). Large volumes of concrete are needed to build large-scale components like these in conventional WWTPs.

1. **Primary Sedimentation Tanks**: For these to manage the high wastewater inflow, reinforced concrete structures are necessary.
2. **Aeration Basins**: Large aeration tanks made of high-strength concrete are necessary for activated sludge systems in order to sustain mechanical aeration forces.
3. **Secondary Clarifiers**: Also made using concrete to facilitate the settling of suspended solids followed just past biological treatment.
4. **Sludge Digesters and Storage Tanks**: Sludge digestion systems, which produce and stabilize methane under controlled conditions, are housed in concrete structures (Eddy, 2014).

   WWTPs are a major contributor to climate change because of the carbon emissions from the concrete used in these components, which build up over the course of the plant's construction and operation.

2.19.1.2 High Embodied Energy in Construction

The environmental impact of traditional wastewater treatment facilities is further increased by the embodied energy of concrete, which is the entire energy needed for its manufacture, transportation, and construction. According to Gursel et al. (2014), the production of cement, aggregate mining, and transportation account for the majority of the approximately 1.7 GJ of energy contained in one cubic meter of concrete. The total embodied energy is significant since large WWTPs can consume thousands of cubic meters of concrete.

Freshwater supplies are further taxed by the high water requirement for concrete manufacture. The production of concrete is thought to be responsible for 9% of industrial water withdrawals worldwide (BAA & TRB, 1998), which exacerbates worries about water scarcity.

2.19.1.3 Land and Resource Consumption

Environmental deterioration is frequently caused by the enormous land footprint needed for WWTP infrastructure. Facilities that use a lot of concrete require a lot of excavation, site preparation, and resource extraction for raw materials like sand and gravel, which causes soil erosion and habitat degradation (Arata, March 2003). Additionally, concrete construction produces impermeable surfaces that increase the danger of flooding and stormwater runoff by disrupting natural water infiltration and contributing to urban heat islands (MOPIT / JICA, 2012).

2.19.2. Constructed Wetlands: A Sustainable Alternative with Lower Concrete Usage

2.19.2.1 Minimal Concrete Requirements

By using natural treatment mechanisms, built wetland systems (CWS) drastically reduce dependency on concrete compared to traditional WWTPs. Shallow basins with gravel, sand, and wetland plants make up the majority of a CWS, therefore inlet and outflow structures only need a small amount of concrete (Bertolini, 2005). In addition to lowering embodied carbon emissions, the decreased requirement for large-scale concrete tanks also reduces the amount of resources extracted during the manufacturing of cement and aggregate.

Constructed wetlands use 60–80% less concrete than traditional treatment plants, according to a European study comparing WWTPs with CWS (EPA, 2014). Both the embodied energy and carbon footprint of wastewater treatment infrastructure are greatly reduced by this substantial reduction.

2.19.2.2 Lower Energy Consumption and Carbon Emissions

Built wetlands use plant absorption and natural microbial activity to remove pollutants, in contrast to traditional treatment systems that use energy-intensive aeration procedures. By doing away with the requirement for aeration basins, this passive

treatment method significantly minimizes the usage of concrete and operational energy (Tchobanoglous, 2014).

Because they rely on natural treatment processes rather than mechanical aeration, research has shown that artificial wetlands emit 40–70% less CO_2 over their lifetime than activated sludge systems (Arata, March 2003). Additionally, CWS lessens the need for containment buildings based on concrete by eschewing chemical dosing tanks, which are frequently present in traditional WWTPs.

2.19.2.3 Sustainable Land Use and Ecosystem Benefits

Because they improve biodiversity and blend in perfectly with their natural surroundings, artificial wetlands also have ecological advantages. CWS preserves natural water retention and filtering capabilities, lowering urban runoff and groundwater depletion in contrast to traditional WWTPs, which turn vast areas of land into impermeable concrete structures (Vymazal, 2010).

Additionally, wetlands manage wastewater and support biodiversity by offering habitat for aquatic species, birds, and amphibians (Kadlec & Wallace, 2009). Some of the emissions related to wastewater treatment are reduced by the vegetation in CWS, which also helps with carbon sequestration.

2.19.3. Comparative Lifecycle Environmental Impact

Operational and Maintenance Impacts

Frequent maintenance is necessary for concrete-intensive WWTPs, including energy-intensive aeration, structural repairs, and chemical dosage changes. In contrast, manmade wetlands require less care, with vegetation management accounting for the majority of upkeep rather than aeration system or concrete repairs (Tanner, 2001).

According to Fonder and Headley's (2010) cost-benefit analysis, CWS have 40–60% lower operating costs than traditional treatment facilities because they require less energy and maintenance. This lessens their dependency on carbon-intensive energy sources, further improving their long-term sustainability.

2.20. Summary

Concrete is often used in traditional wastewater treatment systems, which has a negative environmental impact by increasing carbon emissions, embodied energy, and resource depletion. Massive volumes of cement are needed for large-scale infrastructure including sludge digesters, aeration basins, and sedimentation tanks, which increases the industry's already significant carbon footprint. Constructed wetland systems, on the other hand, provide a sustainable substitute with less concrete needed, lowering emissions associated with construction as well as energy usage during operation. CWS successfully reduces maintenance costs, enhances ecosystem health, and mitigates climate impacts by utilizing natural treatment processes. Moving toward low-carbon wastewater treatment techniques, such as built wetlands, will be crucial in lowering environmental footprints while preserving efficient water treatment capacities as the emphasis on climate resilience and sustainable infrastructure grows globally.

CHAPTER 3 METHODOLOGY

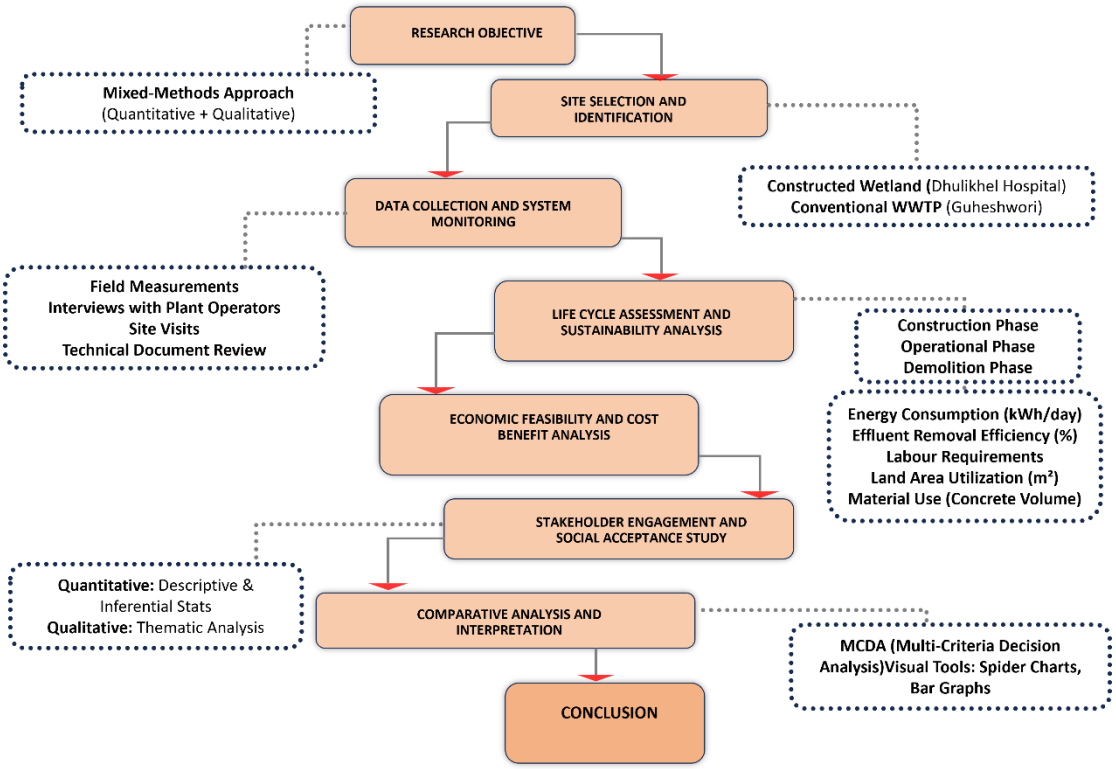

Figure 3.1: Methodology Structure

This study employed a **mixed-methods research design**, combining both quantitative and qualitative approaches to assess and compare the energy conservation potential of two wastewater treatment systems: a **constructed wetland** located at *Dhulikhel Hospital*, and a **conventional wastewater treatment plant (WWTP)** situated in *Guheshwori*, Kathmandu. These two systems were selected for their contrasting technological configurations and operational characteristics, enabling a comprehensive analysis of energy use, environmental sustainability, and life cycle dynamics.

3.1. Research Design

A mixed-methods approach was adopted to integrate field-based quantitative data with qualitative environmental assessments. Quantitative data facilitated the measurement of performance indicators such as energy consumption and effluent treatment efficiency, while qualitative inputs provided contextual understanding of environmental and operational factors, particularly through a **qualitative Life Cycle Assessment (LCA)**.

3.2. Study Area

- **Dhulikhel Hospital Constructed Wetland**: This nature-based treatment system employs subsurface flow wetlands for decentralized wastewater management. It is characterized by low energy consumption, minimal mechanical components, and a high degree of ecological integration.

- **Guheshwori Conventional WWTP**: This is a centralized, mechanized wastewater treatment plant using activated sludge and sedimentation processes. It features intensive energy use and mechanical operation, making it representative of traditional urban wastewater management systems.

3.3. Data Collection

Data were collected through a combination of field measurements, site visits, interviews with plant operators, and review of technical documents. Parameters recorded included:

- **Effluent removal efficiency** (%)
- **Energy consumption** (kWh/day)
- **Labour requirements** (unit person)
- **Land area utilization** (m^2)
- **Material use** and **building footprint** (volume of concrete and infrastructure)

Data accuracy was ensured through **on-site verification** and triangulation with secondary sources and measurements.

3.4. Qualitative Life Cycle Assessment (QLCA)

A **qualitative Life Cycle Assessment** was conducted to evaluate environmental impacts across the three primary phases of each system:

1. **Construction Phase** - assessment of material inputs (e.g., concrete volume), construction activities, and embodied energy.

2. **Operational Phase** - examination of recurring energy demands, maintenance labor, chemical inputs, and emissions.

3. **Demolition Phase** - consideration of resource use and potential environmental burdens associated with decommissioning.

Although no detailed modeling was performed using LCA software, the approach allowed for a conceptual evaluation of life cycle impacts to support the comparative analysis.

3.5. Data Analysis Methods

Quantitative data were analyzed using **descriptive statistics** to summarize core parameters such as mean energy consumption and land use. **Inferential statistical tests**, including independent t-tests and correlation analyses, were employed to determine significant differences and relationships between system variables.

To compare overall system performance, a **Multi-Criteria Decision Analysis (MCDA)** framework was applied, incorporating key metrics such as energy efficiency, land and labor use, and environmental impact indicators. Visual tools, including **spider charts** and comparative bar graphs, were used to represent differences across systems.

Qualitative data from field observations and stakeholder inputs were analyzed using **thematic analysis** to extract patterns related to maintenance challenges, system advantages, and contextual performance issues. The integration of both data types allowed for a holistic comparison of the two wastewater treatment technologies in terms of energy conservation and sustainability.

CHAPTER 4: FIELD STUDY AND DATA ANALYSIS

4.1. Field Study

The Wastewater treatment plant at Guheshwori and the constructed wetland system at Dhulikhel was selected for the study.

4.1.1. WWTP at Guheshwori

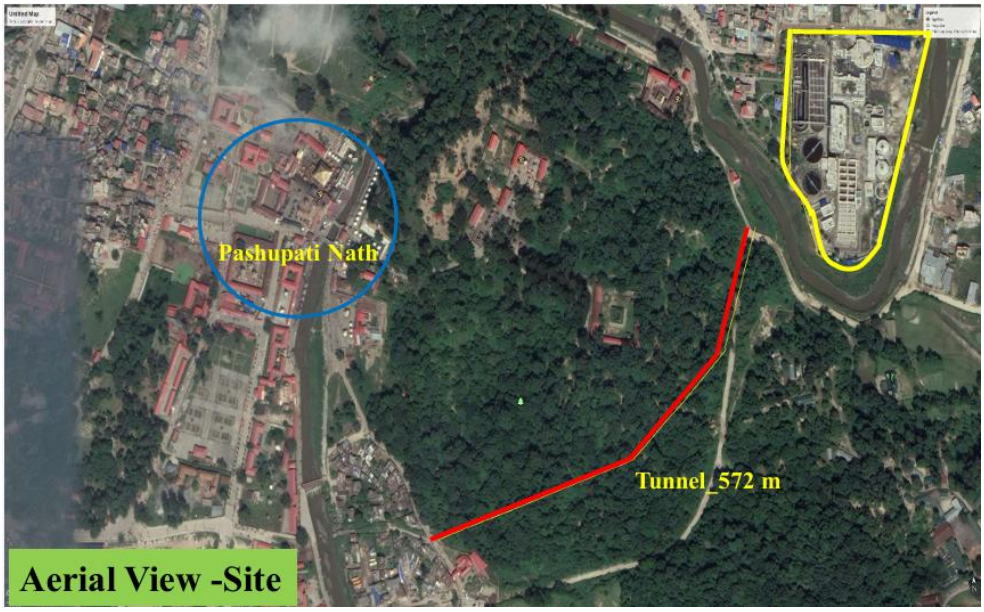

Figure 4.1: Aerial View of the WWTP at Guheswori (Source : PID, 2024)

4.1.1.1 Project Details

The project follows a centralized Wastewater treatment plant concept, covering a service area of 995 hectares, with a treatment plant spanning 2.86 hectares. The project commenced in 2001 with the first phase, and the second phase began in 2020, with design periods of 25 years for the first phase and 20 years for the second phase. The base year population (2020) is estimated at 300,000, with a domestic wastewater generation of 80 liters per capita per day (lpcd).

The project is structured as a Design-Build-Operate (DBO) model, with a total design and construction cost of Rs. 2,04,29,26,328.00, and an operational cost for 10 years

amounting to Rs. 37,22,79,789.00 (including VAT). The industrial wastewater flow is 14 liters per second (Lps), and the system handles combined wastewater from domestic, industrial, and storm sources. The designed wastewater flow is 32.4 million liters per day (MLD) or 0.375 cubic meters per second (Cumec), ensuring effective sewage management in the region.

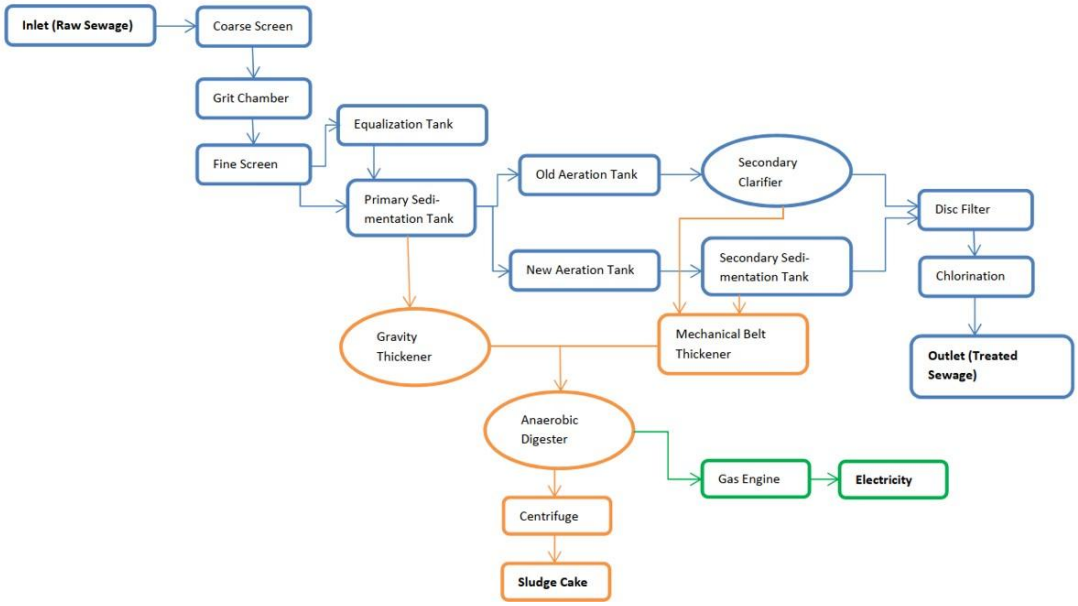

Figure 4.2: Flowchart of the Treatment Process at Guheshwori (Source: PID, 2024)

Figure 4.3: Isometric View of the WWTP at Guheshwori (Source: PID, 2024)

4.1.1.2 Data collection and analysis

The data was analysed for the whole year of 2024. The overall energy consumed and generated from electricity is approximately 3,01,009 kWh per month for the year 2024. The gaseous byproducts were utilized to generate biogas, which was around 12,775 kWh per month for the year of 2024. This accounted for about 4% of the total energy consumed.

Month (2024)	Energy Generation (kWh)	Energy Consumption (kWh)	Net Energy (kWh)
Jan	25700	280383	254683
Feb	17700	330874	313174
Mar	14600	377800	363200
Apr	14100	390740	376640
May	13500	340621	327121
Jun	10900	276280	265380
Jul	5900	236375	230475
Aug	6900	237280	230380
Sep	5700	227040	221340
Oct	7200	274490	267290
Nov	19800	345180	325380
Dec	11300	295050	283750
Total	**153300**	**3612113**	**3458813**

Table 4.1: Energy Usage Year 2024 Guheshwori WWTP (Source: PID, 2024)

The total annual energy consumption of the plant is 3,612,113 kWh, while the total energy generated is significantly lower at 153,300 kWh. This results in a net energy deficit of 3,458,813 kWh, indicating the plant remains heavily dependent on external

energy sources. Energy generation peaked in January (25,700 kWh) and was lowest in September (5,700 kWh), showing seasonal variability in onsite energy production. Despite some monthly fluctuations, net energy deficits remain consistently high, with the lowest in January (254,683 kWh) and highest in April (376,640 kWh). These figures underscore a substantial potential for energy conservation or renewable integration, as less than 5% of the plant's energy demand is currently met through internal generation. The average monthly energy generation is approximately 12,775 kWh, whereas average monthly consumption is about 301,009 kWh, reinforcing the large energy gap.

The highest net energy consumption occurred in April (376,640 kWh), indicating potentially higher process loads or inefficiencies during that month. The summer months (June to August) show lower energy generation, likely due to operational, environmental, or resource-related constraints, suggesting a need for seasonal energy planning. November is the second-highest month for energy generation (19,800 kWh), yet it still falls short of meeting even 6% of that month's consumption. The consistent pattern of high energy consumption with minimal onsite generation suggests that the plant could significantly benefit from efficiency upgrades, energy recovery technologies, or renewable energy integration, such as biogas utilization or solar PV systems.

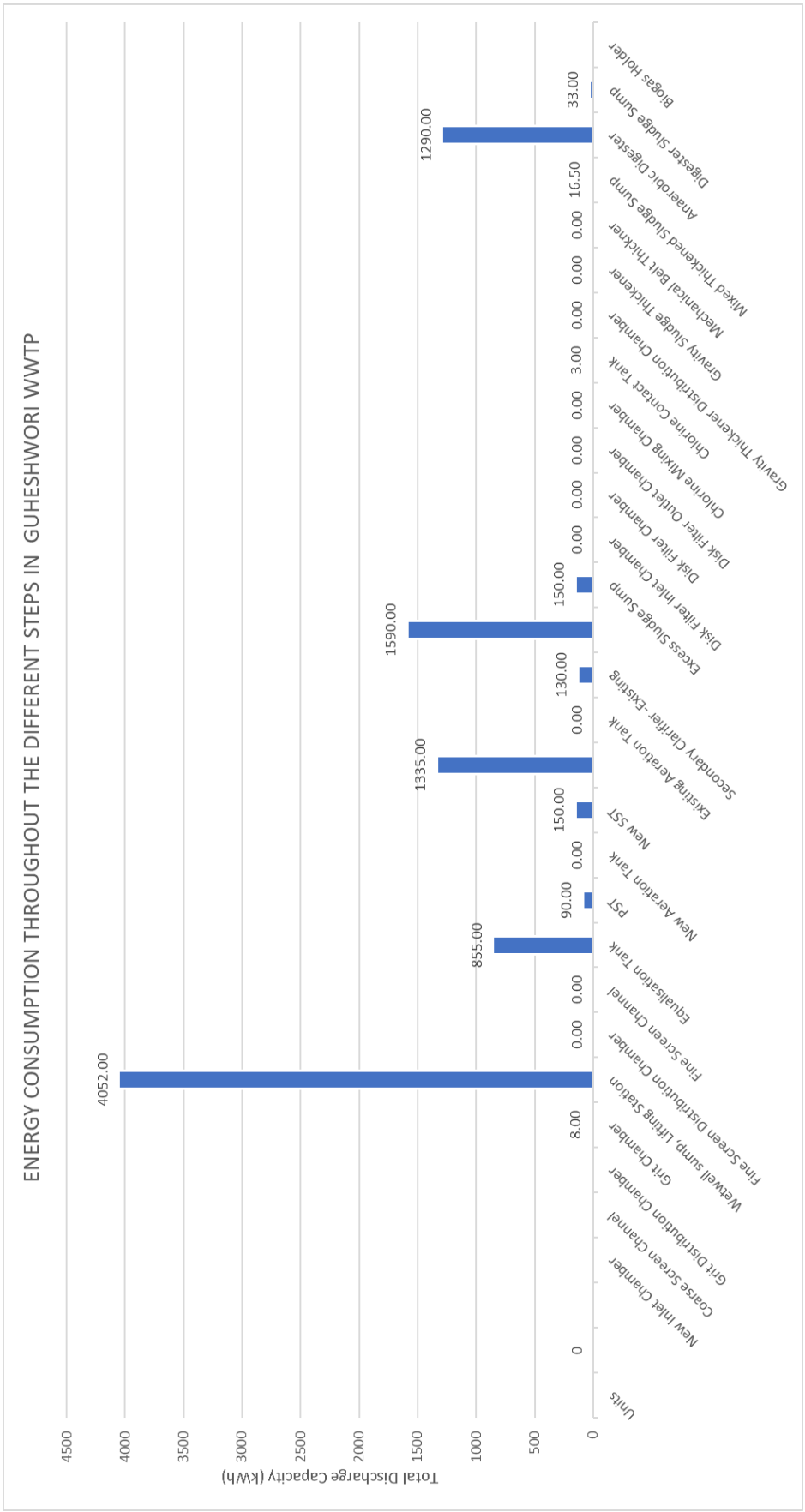

Figure 4.4 Energy Consumption throughout the different steps in Guheshwori WWTP

The highest energy-consuming unit is the “Total Discharge” process (4,052 kWh), followed by the “Dewatering” (1,590 kWh) and “Aeration” (1,335 kWh) units—indicating major targets for energy-saving interventions. The “Excess Sludge Sump” (150 kWh) and “Disk Filter Outlet Chamber” (150 kWh) are moderate consumers, suggesting partial automation or mechanical operations. Several units, including “Screen Chambers,” “Equalization Tanks,” and “Chlorine Contact Chambers,” show zero recorded energy consumption, which might imply passive operation or data gaps. The significant load on aeration and sludge handling units highlights a common energy pattern seen globally, suggesting a potential fit for energy-efficient blowers or anaerobic digestion technologies. This breakdown supports targeted retrofitting strategies, where high-consumption units can be prioritized for upgrades, such as variable-frequency drives (VFDs), process control automation, or energy recovery from biosolids.

Month (2024)	Energy Generation (kWh)	Energy Consumption (kWh)	Net Energy (kWh)	Total Inflow (MLD)	BOD5 Inflow (mg/l)	BOD5 Outflow (mg/l)	BOD5 Reduction %	COD Inflow (mg/l)	COD Outflow (mg/l)	COD Reduction %	TSS Inflow (mg/l)	TSS Outflow (mg/l)	TSS Reduction %
Jan	25700	280383	254683	423.622	20192.1	311.8	1.5	42672	1708	4	20185	369.2	1.8
Feb	17700	330874	313174	347.903	16606.9	224.2	1.3	34060	855	2.5	16870	260.1	1.5
Mar	14600	377800	363200	374.286	18703.4	380	2.0	35356	1588	4.4	20355	529.4	2.6
Apr	14100	390740	376640	423.174	19216.1	384.5	2.0	32559	1718	5.2	18315	539.7	2.9
May	13500	340621	327121	476.193	13994.7	157.3	1.1	28690	1132	3.9	15420	241.6	1.5
Jun	10900	276280	265380	516.496	16789.1	194.3	1.1	28511	1008	3.5	13581	236.1	1.7
Jul	5900	236375	230475	515.954	9725.7	154.6	1.5	20311	1661	8.1	9010	215.7	2.3

Aug	6900	237280	230380	616.595	8902.7	137.9	1.5	19051	1852	9.7	9655	197.8	2.0
Sep	5700	227040	221340	522.33	11314.4	155.1	1.3	18446	1771	9.6	9690	182.2	1.8
Oct	7200	274490	267290	544.13	10168.2	130.9	1.2	16694	1573	9.4	11355	169.4	1.4
Nov	19800	345180	325380	588.351	11819.9	134.5	1.1	16844	1327	7.8	11215	153.4	1.3
Dec	11300	295050	283750	498.827	17914.4	278.4	1.5	29328	1683	5.7	17390	352.1	2.0

Table 4.2: Overall Treatment and effluent data, Guheshwori WWTP 2024 (Source: PID, 2024)

The total energy generation across the year is 153,300 kWh, while total energy consumption is 3,612,113 kWh, leading to a net energy deficit of 3,458,813 kWh, confirming heavy reliance on external energy sources. Monthly energy generation peaks in January (25,700 kWh) and dips in September (5,700 kWh), indicating potential seasonal variability in energy production capability. Despite an average daily inflow exceeding 470 MLD, only about 4.2% of energy demand is met through onsite generation, reflecting a clear opportunity for enhancing energy recovery. Biological Oxygen Demand (BOD_5) reduction efficiency remains consistently high throughout the year, generally exceeding 98%, indicating effective organic matter removal. Chemical Oxygen Demand (COD) reduction also performs well, with highest reductions occurring in the summer and autumn months (up to 9.7% in August), likely due to optimal microbial activity or longer retention times. Total Suspended Solids (TSS) reduction shows moderate variability, with the most efficient month being March (2.6%), and least efficient in January (1.8%), possibly due to seasonal changes in inflow composition or process efficiency. Inflow BOD_5 concentrations peak in January (20,192.1 mg/L), with the lowest in August (8,902.7 mg/L), suggesting significant variability in influent load due to seasonal or industrial discharges. Higher treatment loads (e.g., April and January) correlate with higher net energy deficits, suggesting that energy usage scales with treatment intensity, highlighting the importance of energy-efficient process optimization. The months with higher inflows (e.g., November and August) demonstrate steady treatment efficiency, suggesting robust plant performance under high hydraulic load conditions. Overall, the plant maintains excellent pollutant removal efficiency, but its low energy self-sufficiency underscores the need for adopting advanced energy recovery technologies, such as anaerobic digestion with biogas recovery or solar integration.

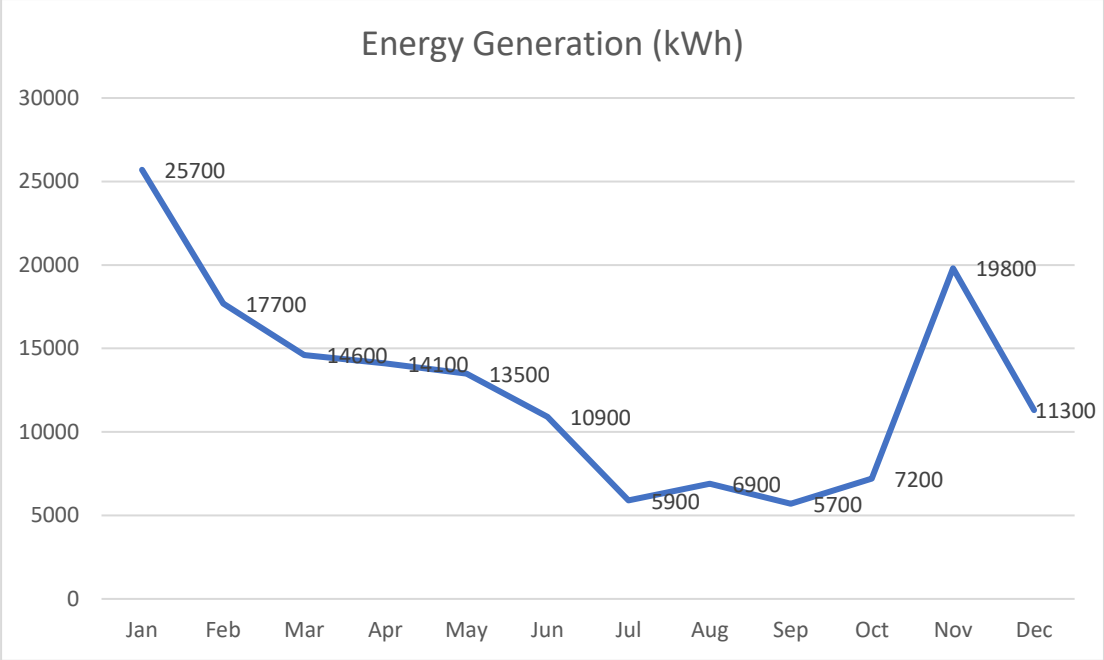

Figure 4.5: Energy Generation Guheshwori Wastewater Treatment Plant 2024

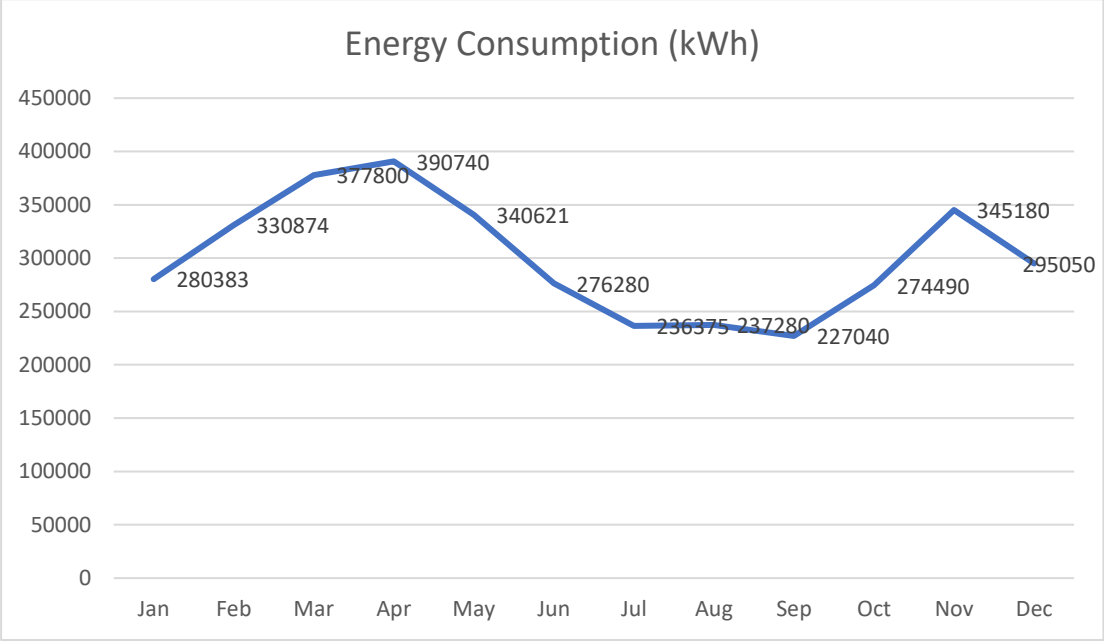

Figure 4.6: Energy Generation Consumption of Wastewater Treatment Plant 2024

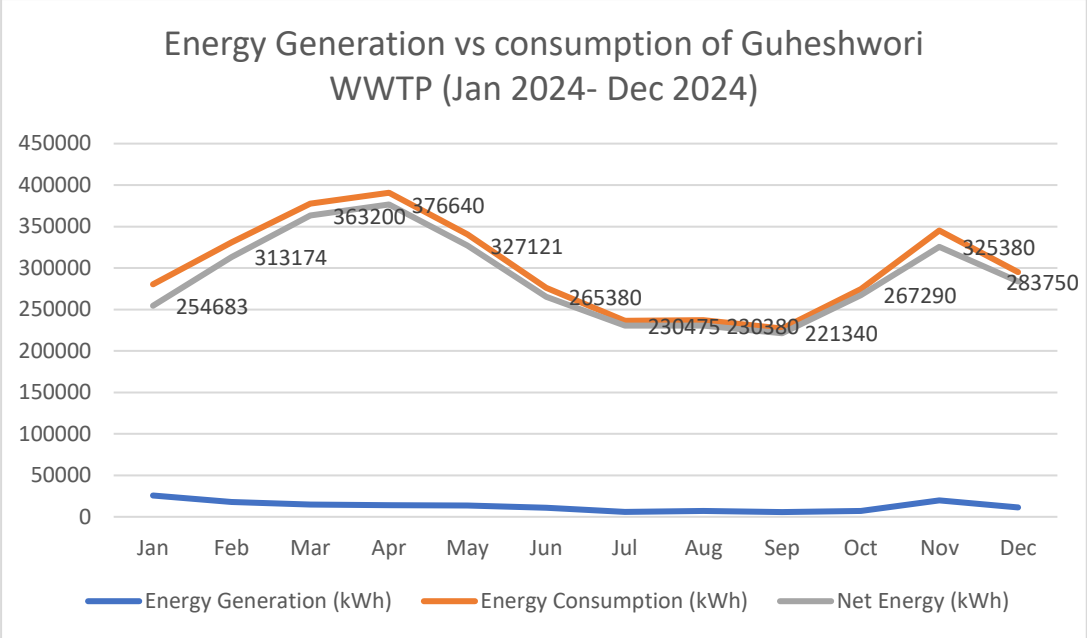

Figure 4.7: Energy Consumption vs Generation of Guheshwori Wastewater Treatment Plant 2024

Energy consumption follows a clear seasonal trend, peaking in April (390,740 kWh) and reaching its minimum in September (227,040 kWh), likely corresponding with influent load variations or operational demands. Energy generation remains almost constant throughout the year, ranging between 5,700–25,700 kWh, highlighting a lack of scalability in renewable or onsite generation systems. Net energy (deficit) closely mirrors consumption trends, reinforcing that increased plant load directly increases energy dependency. July to September mark the lowest energy consumption period, which could suggest reduced biological loading or improved operational efficiency during monsoon months. The gap between generation and consumption remains wide, indicating that the current energy recovery system is not proportionally contributing to operational demands at any time of the year.

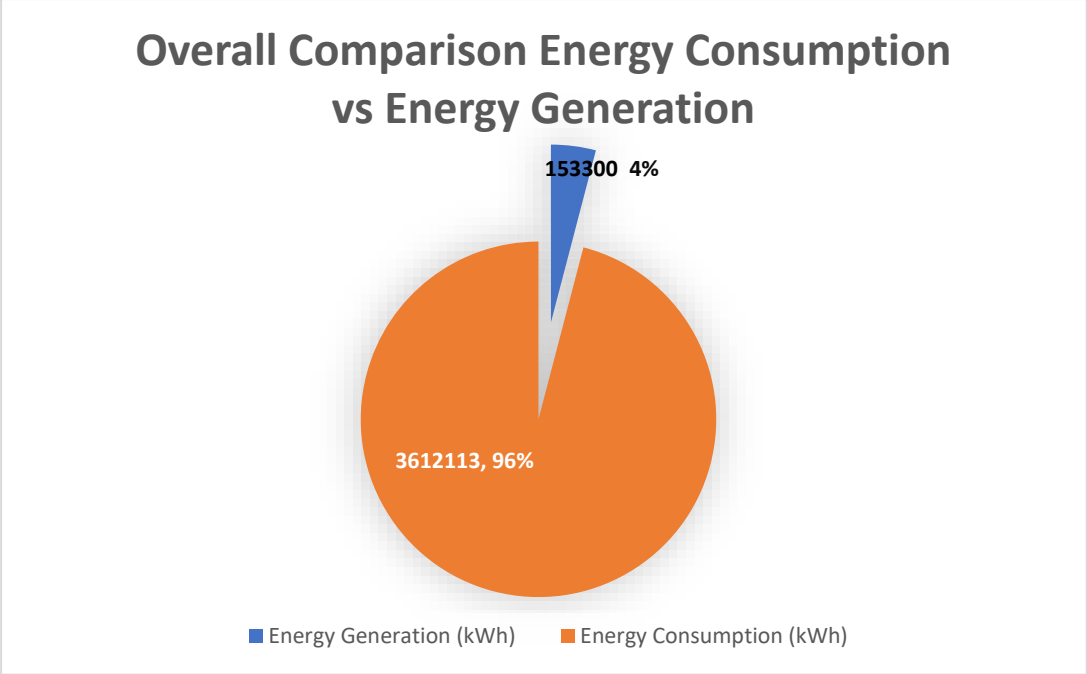

Figure 4.8: Overall Comparison of Energy consumption vs Energy Generation of Guheshwori Wasteawter Treatment Plant

The pie chart illustrates a stark imbalance—only 4% of the plant's total energy demand is met through internal generation, with 96% fulfilled through external supply. This disproportionate ratio emphasizes the urgency of enhancing energy recovery mechanisms or integrating renewables like biogas, solar PV, or microturbines. With total annual energy consumption at 3,612,113 kWh and generation at just 153,300 kWh, the plant's energy system is neither cost-effective nor sustainable in its current state. The visual contrast underscores the potential for Guheshwori WWTP to serve as a pilot site for energy-neutral wastewater treatment upgrades. The chart reinforces the importance of energy audits and efficiency optimization, especially in high-energy-use units identified in the bar chart .

4.1.2. Constructed Wetland System at Dhulikhel Hospital

Figure 4.9: Constrcuted Wetland System at Dhulikhel Hospital

4.1.2.1 Project Details

Located in Dhulikhel Municipality, Kavrepalanchok District, Nepal, Dhulikhel Hospital is associated with Kathmandu University. Established in 1997, the hospital's wastewater treatment system was Nepal's first constructed wetland wastewater treatment plant. However, after the hospital was built, the system was improved in 2008 to handle the increased wastewater flow and meet current and future needs. Dhulikhel Hospital funded the DEWATS-SME (Hospital) initiative on its own, with additional funding from ENPHO and technical assistance from BOKU Austria. The upgrade, which cost NRs. 2,500,000 (about US$ 39,683), took place in 2008 after the original system was built in 1997. (ENPHO, 2010)

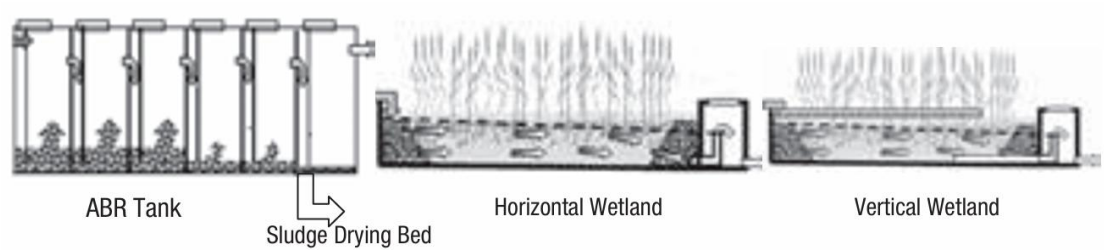

Figure 4.10: Operation system of Constructed Wetland at Dhulikhel Hospital Source (ENPHO, 2010)

In order to reduce the negative environmental effects on neighboring rivers, the wastewater treatment system processes the wastewater generated by the hospital and its staff housing. Additionally, the treated wastewater is collected and used for irrigation. The system is a medium-sized, three-phase treatment setup that includes a vertical wetland, a horizontal wetland, and an anaerobic baffle reactor (ABR). Two of the systems work together. A sludge drying bed is another component of the system that completes the treatment procedure.

A diversion tank is used in the system to split the flow between different treatment systems. A sludge drying bed, two parallel horizontal flow created wetlands, two parallel vertical flow constructed wetlands, and two parallel settlers (one large anaerobic baffled reactor and one smaller settler) are all part of the system. This design encourages sustainable water use in the hospital's operations by ensuring effective treatment and control of hospital wastewater.

Figure 7 Layout Plan of the proposed DEWATS

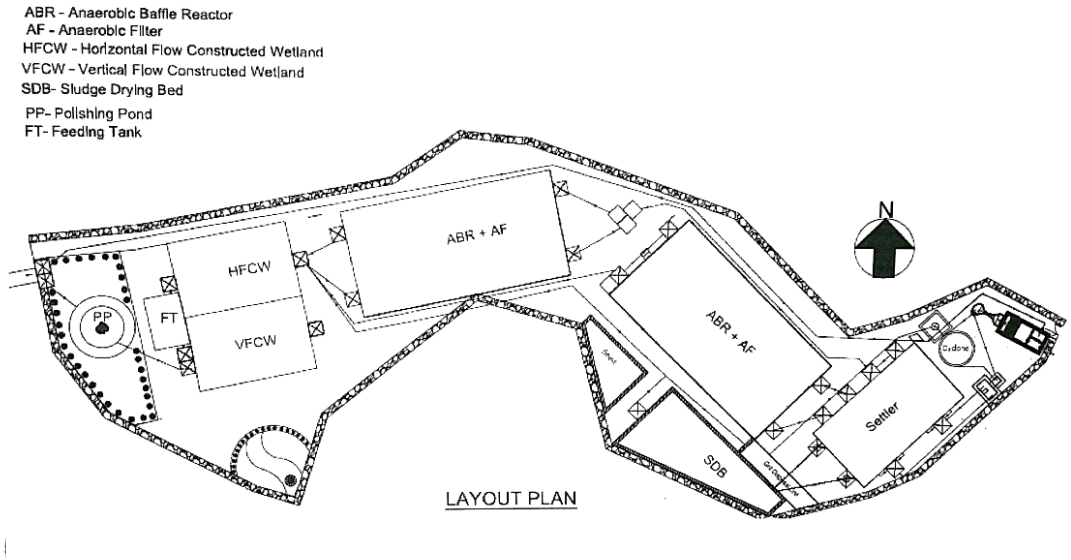

Figure 4.11: Layout plan of the Constructed Wetland System at Dhulikhel (Source: ENPHO, 2010)

4.1.2.2 Data collection and analysis

Source	**Hospital & staff quarters**
Design Capacity	90 m^3/d, as of now, 65 m^3/d
Users	250 beds
Peak Flow	210 m^3/d
Influent Quality (July 2010)	**BOD**: 60 mg/L, **COD**: 432 mg/L
Effluent Quality (July 2010)	**BOD**: 6 mg/L, **COD**: 223 mg/L

Efficiency	90% BOD, 48% COD

Table 4.3: Dhulikhel Hospital Wastewater Treatment Data (Source: ENPHO, 2010)

Currently handling 65 m^3/day, the system is functioning at about 72% of its design capacity, which can improve treatment effectiveness and lifespan due to less stress. The system was intended to handle 90 m^3/day. The current flow is equivalent to about 260 liters per person per day, which is commensurate with the average water use in healthcare institutions, given that the hospital has 250 beds. A combined sewer system or inadequate stormwater separation may be the cause of the peak flow, which exceeds 210 m^3/day and is mostly driven by stormwater inflow. This could result in a hydraulic shock danger during periods of precipitation. The requirement for equalization tanks or buffer capacity to control fluctuations and prevent overtaxing the biological treatment system is indicated by the high peak-to-average flow ratio (>3x). The plant may run the danger of diluting influent organics under such fluctuating inflows, which could reduce the effectiveness of biological treatment during storm occurrences.

Component	**Small Settler**	**Large ABR**
No. of Tanks	3 chambers	4 baffle walls
Settler Volume	26 m^3	52 m^3
Area of Construction	17.5 m^2	35 m^2
Planted Gravel Filter: 2 Horizontal Reed Beds	1 small	1 large
Surface Area	117 m^2	180 m^2
Depth	0.6 m	
Filter Material	Gravel (2-5 mm)	
Plants Used	Phragmites karka	
Planted Gravel Filter: 2 Vertical Reed Beds		

Surface Area	120 m²	198 m²
Depth	0.9 to 1.05 m	
Filter Material	Coarse sand (main media) & gravel (drainage layer)	
Plants Used	Phragmites karka	
Sludge Drying Bed: 1 Unit		
Surface Area	100 m²	
Depth	0.5 m	
Filter Material	Coarse sand & gravel	
Plants Used	Phragmites karka	
Total System Area	800 m²	

Table 4.4: Component data of CW at Dhulikhel Hospital (Source: ENPHO, 2010)

Constructed Wetland System Component Analysis

Settler and Anaerobic Baffled Reactor (ABR) Units

The system's two main anaerobic treatment components—a large ABR with four baffle walls and a compact settler with three chambers—effectively enable staged anaerobic digestion and primary settling for improved organic reduction. With comparable building footprints of 17.5 m² and 35 m², the settlers' volumes of 26 m³ (small) and 52 m³ (large) showcase space-efficient primary treatment units that are ideal for decentralized or peri-urban setups. By increasing solids retention and hydraulic contact time, the use of several chambers and baffles improves the effectiveness of anaerobic digestion and lowers the organic load before it enters the reed beds.

Horizontal Flow Reed Beds (Planted Gravel Filter)

With surface areas of 117 m² and 180 m², respectively, the horizontal reed beds consist of one small unit and one big unit. Both units function at a shallow depth of 0.6 m for

subsurface horizontal flow. For biological treatment, the use of gravel media (2–5 mm) encourages microbial colonization on the media surface while offering sufficient porosity and hydraulic conductivity. A native wetland plant called Phragmites karka helps remove nutrients and pathogens by facilitating organic absorption, oxygen transfer to the rhizosphere, and root-zone filtration.

Vertical Flow Reed Beds

With surface areas of 120 m² for small and 198 m² for large, the vertical flow beds function at deeper depths (0.9–1.05 m) and use a dual media system that supports vertical percolation and aeration by placing coarse sand (treatment media) above gravel (drainage layer). Compared to horizontal beds, vertical beds enhance aerobic degradation and nitrification, and their intermittent or alternating batch loading can boost treatment effectiveness and avoid clogging. Once more, Phragmites karka is utilized because of its strong durability, development rate, and adaptability, which makes it perfect for vertical systems that require constant filtering and evapotranspiration.

Sludge Management and Overall System Design

In order to dewater and reduce the volume of biosolids, a single sludge drying bed (100 m², 0.5 m deep) filled with coarse sand and gravel offers a passive, low-energy option. This reduces the need for external sludge handling and permits on-site reuse or safe disposal. The system's 800 m² total construction area is somewhat small for a multi-stage natural treatment system that provides ecological integration, scalability, and sustainability for decentralized wastewater treatment.

The engineering department at Dhulikhel Hospital oversees the operation and maintenance (O&M) of the DEWATS unit, with all expenses paid for by the hospital's yearly budget. The system, which has been in use for more than 13 years, was upgraded in 2008 because of its excellent performance. Stormwater infiltration, the need for plant cropping, a broken tipping bucket, and a blocked bar screen at the smaller ABR intake

were among the problems found during a visit in July 2010. These difficulties caused flow diversion into the bigger wetland, resulting in ponding and perhaps inadequate treatment. The sludge drying bed was recently used and is used every two and a half months when there is sludge on the wetland media surface. With planned hospital and residential developments, the wetland is anticipated to function below capacity; however, performance may be impacted by stormwater infiltration during the monsoon. Although the treated wastewater is now dumped into an existing canal, the treated water may be used again for irrigation, and the sludge is utilized as fertilizer. Although monsoon rains and system obstructions affected system performance, monitoring findings from July 2010 indicate that the system is still operating effectively.

It was observed that the created wetland could only accommodate 100,000 liters, which is half of the 2,00,000 liters that were intended to be held there. The establishment planned to complete the remaining building at a later time.

4.2. Comparison and Discussion

S. No.	Name	WWTP Type	Total constructed area(sq.m.)	Total construction cost (Nrs)	Total Treatment capacity (cu.m./D)	Treatment Efficiency BOD (%)	Treatment Efficiency COD (%)	Per unit treatment area(cu.m/sq.m.)	Per unit treatment cost(Nrs/cu.m.)	Average energy consumed per day(kWh/day)	Average energy Generated per day	Net energy consumed per day	Per unit energy consumed per day (kWh/cu.m.)
1	Guheshwori Wastewater Treatment Plant	Centralised Activated Sludge	28600	2,042,926,328	32400	98.5	93.8	1.132867133	63,053.28	9,896.20	420.00	9,476.20	0.31
2	Dhulikhel Hospital	Constructed Wetland	767.5	2500000	65	90	48	0.084690554	38,461.54	0	0	0	0
	Difference		27,832.5	2,040,426,328	32335	8.5	45.8	1.048176579	24591.74327	9896.2	420	9476.2	0.31

Table 4.5: Overall Comparison of the Guheshwori WWTP and Dhulikhel CW

Comparative Analysis of Guheshwori WWTP and Dhulikhel Hospital Constructed Wetland System

Treatment Capacity and Scale

The two systems differ most obviously in their spatial scale and treatment capability. Guheshwori WWTP can serve sizable metropolitan populations because of its capacity of 32,400 m^3 per day. The Dhulikhel CW, in comparison, only treats 65 m^3 per day, which is indicative of its intended use for a 250-bed hospital and related staff quarters. The 32,335 m^3/day gap in treatment capacity makes it evident that Dhulikhel is meant for localized, decentralized applications, whereas Guheshwori is an urban, regional-scale facility. The enormous disparity between their created areas—28,600 m^2 for Guheshwori and 767.5 m^2 for Dhulikhel—is clearly evident.

Construction Cost and Economic Efficiency

Guheshwori WWTP's construction was estimated to have cost NPR 2.04 billion in capital expenditures, or NPR 63,053.28 per cubic meter of treatment capacity per day. On the other hand, Dhulikhel Hospital CW was built for a total of only NPR 2.5 million, or NPR 38,461.54 per m^3/day. Because of its smaller size, the CW method is less cost-effective per cubic meter treated even though it seems to be less expensive overall. However, because of the modest initial investment needed, CW systems are more affordable for small-scale organizations, rural communities, and developing nations with limited financial resources.

Treatment Performance and Environmental Compliance

Although there are notable performance discrepancies, both systems show satisfactory pollution removal. Advanced biological treatment using mechanical and aerated processes is demonstrated by the Guheshwori WWTP's 98.5% removal of Biological Oxygen Demand (BOD) and 93.8% removal of Chemical Oxygen Demand (COD). Because of its excellent performance, the plant can meet strict effluent discharge regulations that are appropriate for disposal in rivers or on land.

Conversely, the Dhulikhel CW removes 48% of COD and 90% of BOD. These results are in line with what is anticipated for passive treatment systems, which use planted gravel beds for filtration, sedimentation, and biological degradation. Some refractory organic molecules may still be present in the effluent, which is a frequent drawback of artificial wetlands, as indicated by the decreased COD removal efficiency when compared to BOD. However, considering the ease of use and inexpensive cost of the system, the effluent BOD of 6 mg/L at Dhulikhel in July 2010 was within permissible regulatory limits.

Energy Profile and Operational Sustainability

The two systems' energy performance differs significantly. With an average daily energy recovery of 420 kWh, the Guheshwori WWTP uses 9,896.2 kWh, most likely from small-scale cogeneration or biogas. With a per-unit energy intensity of 0.31 kWh/m^3 and a net energy consumption of 9,476.2 kWh/day, this is typical of well-optimized activated sludge systems in developing nations.

However, because of its passive design, which does not require pumps, blowers, or electrical control systems, the Dhulikhel CW runs with zero energy creation or consumption. Due to its high sustainability and durability and low operational reliance on external energy sources, this attribute makes the CW system especially appealing for off-grid or low-resource communities.

Spatial and Hydraulic Efficiency

Another area of comparison is hydraulic efficiency, which is expressed as the volume of wastewater treated per square meter of land. Due to the intense nature of activated sludge procedures, which can treat more water in less space, Guheshwori's 1.13 m^3/m^2 greatly surpasses Dhulikhel's 0.085 m^3/m^2. Because of this, Guheshwori is better suited for urban locations with limited land, while Dhulikhel's large land footprint restricts its scalability in areas with high population densities but makes it advantageous where land is abundant and costs are low.

4.3. Comparison of Life Cycle Assessment (LCA) of Activated Sludge Treatment Systems (ASTS) and Constructed Wetlands (CWs)

A vital technique for evaluating the environmental sustainability of different wastewater treatment methods is life cycle assessment (LCA), which provides insightful information on resource usage, energy consumption, greenhouse gas emissions, and long-term ecological effects. Based on particular environmental indicators, Life Cycle Assessment (LCA) can assist in comparing Constructed Wetlands (CWs) and Activated Sludge Treatment Systems (ASTS) to identify which system provides the best mix of sustainability and performance. An outline of the application of Life Cycle Assessment (LCA) to these two systems is given below, with an emphasis on resource use, energy consumption, greenhouse gas emissions, and overall environmental effect.

The life cycle of the plants can be briefly divided into the following three phases:

- **Construction phase**
- **Operational Phase**
- **Demolition phase**

S.No.	Units	Size Details					
		Nos.	**Rad**	**L**	**W**	**D (liquid)**	**Concrete**
			m	**m**	**m**	**m**	**m^3**
1	New Inlet Chamber	1	-	2	3.5	1.3	1.1
2	Coarse Screen Channel	2		7.4	0.9	1.2	3.0
3	Grit Distribution Chamber	1	-	2	3.6	1	0.8
4	Grit Chamber	2	-	7	1.7	3.22	8.4
5	Wetwell sump, Lifting Station	1	-	9	7	3.1	7.5

6	Fine Screen Distribution Chamber	1	-	1.2	9	1.2	1.8
7	Fine Screen Channel	2	-	6.9	1.1	1	2.4
8	Equalisation Tank	1	14	-	-	6	77.1
9	PST	8	-	23	5	3.5	118.8
10	New Aeration Tank	2	-	46.6	11	6	105.1
11	New SST	4	-	40	5.375	3.5	96.5
12							0.0
13	Existing Aeration Tank	2	-	84.4	41	3.7	141.2
14	Secondary Clarifier - Existing	2	14			1.7	43.7
15							0.0
16	Excess Sludge Sump	1	-	6.5	4.3	2.5	4.1
17	Disk Filter Inlet Chamber	1		1.5	6.7	3.5	4.3
18	Disk Filter Chamber	2		7	3.2	3.6	11.0
19	Disk Filter Outlet Chamber	1		1.5	3.2	3.2	2.2
20	Chlorine Mixing Chamber	1		4	2	3.1	2.8
21	Chlorine Contact Tank	2		7.5	12.8	3	18.4
22	Gravity Thickener Distribution Chamber	1		1.8	1	0.8	0.3
23	Gravity Sludge Thickener	2	4.8			3.5	31.7
24	Mechanical Belt Thickner	2					
25	Mixed Thickened Sludge Sump	1		8	2	2.5	3.8
26	Anaerobic Digester	2	8			17.65	250.94

27	Digester Sludge Sump	1		2.5	2.5	2	1.5
28	Biogas Holder						
						Total Concrete (m^3)	**938**

Table 4.6: Carbon Footprint and built up area of the Guheshwori WWTP (Source: PID, 2024)

Analysis of Structural Components and Concrete Utilization in a Wastewater Treatment Plant

Designing an effective and sustainable wastewater treatment system requires careful structural and civil engineering planning in addition to optimizing biological and chemical processes. The unit-wise design and concrete use of a wastewater treatment plant (WWTP), including intake structures, primary and secondary treatment units, sludge management, and tertiary treatment facilities, are assessed in the following analysis. Understanding the infrastructure's capacity and material efficiency requires a thorough examination of tank sizes, concrete volumes, and design features.

Inlet and Preliminary Treatment Units

In order to preserve downstream treatment operations, the preliminary section contains a number of structures that are essential for screening and grit removal. The New Inlet Chamber serves as the initial site of hydraulic entry and is 2 m × 3.5 m × 1.3 m in size. It employs 1.1 m^3 of concrete. The removal of bigger debris and fine solids is then handled by the Coarse Screen Channels (2 units) and Fine Screen Channels (2 units). With corresponding concrete requirements of 3.0 m^3 and 2.4 m^3, these structures are comparatively compact.

Sand and silt are examples of inorganic materials that are settled by the Grit Chambers and Grit Distribution Chamber. With an approximate concrete volume of 8.4 m^3, the Grit Chambers (2 units) are larger, indicating a longer retention period to enhance grit

removal. Despite their small capacity, these preparatory units are essential for preventing wear and safeguarding mechanical equipment.

Pumping and Flow Equalization Infrastructure

Using 7.5 m^3 of concrete, the Wetwell Sump and Lifting Station (9 m × 7 m × 3.1 m) manages influent pumping. It is an essential hydraulic component that keeps the flow to downstream operations constant. Similar to this, the Equalization Tank, which has a 77.1 m^3 concrete capacity, buffers flow variances, which is crucial for regulating shock loads during storm or peak inflow occurrences. The strategic significance of this unit in systems receiving changing hydraulic or biological loads is highlighted by its huge capacity..

Primary and Secondary Treatment Structures

Eight units, each measuring 23 m × 5 m × 3.5 m, make up the Primary Settling Tanks (PSTs), which use a total of 118.8 m^3 of concrete. These structures serve as the basis for physical treatment by facilitating the sedimentation of suspended particles.

Both new and old aeration tanks are essential parts of the secondary stage. The previous aeration tanks are much larger (84.4 m × 41 m × 3.7 m), using 141.2 m^3 of concrete, whilst the new aeration tanks (2 units) are 46.6 m × 11 m × 6 m and utilize 105.1 m^3 of concrete. Due to the need for aeration equipment and mixing, the activated sludge process is energy-intensive and structurally demanding.

Clarified effluent separation is also managed by Secondary Settling Tanks (SSTs) (4 units) and current secondary clarifiers, which use 43.7 m^3 of concrete and 96.5 m^3 of concrete, respectively. After biological treatment, these units are necessary for solid-liquid separation, which permits the recycling of sludge and the release of clear effluent.

Tertiary Treatment and Disinfection Components

More than 35 m^3 of concrete are used in the advanced treatment, which consists of two disk filter chambers, inlet and outlet chambers, and two chlorine contact tanks. With a concrete volume of 18.4 m^3, the Chlorine Contact Tank is a significant disinfection equipment that guarantees pathogen elimination before to discharge or reuse. This

function is additionally supported by the Chlorine Mixing Chamber (4 m × 2 m × 3.1 m), which exemplifies an integrated approach to safe wastewater management.

Sludge Management and Energy Recovery Infrastructure

The Gravity Thickener Distribution Chamber, Disk Filter Inlet Chamber, and Excess Sludge Sump are three systems that facilitate sludge handling. The concrete volume of these compact buildings, which range from 1.5 to 4.3 m^3, permits volume reduction and thickening prior to additional treatment.

The Gravity Sludge Thickeners (2 units, totaling 31.7 m^3) are larger sludge components that aid in passive sludge volume reduction. With a total area of 250.94 m^3, the two anaerobic digesters are among the most concrete-intensive units, which is indicative of their depth and volume needs (down to 17.65 m). These digesters are probably employed for energy production, sludge stabilization, and biogas recovery.

The energy recovery and sludge treatment chain is completed by the Digester Sludge Sump, Mixed Thickened Sludge Sump, and the unidentified Biogas Holder. Despite the absence of volumetric data, the Mechanical Belt Thickener's existence indicates an attempt to mechanically dewater sludge, which would cut down on drying time and manual labor.

Overall Concrete Utilization and Design Implications

938 m^3 of concrete were used in all units, which were split between solid-phase/sludge units and liquid-phase treatment structures. A modular and integrated design concept is shown in the large range of unit sizes and configurations, which enable disinfection, sludge handling, solid-liquid separation, biological operations, and influent pretreatment all within a single plant.

The material-intensive nature of centralized treatment systems, especially those that use activated sludge and anaerobic digestion, is also demonstrated by this structural variety. Even though these designs are efficient in terms of treatment capacity and pollution removal, they necessitate large investments in civil infrastructure, which must be supported by possible energy/resource recovery, durability, and long-term performance.

S.No.	Description	Length(m)	Width(m)	Dia(m)	Depth(m)	Remarks	No.s	Volume
1	Screen chamber with parshall flume	1.77	0.55		0.075	75mm P.C.C.	1	0.072
2	Cyclone			2.7	2.1	R.C.C. Section	1	9.46
3	cyclone chamber	1.80	1.80		2.3	R.C.C. Section	1	1.20
4	Settler	5.00	5.30		2.69	R.C.C. Section	1	4.16
5	Anaerobic baffle reactor and anerobic filter	14.90	7.60		2.69	R.C.C. Section	1	9.16
6	Baffle walls Along x-axis	14.90	2.45		0.2	R.C.C. Section	1	0.68
7	Baffle walls Along y-axis	7.46	2.45		0.2	R.C.C. Section	10	3.88
8	Horizontal Flow Constructed wetland	8.00	5.40		0.075	75mm P.C.C.	1	3.24
9	Feeding tank	2.40	3.80		1.17	R.C.C. Section	1	1.078
10	Vertical Flow Constructed Wetland	8.00	5.40		0.075	75mm P.C.C.	1	3.24
11	Retaining wall	8.00	5.40		3.624	R.C.C. Section	1	7.31
12	Polishing Pond			4.8	1.15	100mm P.C.C.	1	18.25
13	Sludge Drying Bed	11.90	4.00		0.1	100mm P.C.C.	1	4.76
14	Sludge Storage Shed	7.70	3.25		0.1	100mm P.C.C.	1	2.50

S.No.	Description	Length(m)	Width(m)	Dia(m)	Depth(m)	Remarks	No.s	Volume
15	Grit Disposal Chamber	6.00	1.50		1.67	100mm P.C.C.	1	15.03
16	Typical Manhole	0.30	0.30		0.075	75mm P.C.C.	23	0.16
							Total concrete(m3)	84.22

Table 4.7: Carbon Footprint and built up area of the CW at Dhulikhel Hospital (Source: ENPHO, 2010)

Structural and Material Analysis of the Constructed Wetland System

For decentralized wastewater treatment systems to operate sustainably and economically, excellent civil design and low material consumption are essential. The analysis that follows examines the main structural components, their measurements, and the amounts of concrete, 84.22 m^3, used in a small wastewater treatment plant. A modular, resource-conscious design appropriate for institutional or small-scale community treatment is reflected in its comparatively tiny concrete footprint.

Preliminary Treatment Units

Preliminary units that remove big materials and condition the flow hydraulically are the first steps in the treatment process. Measuring only 1.77 m × 0.55 m × 0.075 m in depth, the screen chamber with Parshall flume is made of 75 mm plain cement concrete (P.C.C.), which contributes a minimum of 0.072 m^3 of concrete. This unit is functionally essential for flow measurement and initial screening despite its modest volume.

With a combined volume of 10.66 m^3, the reinforced cement concrete (R.C.C.) cyclone unit (2.7 m diameter, 2.1 m depth) and cyclone chamber (1.8 m × 1.8 m × 2.3 m) greatly aid in the separation of grit and sand. By supporting hydraulic rotation and sedimentation, these units aid in shielding downstream units from abrasive substances.

Primary and Anaerobic Treatment Units

A settler unit (5.0 m × 5.3 m × 2.69 m) that takes up 4.16 m^3 of concrete is used to accomplish primary treatment. This unit lowers the organic load entering biological treatment zones by allowing solids to settle and scum to rise.

The Anaerobic Baffled Reactor (ABR) and Anaerobic Filter is a more intricate construction, measuring 14.9 m × 7.6 m × 2.69 m and having a concrete volume of 9.16 m^3. Through plug-flow behavior, this device improves the breakdown of organics by introducing segmented anaerobic digestion. It is accompanied with baffle barriers that are positioned carefully to maximize contact duration. Ten repetitions of one set each run along the x-axis (14.9 m × 2.45 m × 0.2 m, 0.68 m^3) and the y-axis (totaling 3.88 m^3). The practical importance of internal hydraulic zoning is highlighted by these vertical walls, which direct flow and increase separation efficiency.

Constructed Wetlands and Natural Treatment Units

In artificial wetlands, which depend on subsurface flow and plant-microbe interactions, the biological treatment process continues. Included are artificial wetlands with a size of 8.0 m × 5.4 m × 0.075 m with a horizontal or vertical flow. These shallow beds, which are constructed with 75 mm P.C.C. and use 3.24 m^3 of concrete apiece, provide an inexpensive and energy-free method of treating secondary wastewater. Their moderate depths are ideal for sustaining planted vegetation, usually Phragmites karka species, and microbial biofilms.

Using 1.078 m^3 of concrete, a feeding tank (2.4 m × 3.8 m × 1.17 m) made of R.C.C. allows for batch loading or equalized distribution to the wetlands. By stabilizing the flow, this tank shields the biological system from shock loads.

Tertiary Treatment and Effluent Polishing

Polishing ponds and retaining structures improves the quality of the final effluent. Built with 100 mm P.C.C. and measuring 4.8 m in diameter and 1.15 m in depth, the polishing pond has a comparatively large concrete capacity of 18.25 m^3, which reflects its function as a pathogen elimination and final polishing unit through solar disinfection and natural aeration.

A retaining wall (8.0 m × 5.4 m × 3.624 m) next to the wetlands adds 7.31 m^3 of concrete volume. It offers structural stability to stop erosion or lateral movement, particularly in areas that are prone to slopes or heavy rainfall.

Sludge Management and Ancillary Structures

In order to manage solids without expensive mechanical equipment, sludge drying and storage are essential. Together, the Sludge Storage Shed (7.7 m × 3.25 m × 0.1 m) and Sludge Drying Bed (11.9 m × 4.0 m × 0.1 m), both built with 100 mm P.C.C., add 7.26 m^3 of concrete. These structures facilitate covered storage and passive drying, allowing biosolids to be handled, disposed of, or reused safely.

Pretreatment inert solids are handled via a 6.0 m × 1.5 m × 1.67 m grit disposal chamber with 15.03 m^3 of concrete. Its large size allows for sporadic mechanical or manual emptying.

In addition, 0.16 m^3 of concrete is used for 23 manholes, each measuring 0.3 m × 0.3 m × 0.075 m. Despite their modest size, these access ports are crucial for maintaining, cleaning, and inspecting subterranean components.

Concrete Usage and System Implications

In comparison to centralized systems (such as the 938 m^3 Guheshwori WWTP), the total concrete volume used across all units is 84.22 m^3, suggesting a lightweight and modular building method. The application of both P.C.C. and R.C.C. indicates material efficiency: P.C.C. is employed in areas with low load bearing (such as polishing ponds and wetlands), while R.C.C. is utilized in structural zones that require durability and strength (such as digesters, chambers, and reactors).

As is typical of nature-based, decentralized systems, the volumetric and material distribution exhibits an optimal balance between cost containment, treatment functionality, and structural integrity. The plant is a prime example of low-cost, low-energy sanitation infrastructure that is perfect for peri-urban or institutional locations, with a footprint that supports physical, biological, and natural treatment in a compact form.

S.No.	Name	WWTP Type	Total constructed area(sq.m.)	Total concrete Volume(m^3)	Per Unit Concrete Volume(m3)
1	Guheshwori Wastewater Treatment Plant	Centralised Activated Sludge	28600	980	29.18
2	Dhulikhel Hospital	Constructed Wetland	767.5	84	9.13
	Difference				**20.04**

Table 4.8: Comparison of Concrete Volume of the two Waste water treatment systems

This comparative analysis underscores the structural and material contrasts between conventional and sustainable wastewater treatment systems. A full-scale treatment plant exhibits a complex volumetric composition, with a wide range of unit sizes and depths tailored to different treatment stages, utilizing approximately 938 m^3 of concrete—highlighting the substantial material demands of traditional, high-capacity systems. In contrast, a more sustainable system achieves multi-stage treatment using only 84.22 m^3 of concrete, reflecting a material-efficient design that integrates reinforced cement concrete (R.C.C.) for structural strength and plain cement concrete (P.C.C.) for lightweight components. This compact configuration includes anaerobic baffled reactors, constructed wetlands, and polishing ponds, supporting passive operations and low-energy performance. Designed for small communities, healthcare facilities, or decentralized applications, it prioritizes reduced mechanical complexity, integrated sludge handling, and replicability. As the field shifts toward sustainable and cost-effective practices, future plant designs may benefit from adopting such optimization strategies, incorporating prefabricated elements, and combining mechanical and nature-based solutions for holistic wastewater management.

Phase	Activated Sludge Treatment System (ASTS)	Constructed Wetland System (CWS)
1. Pre-Construction	- High material demand (concrete, steel, machinery)	- Uses natural materials (gravel, sand, vegetation)
	- Energy-intensive construction process	- Lower energy and material input
	- Requires skilled labor for installation	- Simpler construction, minimal infrastructure

	- High carbon footprint from cement and steel	- Lower carbon footprint due to minimal construction
2. Operational	- High energy consumption (aeration, pumping, sludge treatment)	- Low energy consumption, relies on passive treatment
	- Requires skilled personnel for operation and maintenance	- Minimal maintenance, self-sustaining biological process
	- Uses chemicals for nutrient removal	- No chemical usage, natural nutrient removal
	- Generates large sludge volumes needing disposal	- Low sludge production, often naturally decomposed
3. Demolition	- High environmental impact due to concrete disposal	- Minimal environmental impact, natural materials decompose
	- Requires heavy machinery for decommissioning	- Easier decommissioning with lower disposal costs
	- Potential contamination from sludge residues and chemicals	- Land can be restored for ecological/agricultural use

Table 4.9 LCA of the two Wastewater treatment systems in their different phases

Pre-Construction Phase

A wastewater treatment plant's pre-construction stage entails site preparation, civil engineering, and mechanical infrastructure installation. The increased need for industrial materials like steel, reinforced concrete, and electro-mechanical equipment is what defines ASTS. In addition to being expensive, these materials have substantial carbon footprints, especially when it comes to the fabrication of steel and cement. Additionally, ASTS systems necessitate energy-intensive building processes, such as excavation, lifting, and the use of powerful gear, all of which add to their significant environmental effect.

CWS systems, on the other hand, mostly make use of locally accessible and natural resources like grass, sand, and gravel. By avoiding the need for large machinery and lowering emissions related to the use of fossil fuels during construction, these methods frequently rely on manual labor and simple civil works. Because of its ease of construction, CWS installations can be operated by local or semi-skilled workers,

encouraging community involvement and lowering implementation costs. Furthermore, the pre-construction carbon footprint is greatly decreased by the low embodied energy of materials like sand and plants, which makes CWS a desirable choice from the standpoint of environmental sustainability.

Operational Phase

The biggest difference between ASTS and CWS in terms of energy consumption, maintenance effort, and environmental impact is seen during the operational phase. Continuous energy input is necessary for ASTS, especially for nutrient removal, mixing, sludge pumping, and aeration. ASTS is frequently the most energy-intensive phase in the treatment lifecycle due to these operations' significant electrical demand. Vulnerability to power outages is another consequence of energy dependence, particularly in areas with erratic grids.

Additionally, for daily operation, process management, and mechanical maintenance, ASTS systems require technically skilled staff. Commonly utilized chemical inputs, like alum or ferric chloride for phosphorus removal, increase expenses and pose environmental hazards, particularly if handled improperly. Sludge management and disposal present a supplementary environmental problem because ASTS produces enormous amounts of surplus sludge that need to be mechanically dewatered, stabilized, and transported.

On the other hand, CWS systems use soil filtration, microbial degradation, plant absorption, and gravity to function according to natural treatment principles. These processes use almost no energy because they don't require pumps, blowers, or chemical additives. Because of its passive operation, CWS is ideal for rural and off-grid locations. Maintenance is mainly restricted to periodic vegetation trimming, sediment removal, and hydraulic flow monitoring because the treatment is essentially self-regulating.

Crucially, CWS produces relatively little sludge, and a large portion of it can stabilize or dissolve on-site, negating the need for intricate sludge handling. Additionally, CWS is less likely to cause secondary contamination because to its chemical-free nature.

Demolition and End-of-Life Phase

Significant demolition issues arise when an ASTS system reaches the end of its life cycle. High financial and environmental expenses result from the need for heavy machinery and expert labor to decommission reinforced concrete structures and remove mechanical equipment. The disposal of concrete waste adds to the construction and demolition (C&D) waste, which is frequently dumped in landfills and seldom repurposed. Furthermore, if improperly remedied, sludge residues and leftover chemicals may present a risk of contaminating groundwater and soil.

CWS systems, on the other hand, provide a low-impact demolition method. Many of the parts, including sand and gravel, can be recycled for landscaping or other civic works, and the use of inert or biodegradable materials makes disassembly simpler. Usually, the land can be rehabilitated for agricultural or ecological uses, increasing the site's long-term worth. Cleaner demolition techniques are facilitated by the lack of large machinery during decommissioning, which also lowers emissions from fossil fuels and dust production.

4.4. Energy Consumption

Energy usage is one of the most obvious distinctions between ASTS and CWs. Aeration and pumping are required to support biological therapy, which makes ASTS extremely energy-intensive. About 50–60% of an ASTS's total energy consumption is devoted to aeration, which provides oxygen to microorganisms that break down organic contaminants (Eddy, 2014). When fossil fuels are used as the energy source, this increased energy demand leads to higher carbon emissions and substantial operating expenses. Conversely, CWs require little additional energy to function, mostly depending on solar energy to support the filtering processes that are naturally made possible by microbes and plants. Consequently, CWs contribute to a decrease in greenhouse gas emissions and have a significantly smaller energy footprint (Vymazal, 2010). When it comes to energy consumption and environmental sustainability, CWs typically outperform ASTS in an LCA comparison.

4.4.1. Resource Consumption

Although they do it in different ways, both systems use resources. To remove phosphate and nitrogen, ASTS need chemical inputs like coagulants, flocculants, and fertilizers, which increases their environmental load. The physical infrastructure's development also makes extensive use of industrial commodities like steel and concrete, whose extraction and processing have a substantial negative influence on the environment (Metcalf & Eddy, 2014). On the other hand, CWs reduce the need for industrial resources by using natural resources like plants, gravel, and soil. Additionally, CWs reduce the requirement for external chemical treatment by allowing for nutrient recovery as plants absorb phosphate and nitrogen (Vymazal, 2010). Compared to ASTS, CWs are more resource-efficient since they use harvested plant biomass for composting or the generation of bioenergy, which also helps with resource recycling.

4.4.2. Land Use and Ecosystem Services

Another crucial element in the LCA comparison between ASTS and CWs is land usage. In comparison to CWs, ASTS require comparatively smaller land areas, which might be a big benefit in places that are heavily populated or urbanized. But unlike ASTS, CWs provide a variety of ecosystem services. CWs can promote biodiversity, offer wildlife habitats, and improve the landscape's aesthetic value (Tchobanoglous et al., 2014). On the other hand, aside from their treatment purposes, ASTS are usually confined systems with little ecological value. Even though CWs need more acreage, they improve the quality of nearby ecosystems and support ecological balance, which benefits the local environment.

4.4.3. Waste Sludge and Disposal

Waste is produced by products in both systems that need to be managed. A surplus of sludge produced by ASTS needs to be treated and disposed of, frequently via dewatering or digesting. The environmental burden is increased by the disposal of this sludge, especially in landfills or by incineration (Metcalf & Eddy, 2014). Conversely, CWs generate significantly less sludge, which is mostly made up of leftover organic material and plant biomass. The amount of waste produced can be decreased by periodically harvesting this biomass. More sustainable management alternatives are

provided by the composting, bioenergy production, and environmentally safe disposal of the gathered plant waste (Vymazal, 2010).

4.5. Overall Environmental Impact

Given their lower energy consumption, lower greenhouse gas emissions, minimum resource use, and contribution to ecosystem services, CWs typically outperform ASTS in terms of environmental sustainability in an LCA framework. However, a number of variables, including the amount of land available locally, the climate, and the size of wastewater treatment needed, affect any system's feasibility. For locations with high treatment capacity requirements and limited space, ASTS is still a more practical choice. However, where land is accessible and environmental conservation is prioritized, CWs provide a more sustainable option.

4.6. Operational Challenges

The operation of the Central Wastewater Treatment plant at Guheshwori faces several challenges that affect its efficiency and long-term sustainability. One of the primary issues is the high fluctuation in the quantity and quality of raw sewage, which varies due to seasonal changes, population growth, and irregular water usage patterns. This inconsistency makes it challenging to maintain stable treatment processes and necessitates ongoing monitoring and adjustments. Additionally, the presence of unexpected debris in municipal wastewater, such as plastics, solid waste, and non-biodegradable materials, creates blockages in pipelines and damages treatment equipment, increasing maintenance costs and downtime.

Another major challenge is power fluctuation, which disrupts the operation of pumps, aeration systems, and other essential machinery. Given the energy-intensive nature of wastewater treatment plants, frequent power instability can lead to inefficient processing and potential system failures. Moreover, the project struggles with non-readily available spare parts, making routine maintenance and emergency repairs difficult. This issue is further compounded by difficulties in importing materials and spare parts, as bureaucratic procedures, import regulations, and transportation delays hinder timely replacements, resulting in prolonged service interruptions.

Financial constraints also pose a significant challenge. Budget limitations hinder the ability to implement necessary upgrades, hire skilled personnel, and ensure the facility's proper functioning. Insufficient funding leads to delayed maintenance, reduced treatment efficiency, and, ultimately, environmental and public health risks. Addressing these operational challenges requires improved planning, investment in reliable infrastructure, the establishment of local supply chains for spare parts, and enhanced financial management to ensure the long-term sustainability of the wastewater management system.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

This study comprehensively assessed the energy conservation potential and sustainability of decentralized wastewater treatment systems—specifically Constructed Wetlands (CWs)—in comparison to traditional Activated Sludge Treatment Systems (ASTS) within the Kathmandu Valley. In doing so, it addressed a critical infrastructure and environmental need in the context of Nepal's ongoing urbanization and energy crisis. Through rigorous field data analysis and Life Cycle Assessment (LCA), the study provided insights into the operational efficiency, environmental impact, and long-term viability of each system.

One of the key findings of this research is the stark contrast in energy consumption between the two systems. The ASTS at the Guheshwori Wastewater Treatment Plant was found to consume approximately 3.2 kWh/m³, largely due to energy-intensive aeration and pumping operations. This energy demand not only imposes high operational costs but also intensifies pressure on Nepal's already unstable and expensive energy supply, particularly in urban settings where demand is high year-round. In contrast, the CW at Dhulikhel Hospital demonstrated exceptional energy efficiency, consuming between 0.01 to 0.02 kWh/m³. This represents a greater than 90% reduction in energy use compared to ASTS, achieved through reliance on passive, nature-based processes for wastewater purification.

However, energy efficiency alone is not a sufficient determinant of system suitability. The study further revealed that while CWs offer significant environmental and economic advantages—such as low operational costs, reduced greenhouse gas emissions, and minimal material requirements—their implementation is challenged by the need for larger land areas. This is a critical limitation in densely populated or land-scarce urban environments like central Kathmandu. The spatial requirement of CWs, particularly for subsurface and free-surface flow systems, makes them more appropriate for peri-urban or rural applications.

Environmental performance metrics derived from the LCA provided additional depth to this comparison. ASTS was found to have a higher embodied carbon footprint due to its reliance on concrete-heavy infrastructure such as sedimentation tanks, aeration basins, and sludge digesters. Specifically, the Guheshwori WWTP utilized approximately 980 m^3 of concrete across its 28,600 m^2 footprint, resulting in significant lifecycle emissions. In contrast, the Dhulikhel CW required only 84 m^3 of concrete for a 767.5 m^2 area, underscoring its materially lighter and more sustainable footprint.

Further, the study's data analysis demonstrated the limitations of energy recovery in centralized systems. Although Guheshwori WWTP was originally designed to recover energy through biogas generation, actual figures revealed that only 4% of its total energy demand was met via internal biogas production. Seasonal performance variations and operational inefficiencies such as feedstock instability, pH imbalance, and temperature fluctuations reduced microbial digestion efficacy. Meanwhile, gas leaks, poor maintenance, and insufficient anaerobic conditions further hindered biogas recovery.

Despite these limitations, ASTS retains value in specific contexts. Its suitability for treating high volumes of wastewater and ability to meet strict effluent standards make it indispensable in urban areas where treatment capacity and regulatory compliance are priorities. The system's ability to adapt to variable influent quality and quantity is also a key advantage in the context of fluctuating sewage profiles driven by seasonal and population changes.

The research also highlighted operational challenges at the Guheshwori WWTP that affect system performance. These include blockages caused by solid waste, power fluctuations affecting pump operations, and a lack of locally available spare parts leading to maintenance delays. Financial constraints further exacerbate these issues by limiting system upgrades and staff training. Conversely, the CW at Dhulikhel demonstrated resilience against such disruptions due to its decentralized, low-maintenance nature, minimal mechanical parts, and passive treatment mechanism.

Another critical contribution of this study lies in its demonstration of the broader sustainability benefits of CWs. These systems not only reduce energy and material use

but also support ecosystem services such as biodiversity conservation, carbon sequestration, and landscape rehabilitation. In addition, CWs offer the opportunity for local resource recovery. The biomass generated can be composted or repurposed for bioenergy, while sludge cake can be safely tested and potentially marketed as fertilizer, introducing avenues for cost recovery and circular economy integration.

Finally, this study fills an important knowledge gap by providing empirical evidence on the comparative energy performance of decentralized wastewater systems in a developing country context. It advocates for a nuanced approach to wastewater infrastructure planning—one that considers energy efficiency, environmental impact, operational resilience, and socio-economic feasibility. The findings underscore the need for hybrid and decentralized treatment strategies, especially in regions where land, funding, and energy resources are constrained.

In conclusion, while centralized ASTS are indispensable in high-demand, space-constrained urban contexts, CWs emerge as a highly sustainable and low-energy alternative for decentralized applications. Their strategic adoption, supported by a robust policy framework, community engagement, and technical innovation, can transform wastewater management in Nepal and similarly challenged regions worldwide. This shift is essential not only for mitigating environmental degradation but also for achieving the broader goals of energy sustainability, climate action, and public health improvement.

5.2. Recommendations

The central system of wastewater treatment utilizes significant energy but also has the potential to generate renewable energy from by-products, such as biogas. However, the biogas is generally not being generated to its full potential, and it is very hard to maintain the technical environment for its full generation potential. According to the initial design plan, biogas generation was intended to cover a significant portion of the total energy consumption; however, due to various reasons, the actual generation has been limited to only 4% of the total energy consumption. This can be attributed to low organic content, the presence of toxi c compounds, or unstable feedstock. Inadequate anaerobic conditions, such as oxygen intrusion or improper pH balance, inhibit

microbial activity. Temperature issues, especially low or fluctuating temperatures, slow down digestion. An imbalance between hydrolytic, acidogenic, and methanogenic bacteria can lead to acid accumulation, thereby reducing methane production. Poor mixing, short hydraulic retention time, scum formation, and sludge buildup also hinder efficiency. Gas leaks, inefficient collection systems, and an improper carbon-to-nitrogen (C/N) ratio further reduce output. Additionally, inhibitory substances such as antibiotics, high salinity, and operational issues, including a lack of skilled personnel or poor maintenance, can significantly affect biogas yield. Proper system design, monitoring, and maintenance are essential to optimize biogas production (Afamia I. Kouzi, 2020).

Apart from this, the dry sludge cake formed as a by-product can also be used as manure or compost at various agricultural sites and may even be exported to different fields. So, proper testing of this manure can be done for resell utilization to further support the financial aspect of operating the wastewater treatment plant.

Figure 5.1: Aeration using tubes with holes to increase the Dissolved Oxygen in the Treated Water

In the case of the Constructed wetland system at Dhulikhel, several methods have been applied to raise Dissolved Oxygen (DO) concentration in CW: hybrid CW (the mix of VFCW and HFCW), step feeding of effluent, nozzle approach, batch operation, etc. Using tubes with holes is one of the least expensive ways of aerating CW. These tubes link the inner beds of CW with the surrounding environment, therefore facilitating nitrite (A. Shukla, 31 August 2020). Therefore, intermittent aeration of 4–6 h a day not only lowers the aeration cost but also boosts the treatment efficiency of CW in terms of nitrogen and organic elimination.

Along with this, a significant hurdle in the proper functioning of a CW is clogging. Clogging is the predominant problem encountered in constructed wetlands if appropriate medium and design are not utilized. Clogging creates dead zones in a constructed wetland, resulting in a significant volume of water flowing over the filter bed and thereby diminishing the overall effectiveness of the system. (A. Shukla, August 31, 2020) Clogging mostly results from porosity and duration; it diminishes over time due to the formation of reeds and biofilm. Hence, to tackle this, prioritizing Horizontal Flow Constructed wetlands over Vertical Flow Constructed wetlands needs to be done, as the latter tends to clog up more frequently due to the vertical nature of its system.

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ANNEX

Figure 0.1: Aeration Tanks

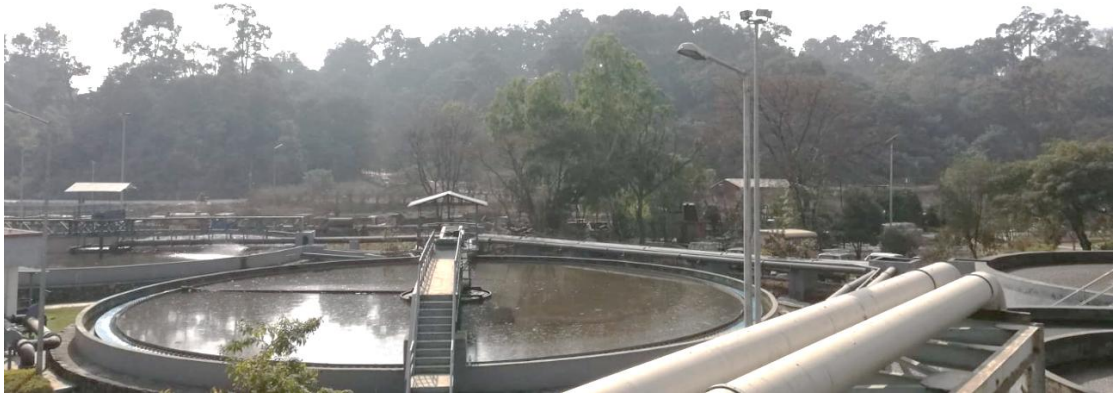

Figure 0.2: Secondary Sedimentation tank

Figure 0.3: Digester at Guheshwori WWTP

Figure 0.4: Screen Chamber and Cyclone at CW at Dhulikhel

Figure 0.5: Anaerobic Baffle Reactor and Anaerobic Filter at Dhulikhel

Figure 0.6: Horizontal Flow Constructed Wetland

Figure 0.7: Vertical Flow Constructed Wetland

Figure 0.8: Sludge drying bed

Figure 0.9 Hydraulic Profile of Dhulikhel CW (ENPHO, 2010)

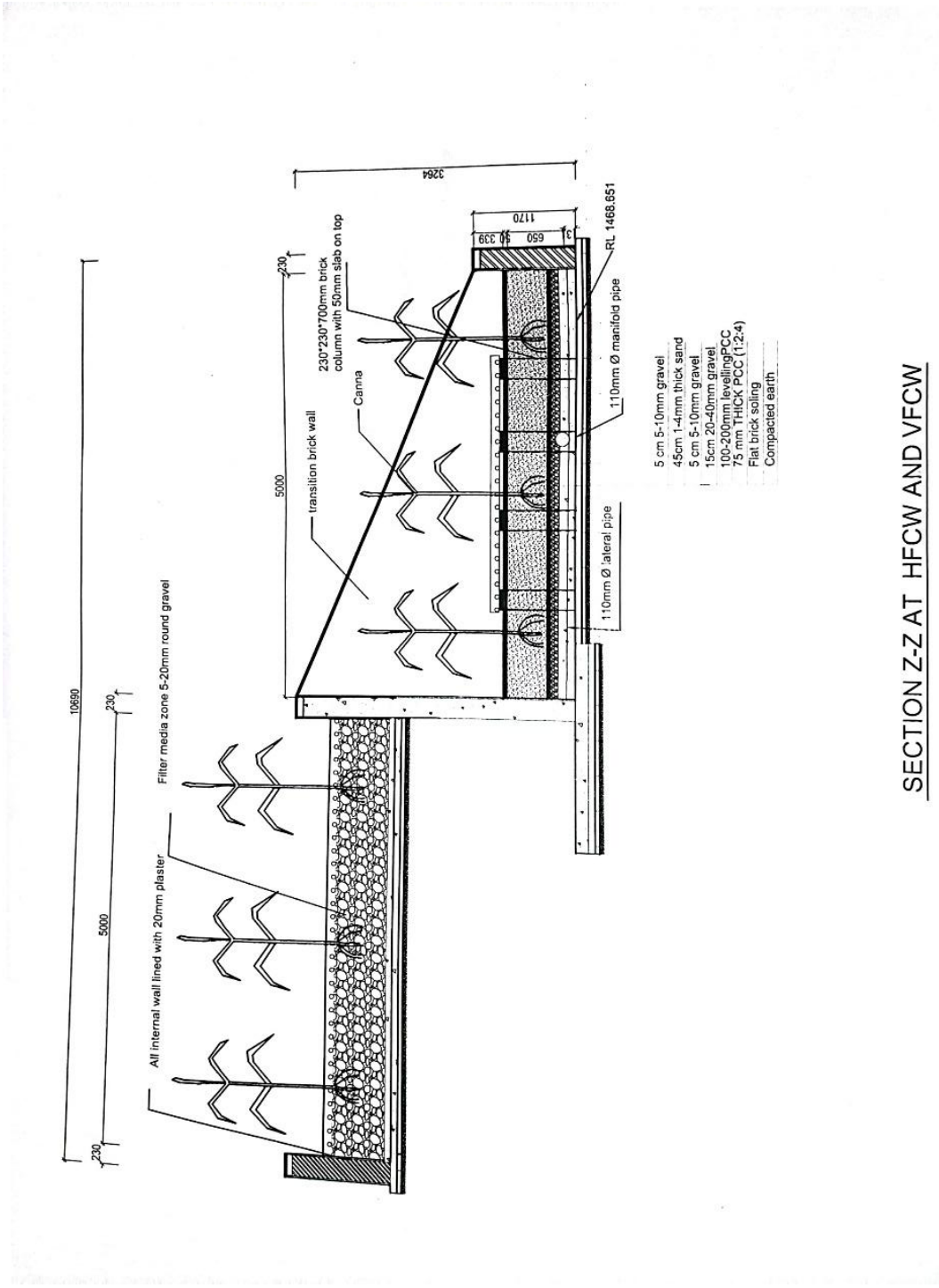

Figure 0.10 Section of constructed wetland at Dhulikhel (ENPHO, 2010)

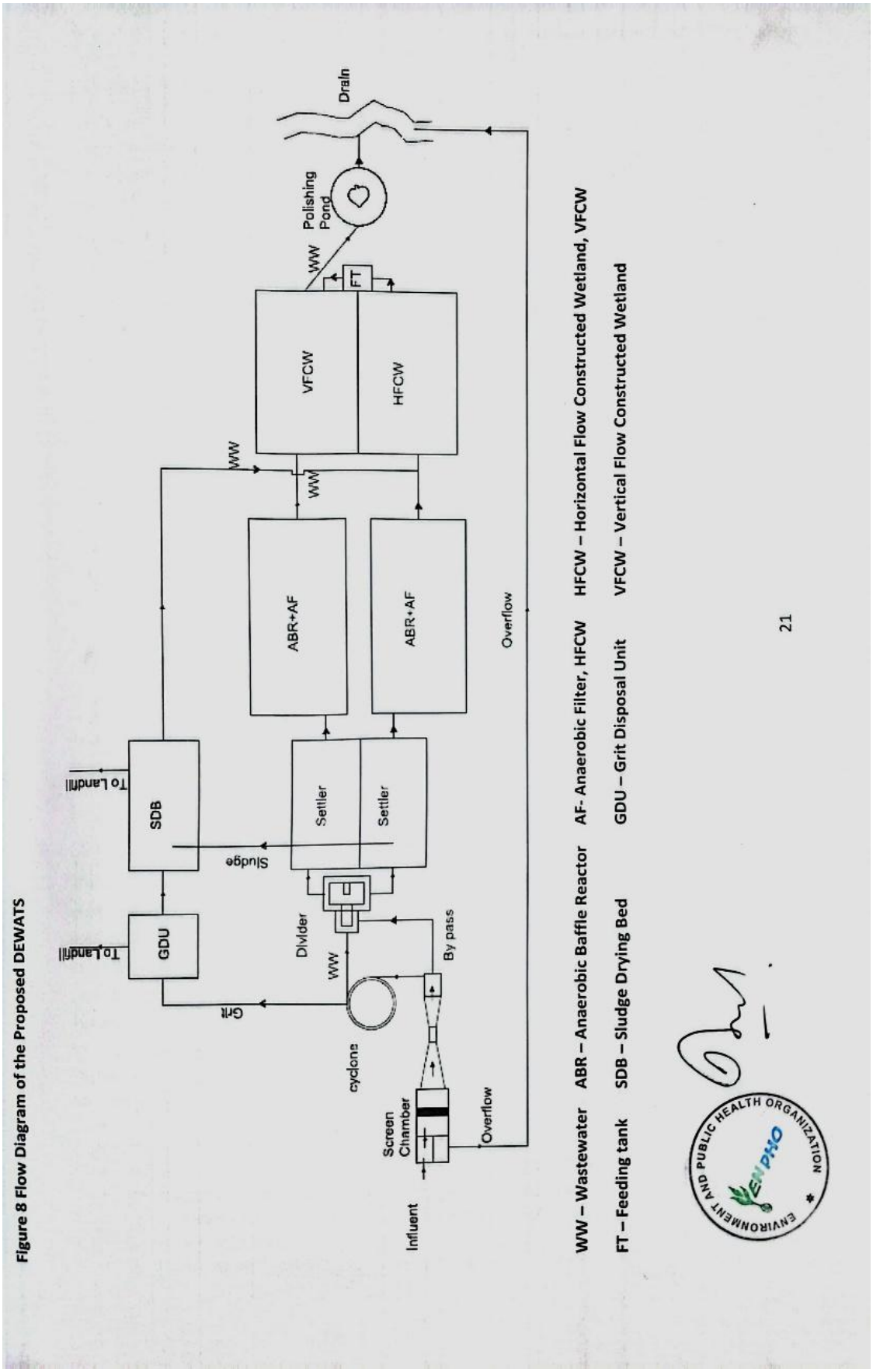

Figure 0.11 Flow Diagram of of the proposed DEWATs (ENPHO, 2010)

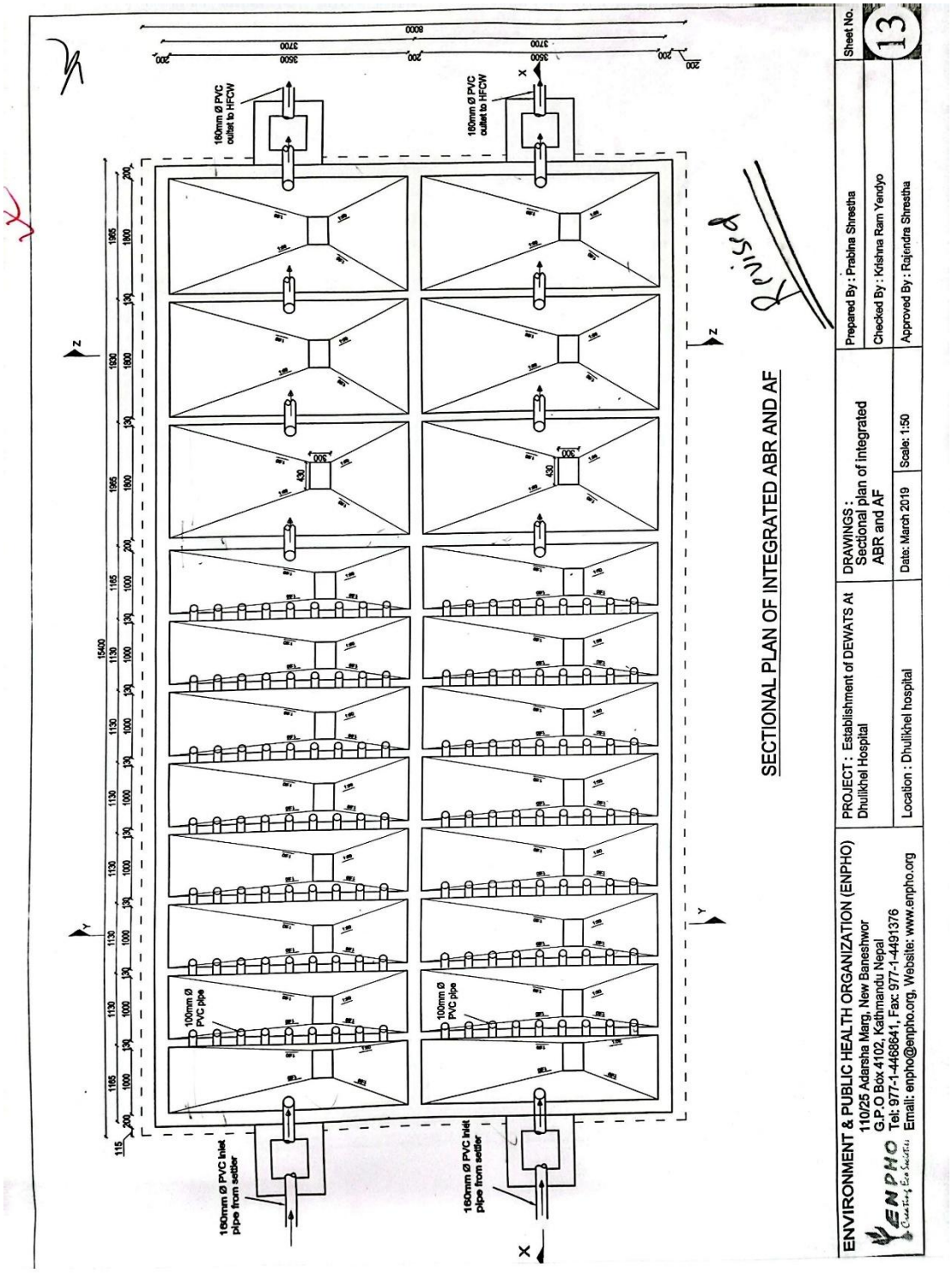

Figure 0.12 Figure 36 Plan of ABR, (Source: ENPHO, 2010)

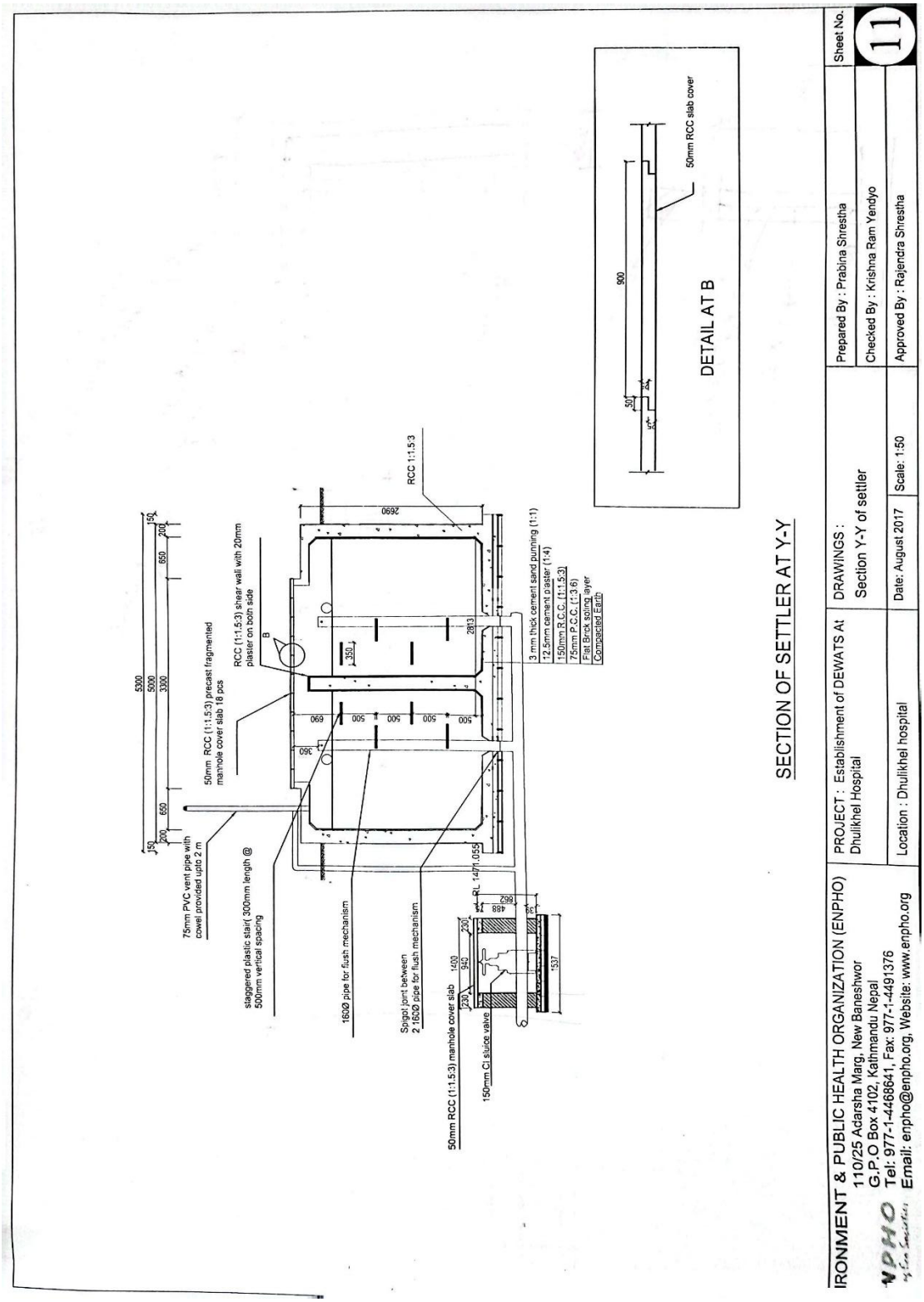

Figure 0.13 Section of Settler

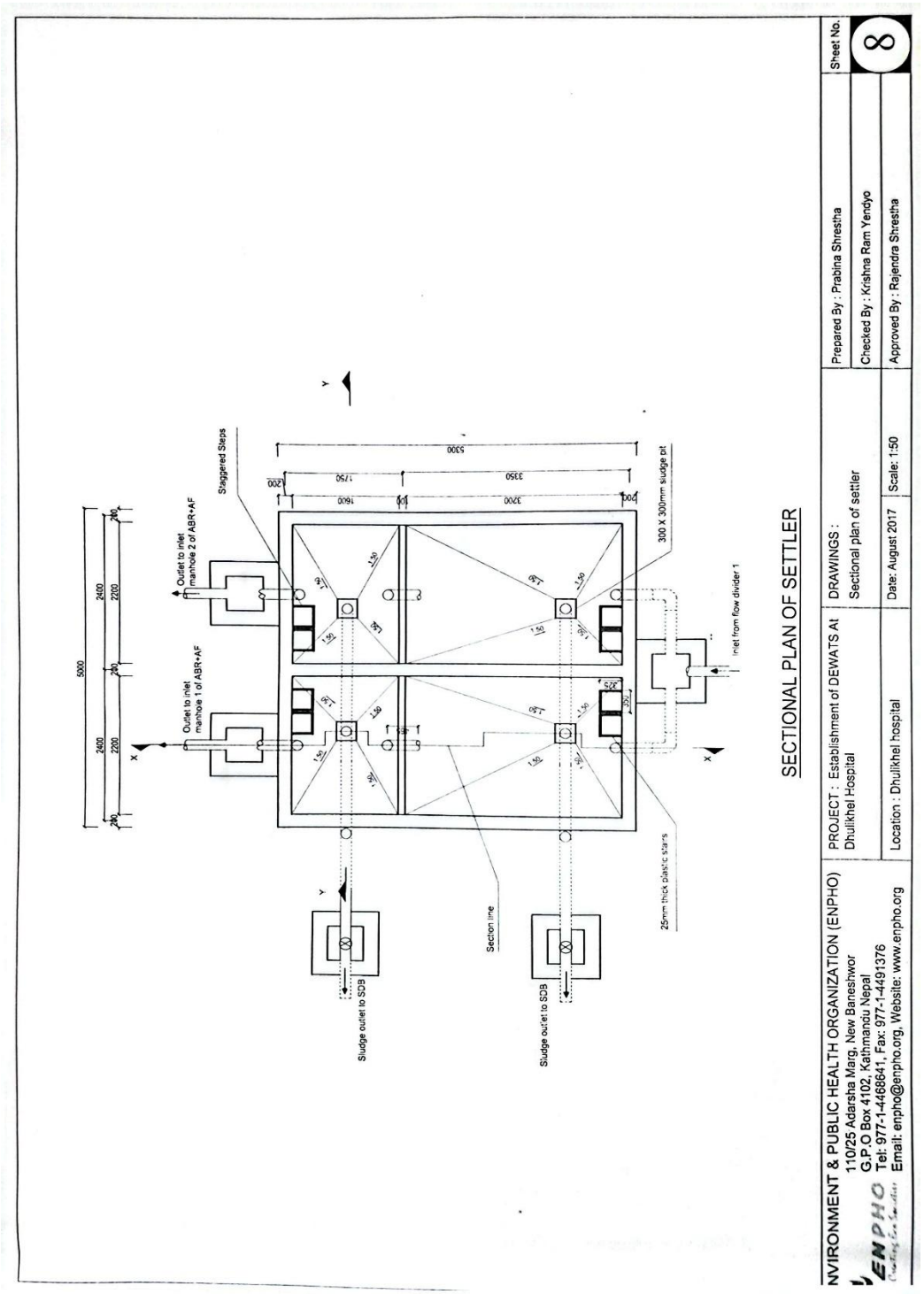

Figure 0.14 Plan of Settler, (Source: ENPHO, 2010)

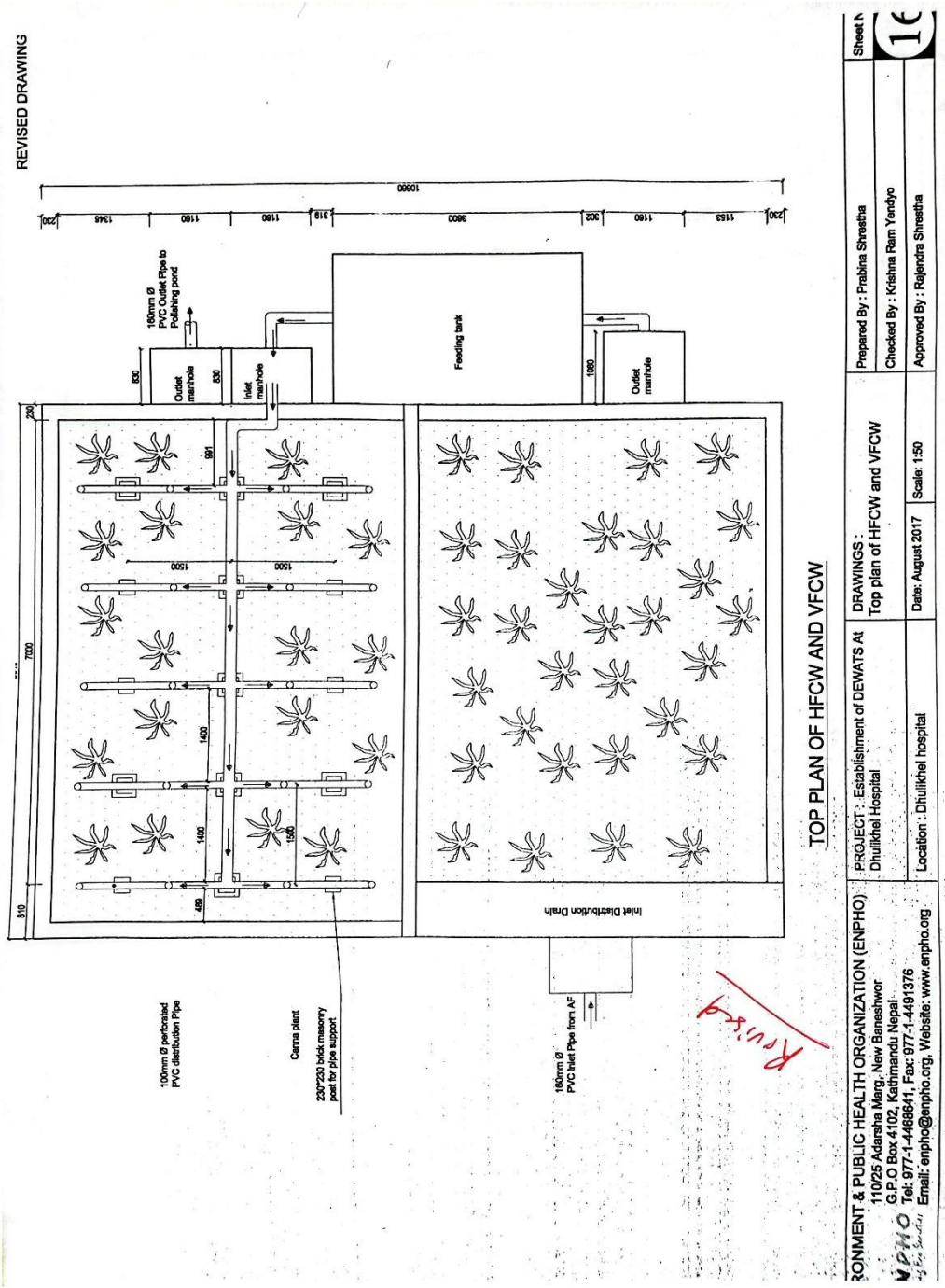

Figure 0.15 Plan of VFCW and HFCW, (Source: ENPHO, 2010)

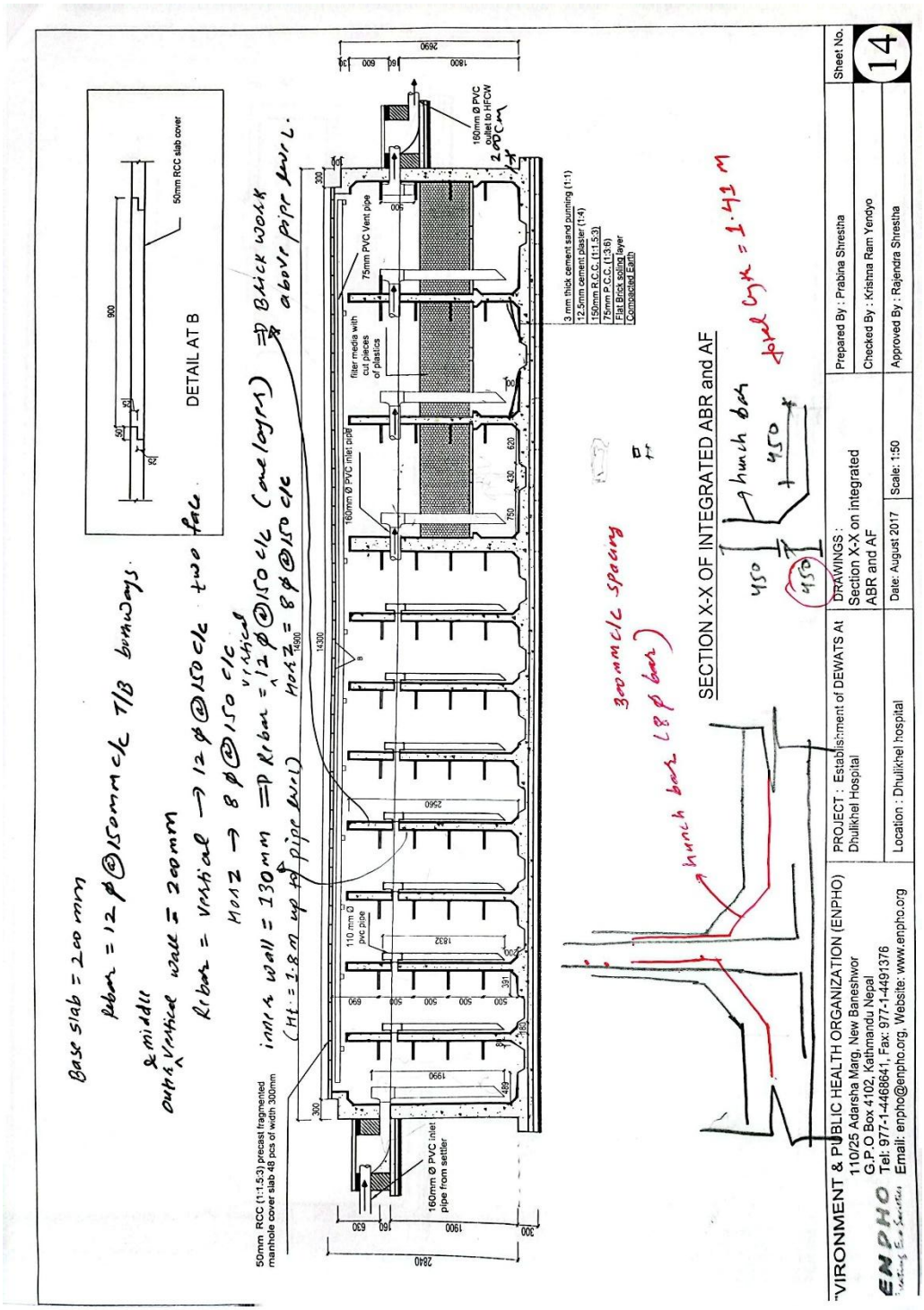

Figure 0.16 Section of ABR and AF, (Source: ENPHO, 2010)

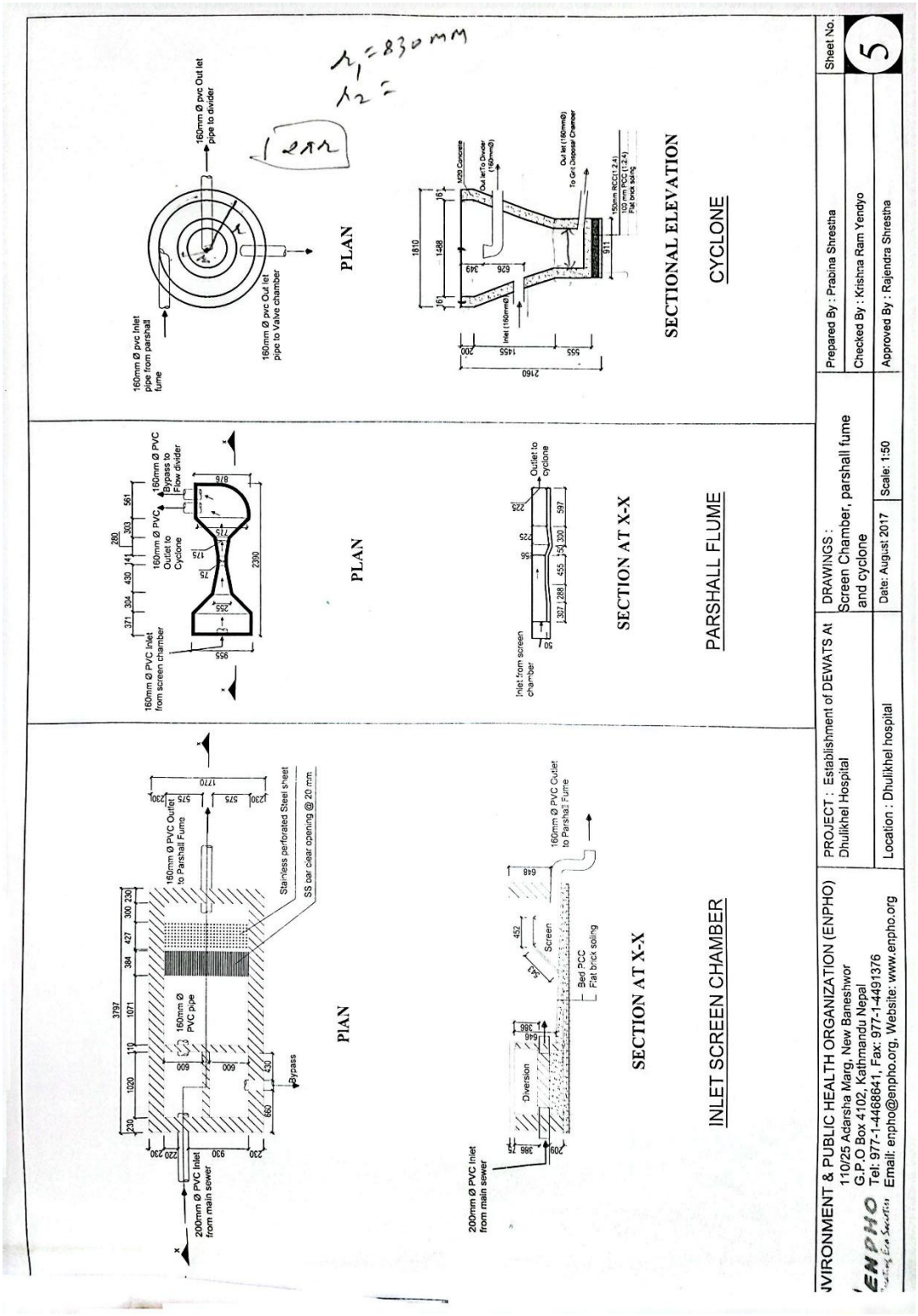

Figure 0.17 Section of Inlet Screen Chamber, Parshall Flume, and Cyclone, (Source: ENPHO, 2010)

ENERGY CONSERVATION POTENTIAL OF WASTEWATER TREATMENT SYSTEMS IN KATHMANDU VALLEY: A COMPARISON OF ACTIVATED SLUDGE SYSTEM AND CONSTRUCTED WETLAND SYSTEM

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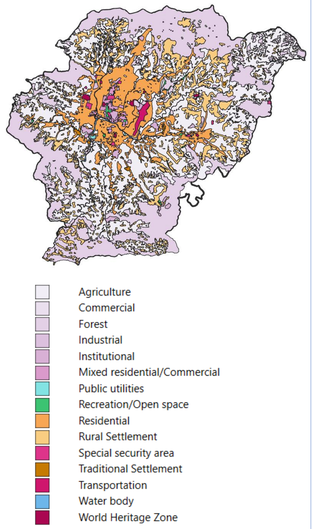
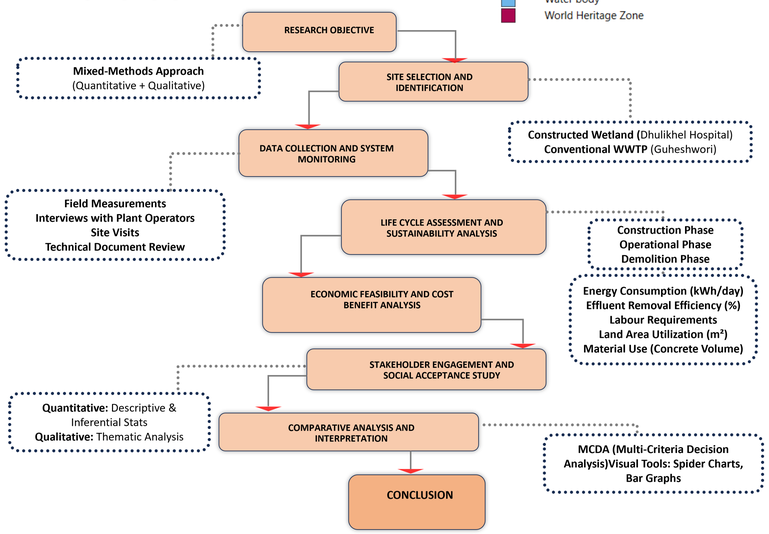
INTRODUCTION

Wastewater treatment is a highly energy-intensive process, particularly in centralized systems that rely heavily on aeration and pumping. In regions like Kathmandu Valley, where energy is both costly and unreliable, such systems pose significant operational and financial challenges. As Nepal seeks sustainable solutions, decentralized wastewater treatment systems (DEWATS) offer a promising alternative. This study compares the energy consumption of two contrasting DEWATS approaches: the activated sludge system, which depends on energy-intensive aeration, and constructed wetlands, which utilize natural processes with minimal energy input. By evaluating their energy performance, the study aims to support energy-efficient and cost-effective wastewater management strategies in Nepal.



METHODOLOGY



IMPORTANCE OF THE RESEARCH

- Nepal faces energy shortages that challenge the operation of energy-intensive wastewater treatment plants (WWTPs).
- Constructed wetlands (CWs) offer a low-energy alternative for wastewater treatment,including carbon sequestration, biodiversity, and flood contro, also, are re more cost-effective due to lower construction and maintenance costs.
- This study evaluates the energy-saving potential of CWs to support sustainable wastewater management in energy-limited regions.

RESEARCH GAP

- Existing research on constructed wetlands (CWs) largely emphasizes treatment efficiency and environmental benefits.
- There is limited focus on the energy conservation potential of CWs, especially in developing countries like Nepal.

OBJECTIVES

- To compare the energy consumption and treatment efficiency of a constructed wetland system and a conventional activated sludge wastewater treatment plant (WWTP) in Kathmandu Valley.

- To evaluate the operational costs, environmental impacts, and feasibility of constructed wetlands as an alternative wastewater treatment solution.

WASTEWATER AND ENERGY CONSUMPTION SCENARIO

- The Kathmandu Valley—comprising Kathmandu, Bhaktapur, and Lalitpur—has undergone rapid urbanization and population growth.
- This growth has strained wastewater infrastructure, causing environmental and public health concerns.
- Conventional treatment systems add to the problem due to their high energy demands.
- In 2011, the Valley consumed 8% (30 PJ) of Nepal's total energy, with the residential sector using 41% and being the main source of wastewater.

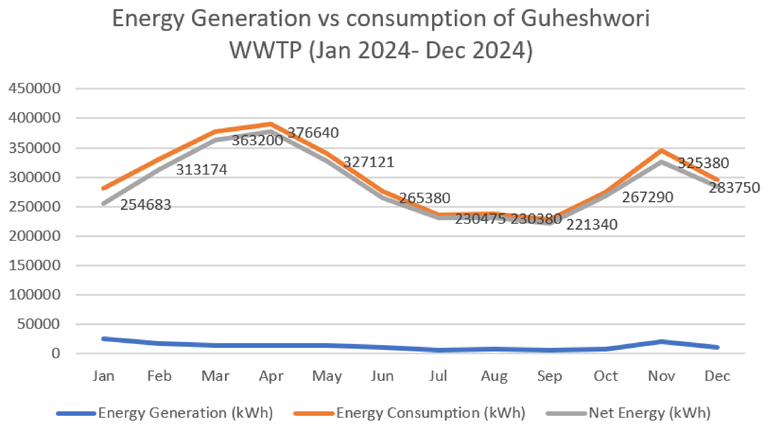
ANALYSIS AND FINDINGS

Parameter	Guheshwori WWTP	Dhulikhel Hospital CW	Difference
WWTP Type	Centralized Activated Sludge	Decentralized Constructed Wetland	
Total Constructed Area (sq.m.)	28,600	767.5	27,832.50
Total Construction Cost (Nrs)	2,042,926,328	2,500,000	2,040,426,328
Total Treatment Capacity (cu.m./day)	32,400	65	32,335
Treatment Efficiency – BOD (%)	98.50%	90%	8.50%
Treatment Efficiency – COD (%)	93.80%	48%	45.80%
Per Unit Treatment Area (cu.m/sq.m.)	1.1329	0.0847	1.0482
Per Unit Treatment Cost (Nrs/cu.m.)	63,053.28	38,461.54	24,591.74
Average Energy Consumed per Day (kWh/day)	9,896.20	0	9,896.20
Average Energy Generated per Day (kWh/day)	420	0	420
Net Energy Consumed per Day (kWh/day)	9,476.20	0	9,476.20
Per Unit Energy Consumed (kWh/cu.m.)	0.31	0	0.31

OVERALL COMPARISON

Criteria	Activated Sludge System (Guheshwori)	Constructed Wetland System (Dhulikhel Hospital)
Energy Consumption	Approximately 3.2 kWh/m³	0.01 - 0.02 kWh/m³
Energy Reduction	High energy demand, largely due to aeration	80-90% less energy use compared to AS
Treatment Efficiency	High treatment efficiency (specific values TBD)	Comparable treatment efficiency using natural processes
Land Area Requirement	Smaller footprint, suitable for urban areas	Requires larger land areas, challenging in dense urban settings
Operational Costs	Higher operational and maintenance costs	Lower operational costs due to minimal mechanical requirements
Environmental Impact	Higher greenhouse gas emissions from energy use	Positive environmental benefits: carbon sequestration and biodiversity
Maintenance Needs	Requires regular monitoring and mechanical upkeep	Minimal maintenance due to natural processes
Implementation Challenges	Conventional system setup with established protocols	Requires community involvement and adaptation to local environmental conditions
Long-Term Viability	Risk of mechanical failure due to reliance on technology	Higher longevity due to fewer mechanical parts
Suitability for Urban Context	More suitable for urban settings	Better suited for peri-urban or rural areas due to space requirements

The Activated Sludge System (AS) at Guheshwori consumes approximately 3.2 kWh/m³ and effectively treats wastewater with over 98% BOD and 93% COD removal. In comparison, the Constructed Wetland (CW) at Dhulikhel Hospital uses only 0.01–0.02 kWh/m³, achieving 90% BOD and 48% COD removal, making it a more energy-efficient option despite requiring larger land areas. Thus, CWs offer significant energy savings of 80-90% compared to AS, highlighting their potential in energy-constrained contexts.



DISCUSSION AND CONCLUSION

1. Constructed Wetlands provide a highly energy-efficient wastewater treatment option, consuming 90% less energy than AS.
2. CW systems emphasize the importance of sustainable and cost-effective solutions amidst energy constraints.
3. The study found that while CWs are environmentally advantageous, their land area requirements make them less suitable for central urban areas.
4. The operational simplicity of CW systems leads to reduced maintenance needs and costs.
5. Energy efficiency alone does not determine system effectiveness; environmental, social, and economic factors must also be considered.
6. Hybrid systems may present innovative solutions to maximize energy efficiency and treatment effectiveness.
7. Enhanced training and education for local stakeholders will improve the management of decentralized systems.
8. Long-term monitoring systems are necessary for evaluating the real-world performance and sustainability of CWs.
9. Future projects should incorporate adaptive management strategies to address site-specific challenges.
10. Promoting CW systems can significantly contribute to the global climate change mitigation efforts.

RECOMMENDATIONS

1. Advocate for the integration of CW systems in urban planning regulations to facilitate sustainable wastewater management.
2. Encourage financial incentives for adopting low-energy treatment systems among local communities.
3. Promote stakeholder workshops to discuss the operational advantages and ecological benefits of CW systems.
4. Increase investment in research focused on optimizing the design and efficiency of decentralized systems.
5. Implement pilot projects to demonstrate the effectiveness of CWs in urban and peri-urban settings.
6. Enhance policy frameworks to support the transition from centralized to decentralized treatment systems.
7. Develop guidelines for designing CWs in diverse environmental contexts.
8. Foster partnerships between governmental agencies, NGOs, and local communities for effective implementation.
9. Advocate for public awareness campaigns to highlight the benefits of constructed wetlands.
10. Explore funding options from international organizations to assist in developing energy-efficient wastewater treatment solutions.

Presented at:
16th IOE Graduate Conference
April 18 - 20, 2025
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Date: April 21, 2025

To Whom It May Concern:

This is to certify that the paper titled **"Energy Conservation Potential of Decentralised Wastewater Treatment Systems in Kathmandu Valley: Comparison of Activated Sludge Wastewater System and Constructed Wetlands"** (Submission# **514**) submitted by **Benison Pradhan** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 16th IOE Graduate Conference held during April 18 - 20, 2025. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.

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