Assessment of Constructed Wetland System in Nepal

by

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ABSTRACT

Environment and Public Health Organization (ENPHO) introduced the use of constructed wetlands for wastewater treatment in Nepal as an alternative to conventional wastewater treatment technologies. However, there is currently no accurate assessment of the hydraulic characteristics of the wetlands.

By conducting NaBr tracer tests, the hydraulic characteristics of two of the existing constructed wetland systems in Nepal, Dhulikhel Hospital and Sushma Koirala Memorial (SKM) Plastic and Reconstructive Surgery Hospital, were determined. The actual detention time, residence time distribution function, RTD (t), variance, σ^2 of the RTD (t), and the reaction rate coefficient, k_r linked to the desired removal efficiencies with the actual hydraulic conditions of the wetland systems were found.

Thesis Supervisor: Heidi M. Nepf

Title: Associate Professor, Department of Civil and Environmental Engineering

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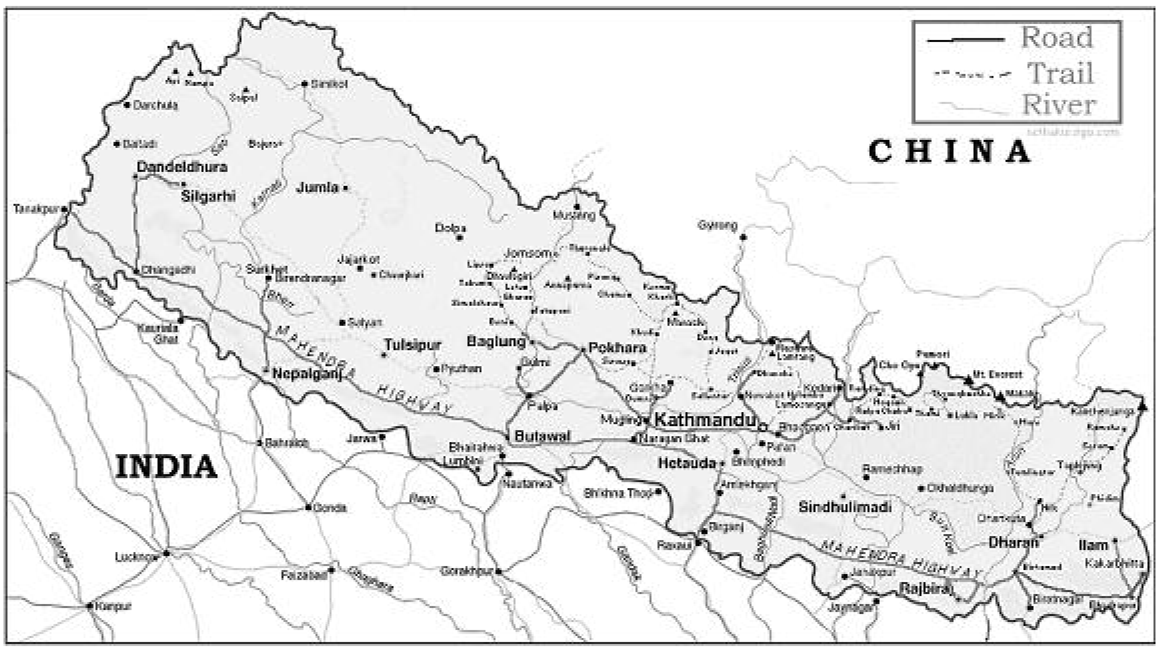
Chapter 1 INTRODUCTION

1.1 Overview of Nepal

Nepal is a mountainous country surrounded by two giant neighbors the People's Republic of China to the north and the Republic of India to the south (Figure 1.1). Nepal has a total area of 147,181-kilometer square, which is divided into five geographic regions from the plain (100 meters above sea level) to the High Himalayas (Mt. Everest –8848 meters). Only 11% of the total land area is 305 meters below sea level and 40% of the land area lies between 300 to 1500 meters.



<u>Figure 1.1</u>:Map of Nepal

In 2002, the estimated population of Nepal was 25.3 million with a population growth rate of 2.32%. The average population density at the time was 125 persons per square km (329 per square mi) with only 12 percent of the population living in urban areas in 2000 (Encarta, 2001). The life expectancy for males and females is 59 years and 58 years respectively.

Water is the major natural resource of Nepal. More than 6,000 rivers with considerable flow variation drain the country. The annual runoff of the country is estimated at 222 billion m^3/sec. Although Nepal is rich in water resources, only 43% of the rural population and 90 percent of urban population are served with piped water supply (Shrestha, 2001). These statistics, on access to a piped water supply, are suspected and the actual number of people with safe water supply in Nepal is probably considerably less. An Asian Development Bank (ADB) report, soon to be revised, will present more accurate data on Nepal's access to safe drinking water and sanitation

1.2 Project Motivation

The MIT Nepal Water Project is an ongoing collaboration with The Environmental Public Health Organization, The International Buddhist Society (IBS), the Nepal Red Cross, the Rural Water Supply and Sanitation Support Program (RWSSSP) and other local organizations in Nepal. All organizations seek to improve the drinking water quality in the Kingdom of Nepal. The MIT Nepal Water Project was established within the Masters of Engineering Program in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology in 1999 after the founder, Susan Murcott, spoke at the 2nd International Women and Water Conference held in Kathmandu, Nepal in 1998, and was asked to join the effort to solve drinking water contamination problems that plague the country.

January 2003 marks the fourth straight year that a group of MIT students and staff have traveled to Nepal to study pressing water quality concerns. In the past, student projects have focused on improvements in drinking water quality, concentrating on household treatment systems such as chlorination or filters for the removal of arsenic and biological pathogens. While these projects are ongoing, three students, Hillary Green, Saik-Choon Poh and Amanda Richards, from the class of 2003 were elected to form a group with a new water quality focus: wastewater treatment and sanitation.

When it comes to basic sanitation, Nepal lags behind all the other nations of South Asia as well as most other developing countries. It has been estimated that only 27% of the population of Nepal has access to sanitation (Human Development Report, 2003), while the average is 44% among developing countries worldwide (UNICEF, 2003).

Nepal's per capita gross domestic product (GDP) is $240 US, and only 0.5% of this (annually $1.20 US per capita) is spent on drinking water and sanitation (Human Development Report, 2003).

In urban areas like the cities within Kathmandu Valley (population 1.3 million) and especially Kathmandu City (population 500,000), the lack of basic sanitation has been devastating to the quality of local streams and rivers, namely the Bagmati and Bishnumati Rivers. Methods of sanitation absent from Kathmandu include adequate wastewater collection and treatment, toilet facilities and solid waste collection and disposal. Agricultural runoff and industrial discharge without pretreatment contribute to the detrimental effects on water quality, not to mention public and environmental health.

Chapter 2 WASTEWATER TREATMENT IN NEPAL

2.1 Introduction

Water pollution is one of the most significant environmental problems in Nepal. The problem is acute in the urban areas due to the discharge of untreated wastewater from households and toxic industrial waste into the river-system, turning them into open sewers (Figure 2.1). Even though most childhood deaths in Nepal are due to water-borne diseases, wastewater treatment is seldom thought of as a solution to reduce these fatalities, as the concept of wastewater treatment or recycling is often regarded as an expensive and unaffordable technology.

Figure 2.1: Bagmati River

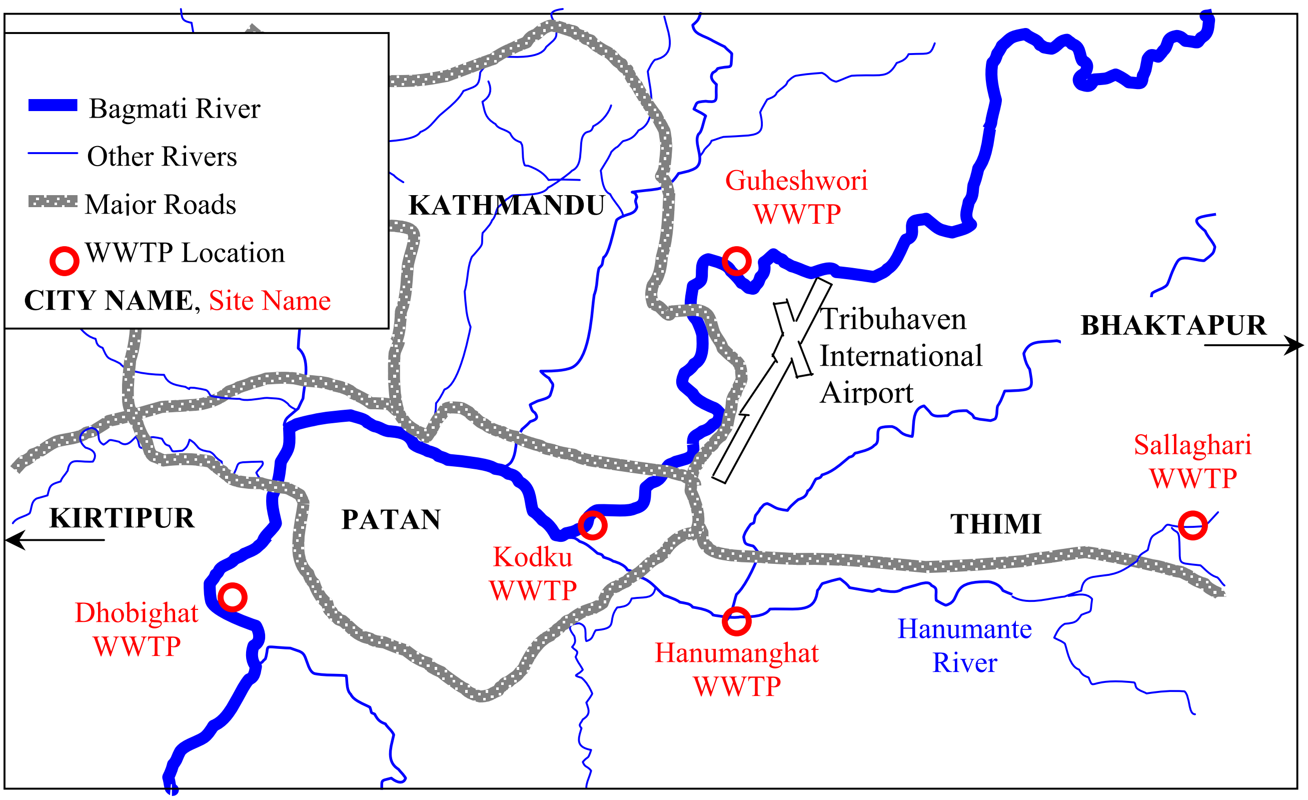
2.2 Wastewater in Kathmandu Valley

Kathmandu Valley constitutes one metropolis (Kathmandu), one sub-metropolis (Lalitpur), three municipalities (Bhaktapur, Thimi and Kirtipur) and over 100 villages.
The estimated population of Kathmandu Valley in 2000 is about 1.43 million people living in an estimated area of 640 square kilometers. Approximately 124 million liters per

day (MLD) of domestic wastewater is generated in this area. It is reported that 38% of the population in Kathmandu Valley of 0.54 million people are covered by the sewage system and only 47 MLD of domestic wastewater is collected in the Kathmandu Valley (Arata, 2003). According to the Asian Development Bank, 2000, there are 1,340 industries in and around the Kathmandu Valley, which generate 0.8 MLD of wastewater. It is estimated that 56.7 MLD of wastewater is discharged into the different river systems in the valley, from which 82% of total volume is of domestic origin. (Stanely, 1994)

2.2.1 Existing Wastewater Treatment in Kathmandu Valley

There are five sewage treatment plants in Kathmandu Valley with a total design capacity of about 35 MLD: Dhobighat sewage treatment plant (15.4 MLD), Kodku (1.1 MLD), Sallaghari (1 MLD), Hanumanghat (0.05 MLD) and Guheshwori (17.4 MLD). The locations of these wastewater treatment plants are shown in Figure 2.2.



<u>Figure 2.2</u>: Map of Wastewater Treatment Plants in Kathmandu Valley (is a reproduction of Figure IV-2 from Metcalf & Eddy, 2000)

These plants are practically non-operational except for Guheshwori. Even if the non-operational plants are rehabilitated, the total treatment capacity is not sufficient to treat total wastewater in the valley (NPC/IUCN, 1995).

Table 2.1: Overview of Wastewater Treatment Plants in Kathmandu Valley.

Wastewater Treatment Plant	Reported Capacity	Status	
		ADB Feb.2000 Report	Arata's Report Jan. 2003
Guheshwori	17.3	Under Construction	Operating
Hanumanghat	0.5	Partially operating	Not operating
Sallaghari	2	Partially operating	Not operating
Kodku	1.1	Partially operating	Partially operating
Dhobighat	15.4	Not operating	Not operating

Dhobighat and Kodku Treatment Plants

In 1981, the Dhobighat and Kodku Treatment Plants were designed and constructed to treat wastewater from the northeast part of Kathmandu and Patan (Lalitpur) respectively. These systems consisted of primary anaerobic ponds followed by secondary facultative ponds with several surface mixers and a system of mixed, shallow tertiary aerobic ponds (Shrestha, 1999). The Dhobighat Treatment Plant was designed for an average flow of 15.4 MLD, however it is not functioning due to the breakdown of the pump station and truncated sewer line along several sectors in the city. Although the design period of this system was 20 years, it could not even operate for 10 years. The stabilization ponds are now serving as a football field for the local people (Arata, 2003). According to the Asian Development Bank, 2000, the Kodku system is partially operating, as the chlorinator had never worked since its installation.

Sallaghari Treatment Plant

The Sallaghari Treatment Plant was designed and constructed in 1983 under the Bhaktapur Development Project with the support of the German Government. The system was originally designed as an aerated lagoon to treat 1 MLD of wastewater. However the operators couldn't pay for the electricity cost and thus the aeration system was removed and sold. Since then, the plant has been partially operating according to the Asian Development Bank as a non-aerated lagoon system (Asian Development Bank, 2000).

Hanumanghat Treatment Plant

The Hanumanghat Treatment Plant was constructed under the Bhaktapur Development Project in 1975. The system consisted of two settlement ponds and two oxidation ponds. When visited in January 2003 by MIT Nepal Wastewater Project Team, the Hanumanghat Treatment Plant pond was full of sludge and not functioning at all and the land was being used as a crop field (Arata, 2003).

Guheshwori Treatment Plant

The Guheshwori Treatment Plant was designed as an activated sludge plant (Figure 2.3).

Figure 2.3: Guheshwori Wastewater Treatment Plant.

The system started its operation in January 2001 and its treatment capacity was 17.3 MLD. It is the only wastewater treatment plant that is fully operating in the Kathmandu Valley. However due to the lack of budget from the government, the operation of the treatment plant may be halted in the near future. (For more on the Guheshwori wastewater treatment plant, see Richards, 2003)

2.3 Constructed Wetlands as an Alternative Technology in Nepal

Due to the failure of the large treatment plants, small and decentralized treatment systems such as constructed wetlands are in high demand. Environment and Public Health Organization (ENPHO) introduced the use of constructed wetlands for wastewater treatment in Nepal as an alternative to conventional wastewater treatment technologies. ENPHO's aim is to produce a sustainable and feasible wastewater treatment system based on the natural ecosystem in this impoverished country. It would be more appropriate if such plants could be installed at a community scale around the valley and maintained by such communities.

The first ENPHO-designed constructed wetland system with a two staged sub-surface flow was for Dhulikhel Hospital. It was built under the leadership of Dr. Roshan R. Shrestha of ENPHO in 1997 to treat domestic wastewater (Shrestha, 1999). Due to the success of the Dhulikhel Hospital system, four more sub-surface constructed wetland systems have been built in and around Kathmandu in the past few years (Shrestha, 2001). The Kathmandu metropolitan city (KMC) established its own septage treatment plant based on this technology. The Malpi International School, located near Panauti, has adopted a similar system to treat household wastewater before discharging the water in De Rosie River. The Sushma Koirala Hospital at Sankhu and Kathmandu University at Banepa have also their own constructed wetlands to treat its domestic wastewater.

There are several additional constructed wetlands systems that are in the design phase in Nepal. The Pokhara Sub-Metropolitan City's system that is under construction will be the largest constructed wetland system in Asia (Figure 2.4).

Figure 2.4: Pokhara Sub-Metropolitan City's system.

The system is designed to treat 100 m^3 of septage and 40 m^3 of landfill leachate per day. The technology introduced and designed by ENPHO, is getting popular and gradually becoming adapted within Nepal.

Chapter 3 OBJECTIVE AND PURPOSE OF STUDY

The objective of the project is to determine the wetland's hydraulic characteristics. These characteristics can be obtained by conducting tracer tests using conservative tracers. The proposed work accounts for the actual detention time and the reaction rate coefficient to link the desired removal efficiencies with the actual hydraulic conditions of the wetland systems.

Chapter 4 LITERATURE REVIEW OF CONSTRUCTED WETLAND

4.1 Introduction of Constructed Wetlands

Constructed wetland is a biological wastewater treatment technology designed to mimic processes found in natural wetland ecosystems. These wetland systems utilize the wetland plants, soil and the associated microorganisms to remove contaminants found in wastewater. The uses of these systems also provide the opportunities to create or restore wetland habitat for wildlife and environmental improvement (Hammer, 1989).
A typical constructed wetland is a series of rectangular plots that are filled with uniform graded sand or gravel. The bottom of the plot is often lined with materials like concrete or plastic to prevent wastewater and solid waste from leaching into the sub-surface of the ground. The wetlands plants, which are generally rooted in the plot that is filled with gravel and sand, offer a root mass for filtration and also provide oxygen and carbon for water treatment. The roots offer attachment sites for microbes that consume the available oxygen in the process of breaking down pollutants.

4.2 Typical Types of Constructed Wetlands

Constructed wetlands systems for wastewater treatment may be classified according to the life form of the dominating macrophytes as:

1. Free-floating Macrophytes
2. Floating-leaved Macrophytes
3. Submerged Macrophytes
4. Emergent Macrophytes

Constructed wetlands with emergent macrophytes can be further classified according to the flow pattern as:

1. Free Water Surface Flow System
2. Sub-surface Flow System
3. Hybrid System.

4.2.1 Free Water Surface Constructed Wetlands

Free Water Surface (FWS) constructed wetlands contain appropriate emergent aquatic vegetation in a relatively shallow bed or channel (Figure 4.1).

Figure 4.1: Free Water Surface (FWS) Constructed Wetlands

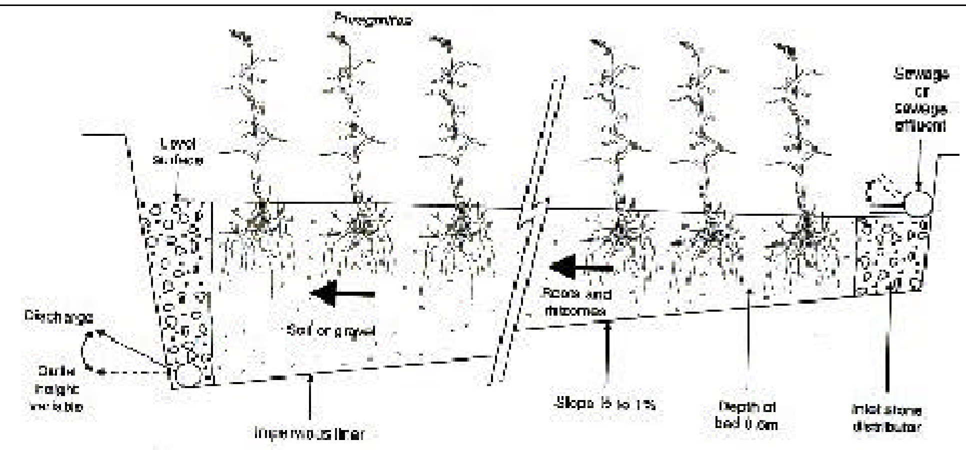
The appearances and functions of these wetlands are similar to natural wetlands. The submergent plants that are underwater act as a substrate for bacteria and other microbes, which provide an important function to improve the water quality. FWS constructed wetlands are normally used as a component in the treatment process that can provide substantial reductions in biological oxygen demand (BOD), total suspended solids (TSS), and total nitrogen (Hammer, 1989). They are especially practical as a polishing step following conventional treatment processes such as lagoon systems, activated sludge, extended aeration, or subsurface flow constructed wetland systems. These systems can also be used for agricultural, storm water, mine drainage and industrial waste treatment.

4.2.2 Sub-surface Flow System

Subsurface flow constructed wetlands usually contain a foot or more of permeable media such as gravel, sand and soil. The widespread root systems of the wetland plants growing in the gravel media provide substrate for the microbial communities responsible for pollutant reduction. These constructed wetland treatment systems use impermeable liners to prevent groundwater contamination. They can be classified as horizontal and vertical, according to the direction of flow.

4.2.2.1 Sub-surface Horizontal Flow Bed

Sub-surface horizontal flow bed (HFB) wetlands have a porous fill of coarse sand or stone (Figure 4.2).



<u>Figure 4.2</u>: Typical Cross-Section of Horizontal Flow Constructed Wetland (Figure Taken directly from Cooper 1990)

Wastewater is fed into the inlet and flows slowly through the porous medium in a horizontal path till it reaches the outlet. During the flow, the water will come into contact with a matrix of aerobic, anoxic and anaerobic zones. The fill and plant roots are the primary filters of pollutants. These wetlands are effective in the anaerobic second step of nitrogen treatment because the wastewater flows below the surface.

Design of Horizontal Flow Bed System

Sizing of the Bed

The equation proposed by Kickuth has been widely used in Europe for sizing of HFB system for wastewater treatment (Kadlec, 1996):

$$A_h = \frac{Q_d(\ln C_i - \ln C_e)}{K_{BOD}} \tag{4.1}$$

Where,

A_h = Surface area of bed, [L^2]

Q_d= Flow rate of water out of the wetland, [L^3/T]

C_i= Concentration of BOD at inlet, [M/L^3]

Ce= Concentration of BOD at outlet, [M/L^3]

K_{BOD}= First order removal rate constant for BOD, [1/T]

The design procedures for the subsurface flow wetland are based on the simplifying assumption for a plug flow reactor:

$$\frac{C_e}{C_i} = \exp(-k_r\tau) \tag{4.2}$$

Where,

k_r = Reaction rate coefficient, [1/T]

τ = Mean hydraulic detention time, [T]

The mean hydraulic detention time will be defined in Chapter 6 and the constant K_{BOD} is defined as:

$$\mathbf{K_{BOD} = k_r dn} \qquad \textbf{(4.3)}$$

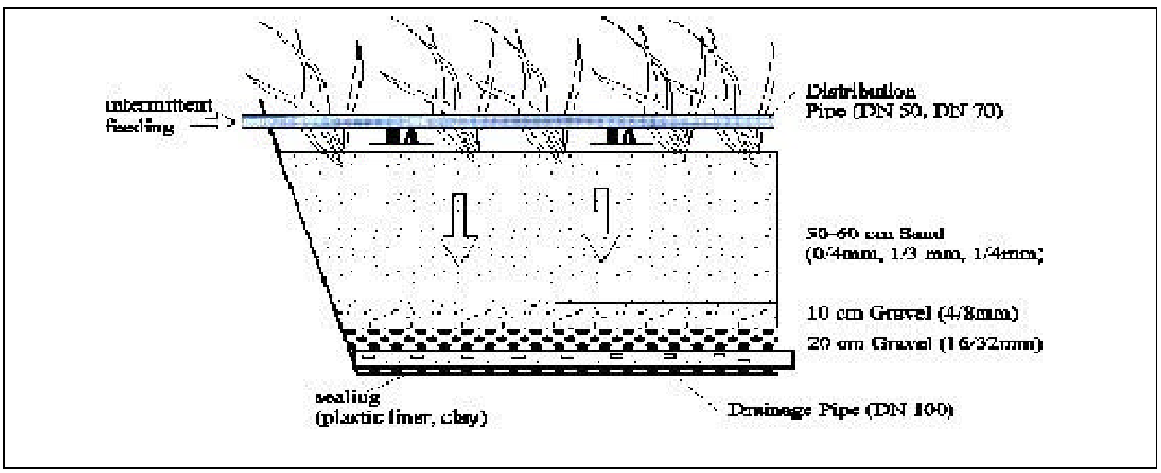
Where,

n = Porosity

d= Wetland depth, [L]

4.2.2.2 Sub-surface Vertical Flow Bed

A sub-surface vertical flow bed (VFB) wetland system has layers of sand over gravel, much like sand filters with plants (Figure 4.3).



<u>Figure 4.3:</u> Typical Cross-Section of Vertical Flow Constructed Wetland (Figure Taken directly from Cooper, 1990).

Wastewater is introduced onto the top of the marsh and allowed to flow down through the sand. Dry periods mean that oxygen is plentiful for the first step of nitrogen treatment. As with subsurface wetlands, plant roots and soil act as effective filters, and a microbial treatment area usually forms around the roots. VFB systems are designed for more aerobic processes and due to its high oxygen transfer capacity; it is ideal for the nitrification process.

Design of Vertical Flow Bed System

For the sizing of VFB system for wastewater treatment, it is defined as (Kadlec, 1996):

$$A_h = \frac{Q_d(\ln C_i - \ln C^*)}{K(\ln C_e - \ln C^*)} \qquad \textbf{(4.4)}$$

Where,

A_h = Surface area of bed, [L^2]

Q_d= Flow rate of water out of the wetland, [L^3/T]

C_i= Concentration of pollutant at inlet, [M/L^3]

Ce= Concentration of pollutant at outlet, [M/L^3]

C*= Targeted concentration of pollutant at outlet, [M/L^3]

K= First order area removal rate constant, [L/T]

The K values depend on the different environmental and operational circumstances (Harberl 1998). The following table displayed some of the values for different pollutants (Kadlec, 1996):

Table 4.1: Typical Values of K

Pollutants	K (m/day)
BOD_5	0.166
COD	0.11
NH_4-N	0.11

4.2.3 Hybrid Constructed Wetland System

HFB wetland systems are known to remove BOD_5 and TSS for secondary wastewater treatment. However due to its limited oxygen transfer capacity, it has limitation in the nitrification process. In contrast, VFB systems have a much greater oxygen transfer capacity, but have limitations in removing BOD_5 and TSS. In the hybrid constructed wetland systems, the advantages and disadvantages of the HFB and the VFB can be combined to complement each other. The combined system can produce an effluent low in BOD_5, fully nitrified and partly denitrified. Basically, there are two types of hybrid systems: HFB followed by VFB and VFB followed by HFB.

4.3 Advantages of Sub-surface Constructed Wetland System

Constructed wetlands have been used for wastewater treatment in Europe and North America for more than two decades. The use of these wetland systems provides a relatively simple and inexpensive solution for treatment of wastewaters from small communities and industries. These low cost systems are found to be highly effective in removing suspended solids, nutrients, biochemical oxygen demand (BOD) and pathogens (Vymazal, 1998). Since the systems can be operated by relatively untrained personnel, the operating cost is extremely low. The designs of these systems are usually more flexible and less receptive to variations in loading rate than conventional treatment system. These wastewater treatment systems will be useful in Nepal as they produce a sustainable and feasible treatment system based on the natural ecosystem (Harbel, 1999).

4.4 Limitations of Sub-surface Constructed Wetland System

One of the limitations of constructed wetland system is that it requires a large area. There is also no development of the design criteria for various types of wastewater. The performance of the wetland systems depends on the seasonal variation.

4.5 Pollutant Removal Mechanism of Sub-surface Flow System

Many contaminants like organic matter, suspended solids, nitrogen, phosphorus, metals and pathogens are reduced by the wetland system with the assistance of various complex physical, chemical and biological processes.

4.5.1 Organic Matter Removal Mechanisms

Sedimentation and filtration are the main processes that remove settable organic matter from the wastewater in the wetland system. Organic compounds are degraded aerobically as well as anaerobically by bacteria attached to plant's roots and media surface. The oxygen required for aerobic degradation is supplied directly from the atmosphere by diffusion from the macrophyte roots and rhizomes into the rhizosphere. However this process of anaerobic degradation is slower than aerobic degradation.

4.5.2 Total Suspended Solids Removal Mechanisms

While the length of the hydraulic residence time plays a vital role in the removal of all settable solids in the wastewater, the major removal mechanism are sedimentation and filtration. The success of the removal of TSS depends on the contact area with the plants and the media. The removal efficiency of TSS in constructed wetlands ranges from 40% to 94% (Kadlec, 1996).

4.5.3 Nitrogen Removal Mechanisms

The nitrogen removal mechanisms in constructed wetlands include volatilization, ammonification, nitrification, denitrification and plant uptake matrix adsorption. A number of physical, chemical and biological transfer processes connect these mechanisms. Many studies have proved that the major removal mechanism in most 'vegetated submerged bed constructed' wetlands is microbial nitrification and denitrification. In 'free water surface constructed' wetlands, ammonia volatilization can significantly contribute to nitrogen removal (Farahbakhshazad 2000).

4.5.3.1 Ammonification

Ammonification, or mineralization is the process where organic nitrogen is converted into inorganic nitrogen, specifically ammonia. This biological process is the first step in the nitrogen removal process. The mineralization of organic nitrogen results in the release of the ammonium ion, which can go through a variety of subsequent reactions. Mineralization rates are the fastest in the oxygenated zone and decrease as the process switches from aerobic to facultative anaerobic and obligate anaerobic mircoflora (Vymazal, 1998). These rates are dependent on temperature, pH values, availability nutrients and soil conditions in the wetlands. Ammonium exists in equilibrium with free ammonia. The equilibrium is pushed towards ammonia at higher pH values.

4.5.3.2 Volatilization

Ammonia volatilization is a physicochemical process where ammonium/nitrogen is known to be in equilibrium between gaseous and hydroxyl forms as shown in the following equation:

$$NH_3\,(aq) + H_2O = NH_4^{\,+} + OH^{\,-} \qquad (4.5)$$

Ammonia is a volatile compound and at high pH value, loss of ammonia gas can occur through volatilization. Under normal conditions where the pH value is less than 8.0, nitrogen loss through this process is minimal. However in constructed wetlands systems, the photosynthetic activity of algal biofilms can result in large diurnal pH changes where the values can exceed 9.3. At this range of pH values, the ratio between ammonia and ammonium ions is 1:1 and the losses through volatilization can be significant.

4.5.3.3 Nitrification

Nitrification is the biological oxidation of ammonium to nitrate, with nitrite as an intermediate in the reaction sequence. A large number of organisms, which use organic carbon as an energy source, are capable of producing oxidized nitrogen compounds. This type of nitrification, which is also know as autotrophic is generally considered the dominant process of converting ammonium to nitrate. Autotrophic nitrification is a two-stage process undertaken by a small group of bacteria. The first step is the oxidation of ammonium to nitrite shown in Equation (4.6). Members of the Nitrosomonas genera usually perform this transformation. The second step is the oxidation of nitrite to nitrate (Shown in Equation (4.7)). Members of the Nitobactor genera mainly perform this transformation. The overall process of nitrification can be summarized by a single expression shown in Equation (4.8).

$$NH_4^{+} + 1.5\,O_2 \Rightarrow NO_2^{-} + 2H^{+} + H_2O \qquad (4.6)$$

$$NO_2^{-} + 2\,O_2 \Rightarrow NO_3^{-} + 2H^{+} + H_2O \qquad (4.7)$$

$$NH_4^{+} + 2\,O_2 \Rightarrow NO_3^{-} + 2H^{+} + H_2O \qquad (4.8)$$

Autotrophic nitrifiers require carbon dioxide as a carbon source to enable them to grow during the nitrification. The rate of growth for this nitrifying bacteria is slow. The generation times for these bacteria are in the 20 to 40 hour range compared to several hours for heterotrophic bacteria. Therefore, it is important to design and maximize the surface area available for biofilm development in order to optimize the nitrification process. The rate of nitrification is controlled by various factors such as the supply of ammonium, the supply of oxygen, the supply of carbon dioxide, the population density of the nitrifying bacteria, temperature, pH values and the alkalinity in the constructed wetlands (Kadlec 1996). The supply of oxygen limits nitrification to oxic surfaces of the benthos and the epiphytic biofilms. As such, the surface area of aerobic biofilm in the system becomes important for this process.

Nitrification can also occur in the oxygenated zone within the rhizosphere of the plant roots. Although this is an important process in sub-surface flow constructed wetland, it is likely that the slow diffusion rate of materials in and out of the sediments and root zone of these wetland systems will limit the importance of this pathway.

4.5.3.4 Denitrification

Denitrification is an energy-requiring reduction process where electrons are added to nitrate or nitrite nitrogen, resulting in the production of nitrogen gases (Kadlec 1996). Dissimilatory denitrification is a process that occurs during the respiration of heterotrophic organisms. The denitrifers are mainly aerobic bacteria that have the capacity to reduce nitrogen oxides when oxygen supply is limited. Representatives of Pseudomonas and Alcaligenes are the most commonly isolated denitrifiers from soils and sediments. Typically, most denitrifies are also heterotrophs involved in general decomposition processes and thus have a widespread distribution.

Nitrification is an aerobic process essentially occurring only after carboneous Biochemical Oxygen Demand (BOD) has been satisfied and when an adequate oxygen supply is available. Denitrification is an anoxic process occurring where the BOD exceeds the oxygen supply. Although the nature of denitifers suggests that denitrification will only occur when the conditions are suitable, it highlights some of the differences between nitrifying and denitrifying bacteria. This creates some difficulties in coupling these processes.

The most efficient coupling occurs when sites are only temporally separated, as in the case where a biofilm contains both algae and bacteria. Algae photosynthesis produces an oxygen source during the day, which can be used for nitrification. During the night, biofilm respiration can exceed the oxygen supply from the water column and results in anoxic conditions that is suitable for denitrification. The physical complexity of biofilms means that aerobic and anoxic sites must be close together to reduce limitations due to diffusion.

4.5.4 Phosphorous Removal Mechanisms

Phosphorous removal occurs from adsorption, absorption, complexation and precipitation processes in the wetlands. It also occurs in biotic processes such as plant uptake, microbes' uptake and mineralization of plants. Removal of phosphorus is limited in sub-surface flow wetlands due to the limited contact with the soil and root zone.

4.5.5 Metal Removal Mechanisms

The processes of metal removal in the wetland system include sedimentation, filtration, adsorption, complexation, plant uptake and microbial mediated reaction.

4.6 Previous Hydraulic Investigation at Dhulikhel Hospital's Constructed Wetland System

A tracer experiment was conducted on the vertical and horizontal flow bed of Dhulikhel Hospital constructed wetlands system on November 6, 1997 and February 22, 1998 respectively (Shrestha, 1999).

Tracer Material:

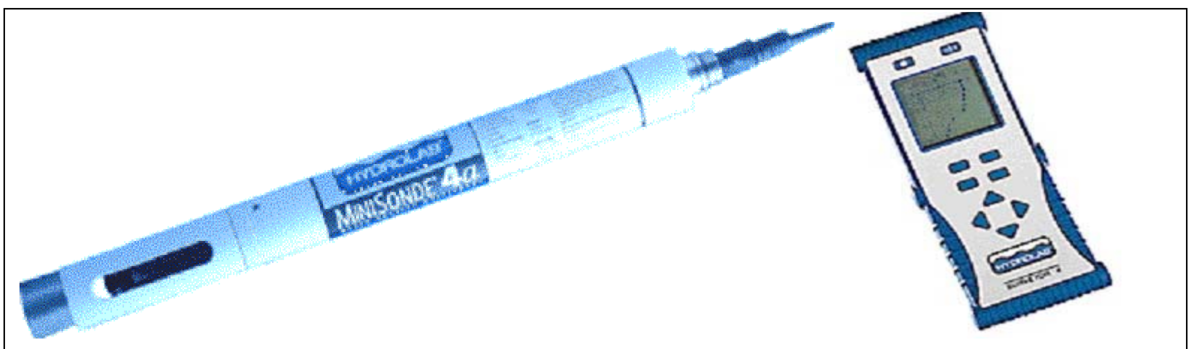
Chloride was chosen as the tracer for the tests as it is conservative in most environments, has low background concentration, is easy to analyze, economic to use and has low toxicity. It was obtained in the form of table salt, NaCl.

Methods:

The tracer solution was prepared in a bucket by mixing 6 kg of Sodium Chloride (NaCl) with 15 liters of water. To flush the salt solution into the beds, it was fed directly into the feeding bucket of the intermittent loading tank (Shrestha, 1999). This method was used for all the tests, as the intermittent loading tanks for all systems were similar in design.

Equipment Used:

The Hydrolab: The MiniSonde® 4a Electrode and the Hydrolab hand-held Surveyor® 4a Meter were used to measure and record conductivity in the effluent (Figure 4.4).



<u>Figure 4.4</u>: Hydrolab: The MiniSonde® 4a Electrode (Left) and the Hydrolab hand-held Surveyor® 4a Meter (Right).

Results:

The average tracer detention time in the HFB was found to be 9 hours. The test for the VFB was incomplete.

Comments:

The test results might not be accurate as conductivity of the chloride ions was measured instead of the concentration. The background conductivity of other dissolved salts might affect the reading, which suggests that the equipment used was not appropriate. There was no information on the mass recovery of the tracer. In addition, the data analysis was based on the assumption that the flow was plug-flow, which was inadequate to determine the detention time of a sub-surface wetland (Kadlec, 1996). A constant flowrate was used in the analysis, which was not the case in the feeding system. This might have caused erroneous results. Since the equipment and the method used were not appropriate, there is a need for a more rigorous tracer experiment to determine the hydraulic characteristics of the wetlands system.

Chapter 5 VISITED CONSTRUCTED WETLANDS IN NEPAL

5.1 Background

In January 3, 2003, the author visited Nepal and stayed in the capital city, Kathmandu, for more than three weeks (Figure 1.1). He was hosted by and worked with Environment and Public Health Organization (ENPHO), a Non-Government Organization (NGO) in Nepal whose mission is monitoring and improving local drinking water supply, wastewater treatment, solid waste disposal, and air quality monitoring.
During the first week of his stay, he visited four constructed wetland systems in Nepal (Table 5.1).

Table 5.1: Visited Constructed Wetlands

Date	Constructed Wetland Systems	Location
January 6, 2003	Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital	Sankhu
January 7, 2003	Dhulikhel Hospital	Dhulikhel
January 7, 2003	Kathmandu University	Dhulikhel
January 8, 2003	Pokhara Municipality	The Pokhara Sub-Metropolitan City

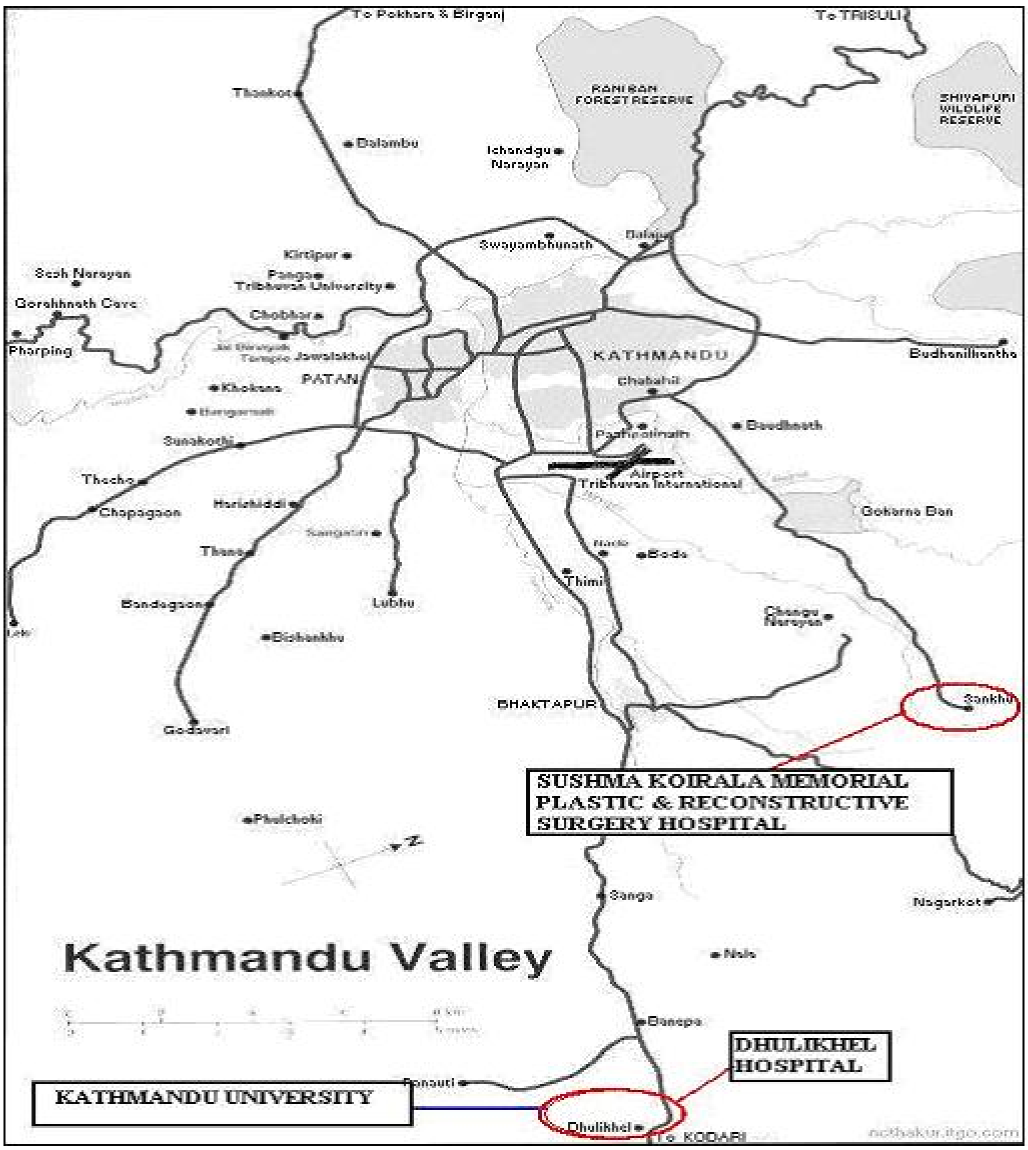
Dr. Roshan R. Shrestha, who is the director of ENPHO and the chief designer for these constructed wetlands, accompanied him. Due to time constraints, only two constructed wetland systems were chosen to conduct the tracer experiment. These were the constructed wetland systems of Dhulikhel Hospital and Sushma Koirala Memorial Plastic & Reconstructive Surgery (SKM) Hospital constructed wetland systems.

5.2 Dhulikhel Hospital

Dhulikhel Hospital is a joint venture of the residents of Dhulikhel, the Dhulikhel Municipality, His Majesty's Government of Nepal and Nepalimed, a non-profit, non-governmental and non-religious organization established in Voralberg, Austria.

Established in 1996, Dhulikhel Hospital is situated in the village of Dhulikhel, approximately 30 kilometers from Kathmandu (Figure 5.1). The location is 1,650 meters above sea level and has a sub-tropical climate with an annual rainfall of about 1,456 mm (HMG, 1996).

In 1995, Dr. Roshan R. Shrestha introduced constructed wetlands in Nepal. With the technical collaboration of the Institute for Water Provision, University of Agricultural Sciences, Vienna, Austria, the constructed wetland system in Dhulikhel Hospital was designed and constructed in 1997 as a first constructed wetland in Nepal (Laber, 1999).



<u>Figure 5.1</u>: Map of Kathmandu Valley

5.2.1 Design of the Dhulikhel Hospital's Constructed Wetland System

The constructed wetland in Dhulikhel Hospital is a two-staged subsurface flow system, which consists of a horizontal flow bed followed by vertical flow bed (Figure 5.2).

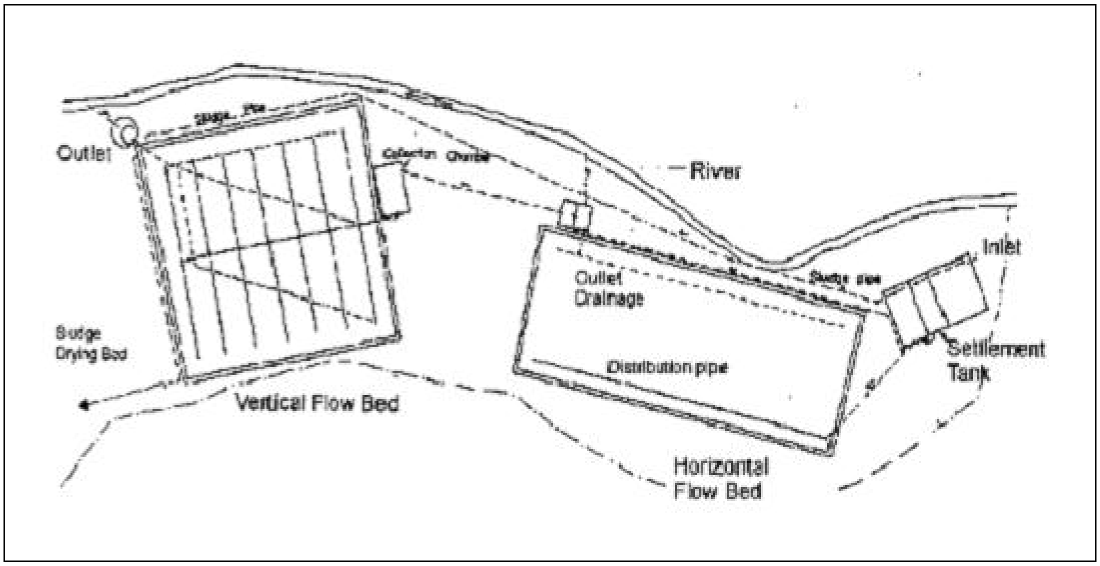


Figure 5.2: Site Plan of The Constructed Wetland System at Dhulikhel Hospital (ENPHO, 1997)

The system was designed to treat 20 m^3/day of wastewater. During the design phase, it was assumed that the hospital capacity was 60 beds and 250 people were using the hospital on a daily basis.

The Dhulikhel Hospital constructed wetland system consists of a three-chambered septic tank with a volume of 16.7 m^3. The area of the horizontal bed and the vertical bed is 140 m^2 and 120 m^2 respectively (Figure 5.3).

Figure 5.3: Horizontal Flow Bed (Left) and Vertical Flow Bed (Right) at Dhulikhel Hospital

The depth of the horizontal bed ranges from 0.60 to 0.65 meters, while the depth of the vertical bed is 0.9 meters (ENPHO, 1997). The main layer of the horizontal bed was filled with crushed gravel with conductivity (Kf) of 0.03 m/s and a pore volume of 39%. The main layer of the vertical bed was filled with clean sand with conductivity (Kf) of 0.001 m/s and a pore volume of 30%. Both of the beds were planted with *Phragmites karka*, a local variety of reeds that was readily available. The system does not need any electric energy as the wastewater is fed hydro-mechanically into the beds. The total cost of the system including the sewer lines was US$ 27,000 in 1997, while the cost of the constructed wetland alone was at US$ 16,400.

Table 5.2: Overview Details of Dhulikhel Hospital Constructed Wetland System.

Type of Flow Bed	Length (m)	Width (m)	Depth (m)	Area (m^2)	Type of Fill	Conductivity (m/s)	Porosity (m^3/m^3)
Horizontal	20	7	0.6-0.65	140	Crushed Broken Gravel	0.03	0.39
Vertical	11	11	0.9	121	Clean Sand	0.001	0.3
Design Capacity (m3/day)					20		
Total Cost (US$)					27,000		

5.2.2 Treatment Efficiency of Dhulikhel Hospital's Constructed Wetland System

The system has shown very high treatment efficiency from the time it began operation in 1997 until the year 2000 (Table 5.3). During that interval of time, it was observed that the major pollutants such as total suspended solids (TSS), organic pollutants, and ammonia-nitrogen had a removal percentage of more than 95%, while the removal percentage of *E. coli* was even higher at 99.99% (Shrestha, 2001).

Table 5.3: Summary Statistics of Inlet and Outlet Concentrations and Mean Elimination Rates of Dhulikhel Hospital Constructed Wetland System (1997 to 2000) (Shrestha, 2001)

Month	Q (m^3/day)	TSS IN (mg/L)	TSS OUT (mg/L)	NH_4-N IN (mg/L)	NH_4-N OUT (mg/L)	PO_4-P IN (mg/L)	PO_4-P OUT (mg/L)	BOD_4 IN (mg/L)	BOD_4 OUT (mg/L)	COD IN (mg/L)	COD OUT (mg/L)	*E.coli* IN (col/mL)	E.coli. OUT (col/mL)
Nos. of Reading	13	12	12	12	11	12	12	13	13	13	11	11	11
Minimum	7	26	0.3	17	0.04	2.2	0.6	31	0	63	4	39000	3
Maximum	40	230	6.7	52	5.4	26	18	210	10	1048	40	8E+08	987
Average	20	83	2.3	33	1.6	8	4	110	3	325	20	1E+08	148
Median	11	41	1.8	19	0.04	2	0.7	41	4	79	18	1E+05	38
Std. Deviation	11	58	1.9	12	2.2	7	5.8	63	3	273	14	2E+08	307
Elimination (%)			97		95		47		97		94		99.99

Although the system was initially designed for 20 m^3/day of wastewater, since 2000 it treats 30 to 40 m^3/day. The removal efficiencies for total suspended solids (TSS), biochemical oxygen demand after 5 days incubation (BOD_5) and chemical oxygen demand (COD) were not significantly affected by the increase in hydraulic loading in 1999 and 2000 (Figure 5.4).

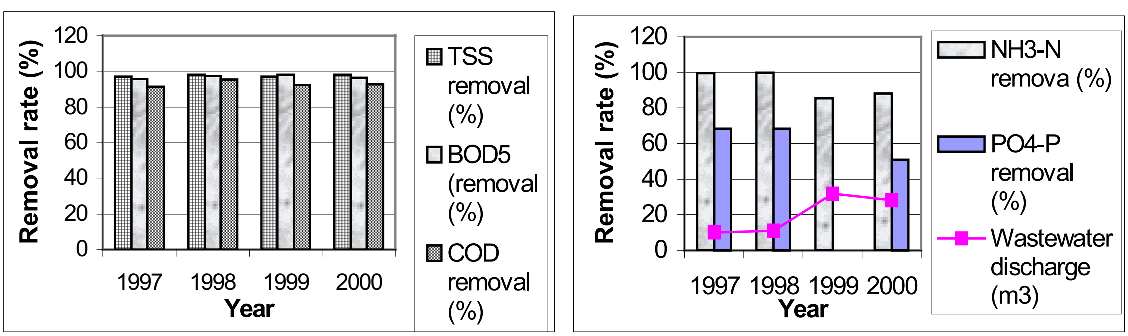


Figure 5.4: Concentration reduction of Dhulikhel Hospital Constructed Wetland System at Different Time Interval.

However, the removal efficiencies of ammonia, phosphorus and pathogens have decreased with the increase in hydraulic load at a shorter time interval. It has been reported that due to the loss of drainage capacity in the upper layer of the vertical flow bed and to the decrease in hydraulic loading interval that resulted in the reduction of oxygen flowing into the vertical flow bed. This reduced the ammonia removal efficiency (Shrestha, 2001).

During the trip to Dhulikhel Hospital, the author noticed that the wetland system was in poor condition. It was observed by the author that the horizontal flow and vertical flow bed were full of sludge (Figure 5.5).

Figure 5.5: Sludge Affected Areas in the Wetland System.

The main reason for the sludge accumulation in the wetlands might be the increase in flowrate above the design flow, which prevents the sludge from settling in the tanks before discharging into the wetlands. The condition of sludge accumulation in the vertical flow bed was more serious, as ponding of wastewater affected almost 90 percent of the surface of the bed, while only 20% of the surface area of the horizontal bed was affected (Figure 5.6).

Figure 5.6: Ponding Effects on the Vertical Flow Bed (Left) and Horizontal Flow Bed (Right) at Dhulikhel Hospital Due to Sludge Accumulation.

The reeds in the wetlands looked unhealthy as the growth was not thick and the reeds were withered. The average height of the reeds was only 0.3 meter in the horizontal flow bed and 0.5 meter on the vertical flow bed compared to reed growth of 2 to 3 meters in the other wetland systems. These problems suggested that the wetland system was not maintained regularly. The removal efficiencies for TSS, BOD_5 and COD from July 2002 to January, 2003 are shown in Table 5.4.

Table 5.4: Summary Results of Inlet and Outlet Concentrations and Mean Elimination Rates of Dhulikhel Hospital Constructed Wetland System (Jul 2002 to Jan 2003) (ENPHO)

Date	Parameters											
	BOD(mg/l)			COD(mg/l)			TSS(mg/l)			PO4(mg/l)		
	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal
12-Jul-02	62.0	1.5	97.6	122.4	20.0	83.7	66.0	3.0	95.5	3.94	3.27	17.0
24-Sep-02	84.0	5.4	93.6	130.6	23.3	82.2	106.0	5.0	95.3	2.5	1.0	60
15-Nov-02	72.0	1.9	97.4	97.6	22.0	77.5	46.0	5.0	89.1	2.8	1.5	44.6
14-Jan-03	349.0	14.3	95.9	680.0	49.5	92.7	380.0	24.7	93.5	8.6	4.9	42.0
Average Removal %			96.1			84.0			93.3			41.2

The elimination rates of the respective pollutants were compared to those shown in Table 5.3. Although it was noted that the removal efficiencies of these pollutants were significantly reduced, the system is still having very good treatment efficiency (Table 5.5).

Table 5.5: Comparison of Average Removal % for Dhulikhel Hospital Constructed Wetland System

Date	%Average Removal			
	BOD_5 (mg/l)	COD (mg/l)	TSS (mg/l)	PO4(mg/l)
1997-2000	**97**	**94**	**97**	**47**
2002-2003	**96**	**84**	**93**	**41**

5.3 Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital

The Sushma Koirala Memorial (SKM) Plastic and Reconstructive Surgery Hospital was built in 1991 as a station for leprosy diseases. The building was reconstructed as a surgical clinic in 1997. As a partnership between Interplast, Germany, a non-profit, non-governmental international cooperation of plastic surgeons and the Nepalese authorities. The clinic was named after the late wife of the present prime minister of Nepal. Sushma Koirala Memorial Plastic and Reconstructive Surgery Hospital is situated in Sankhu, approximately 25 kilometers northeast from Kathmandu City (Figure 5.1). The location is 1382 meters above sea level and has a sub-tropical climate with an annual rainfall of about 1300 mm (HMG, 1996).

After the success of the constructed wetland system in Dhulikhel Hospital, SKM Hospital decided to use a similar design to treat their wastewater. The constructed wetland at SKM hospital was also designed by ENPHO under the leadership of Dr. Roshan R. Shrestha and has been in operation since December 2000 (ENPHO 2002).

5.3.1 Design of the Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's Constructed Wetland System

The constructed wetland in SKM Hospital is a two-stage subsurface flow system, consisting of a horizontal flow bed followed by vertical flow bed. The system was designed to treat 10 m^3/day of wastewater. It was assumed that the hospital capacity was 30 beds that included 125 people in the hospital daily. Currently, there are about 16 beds in the hospital with 25 staff members in the hospital.

The system consists of a three-chambered septic tank with a volume of 10 m^3. The area of the horizontal bed and the vertical bed is 72 m^2 and 67.5 m^2 respectively (Figure 5.7).

Figure 5.7: Horizontal Flow Bed (Left) and Vertical Flow Bed (Right) at SKM Hospital

The depth of the horizontal bed ranges from 0.60 to 0.72 meter, while the depth of the vertical bed ranges from 0.7 to 1.1 meter (ENPHO, 2002). The main layer of the horizontal bed was filled with crushed gravel with an estimated conductivity value (Kf) of 0.03 m/s and a designed pore volume of 39%. The main layer of the vertical bed was filled with clean sand to the depth of 0.7 meter with an estimated conductivity (Kf) of 0.001 m/s and a designed pore volume of 30%. Both of the beds were planted with *Phragmites karka*. The system does not need any electric energy as the wastewater is feed hydro-mechanically into the beds. The total costs of the system including the sewer lines were US$ 27000 in 2000

Table 5.6: Overview Details of Dhulikhel Constructed Wetland System.

Type of Flow Bed	Length (m)	Width (m)	Depth (m)	Area (m^2)	Type of Fill	Conductivity (m/s)	Porosity (m^3/m^3)
Horizontal	9	8	0.6-0.72	72	Crushed Broken Gravel	0.03	0.39
Vertical	9	7.5	0.7-1.1	67.5	Clean Sand	0.001	0.3
Design Capacity (m3/day)					10		
Total Cost (US$)					27,000		

5.3.2 Treatment Efficiency of Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's Constructed Wetland System

The system has shown high treatment efficiency since its operation in December, 2000. The data for treatment efficiency of the constructed wetland system, provided by ENPHO, is summarized in Table 5.7. It was observed that the major pollutants, such as total suspended solids (TSS), biochemical oxygen demand after 5 days incubation (BOD_5) and chemical oxygen demand (COD) and ammonia-nitrogen had removal percentages of 97%, 98%, 95 and 94%, respectively, during this period, while the removal percentage of *E. coli* was even higher at 99.99% (Zandvoort, 2001)

Table 5.7: Summary of Inlet and Outlet Concentrations and Mean Elimination Rates of Dhulikhel Hospital Constructed Wetland System (Jun 2001 to Nov 2002) (ENPHO).

Date	Parameters											
	BOD_5 (mg/l)			COD (mg/l)			TSS (mg/l)			NH3(mg/l)		
	In	Out	% R	In	Out	% R	In	Out	% R	In	Out	% R
1-Jun-01	436.20	18.10	95.85	1746.00	70.80	95.95	225.00	8.00	96.44	148.20	26.28	82.27
25-Sep-01	736.50	4.68	99.36	1416.00	70.80	95.00	520.00	5.33	98.98	131.18	1.09	99.17
8-Jul-02	212.00	1.74	99.18	433.00	20.10	95.36	160.00	3.33	97.92	111.47	1.97	98.23
13-Sep-02	475.00	22.70	95.22	1109.76	83.23	92.50	655.00	6.00	99.08	26.38	0.84	96.82
17-Nov-02	279.00	2.97	98.94	766.16	40.00	94.78	146.00	10.00	93.15	45.38	2.75	93.94
Elimination Rates %			**97.71**			**94.72**			**97.11**			**94.08**

During the trip to SKM Hospital, the author noticed that the wetland system was in good condition. The average height of the plant in the horizontal flow and vertical flow bed were 2.0 meter and 3.0 meter respectively. However the horizontal flow bed had only half of it surface area filled with reeds (Figure 5.8).

Figure 5.8: Horizontal Flow Bed at SKM Hospital

The author was informed by the staff at the hospital that due to the recent failure of the retaining wall of the horizontal bed system, half of the plants were removed to repair the crack. Although the crack in the wall was sealed, some minor leakage on the side of the wall could be seen.

5.4 Kathmandu University

Kathmandu University was established in December 1991 by an act of the Nepalese parliament. The objective of the university is to provide undergraduate and post graduate programs in the fields of engineering, science, management, arts, education and in the ,near future medical sciences. Due to the expansion of the university in recent years, there was a need for a treatment system to treat the wastewater generated by the university. Therefore in 2002, a constructed wetland system was built. The system was designed by ENPHO under the leadership of Dr. Roshan R. Shrestha.
The constructed wetland system of Kathmandu University is situated in Dhulikhel, approximately 30 kilometers from Kathmandu (Figure 5.1). The location is 1650 meters above sea level and has a sub-tropical climate with an annual rainfall of about 1456 mm (HMG, 1996).

5.4.1 Design of the Kathmandu University's Constructed Wetland System

The constructed wetland at Kathmandu University is a two-staged subsurface flow system, which consists of a horizontal flow bed followed by two vertical flow beds. The system was designed to treat 35 m^3/day of wastewater. It was assumed to provide 750 users in the university daily.
The system consists of a three-chambered septic tank with a volume of 40m^3. The area of the horizontal bed and the vertical beds is 290 m^2 and 338 m^2 respectively (Figure 5.9).

Figure 5.9: Horizontal Flow Bed (Left) and Vertical Flow Bed (Right) at SKM Hospital

Both of the beds were planted with *Phragmites karka*. The system does not need any electric energy as the wastewater is feed hydro-mechanically into the beds (Figure 5.10).

Figure 5.10: Hydro-mechanic Feeding Tank

Table 5.8: Overview Details of Kathmandu University's Constructed Wetland System.

Type of Flow Bed	Length (m)	Width (m)	Area (m^2)
Horizontal	29.0	10.0	290.0
Vertical (each Unit)	13.0	13.0	169.0
Design Capacity (m^3/day)		20	
Estimated No. Of Users		350	

5.4.2 Treatment Efficiency of the Kathmandu University's Constructed Wetland System

During the trip to Kathamndu University, the author noticed that the wetland system was in extremely good condition. The plants looked very healthy as the average height of the plant in the horizontal flow and vertical flow bed were more than 2 meter and 3 meter respectively (Figure 5.11).

Figure 5.11: Vertical Flow Bed at Kathmandu University

Although no data was given at this time to monitor the removal efficiency of the major pollutants, it was observed by the author that the water quality of the effluent appeared to be good as it was colorless and did not possess any odor, whereas the influent was colored and smelly.

Figure 5.12: Effluent of the Constructed Wetland System

5.5 Pokhara Sub Metropolis Constructed Wetlands for Septage and Landfill Leachate Treatment

Pokhara Environmental Improvements Project (PEPI) was launched in 1996, using a loan from Asian Development Bank, to improve the overall urban environment and the sanitary living conditions of the people of Pokhara Sub-Metropolis. One of the projects was to build a sanitary landfill site with a treatment facility of landfill leachate and septage collected from the city of Pokhara. In 1998, East Consult (P) Ltd. in association with CEAD Consultants (P) Ltd and ENPHO were awarded the package for survey, design and contract supervision of Pokhara Septage and Solid Waste Management Facility (Shrestha, 1999). The use of constructed wetlands technology as the treatment plant for the landfill leachate and septage was introduced by EHPHO. The system is under the construction phase and the estimated completion date is June 2003. It will be the largest constructed wetland system in Asia (ENPHO, 2002).

Pokhara city, with an estimated population of 150,000 is a tourist attraction center, which is located in the mid-western region of Nepal (Figure 5.13).

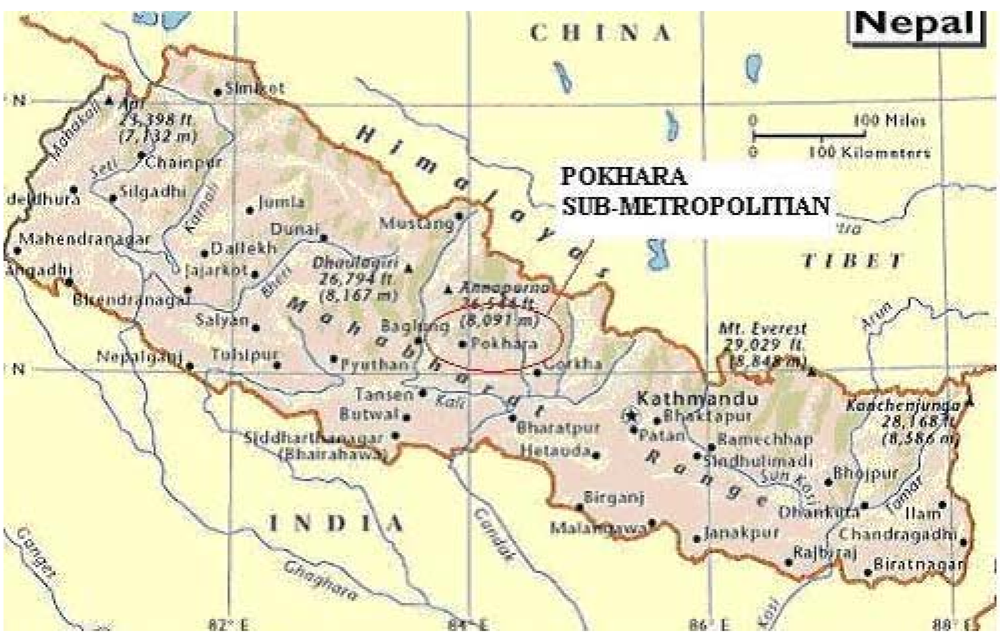
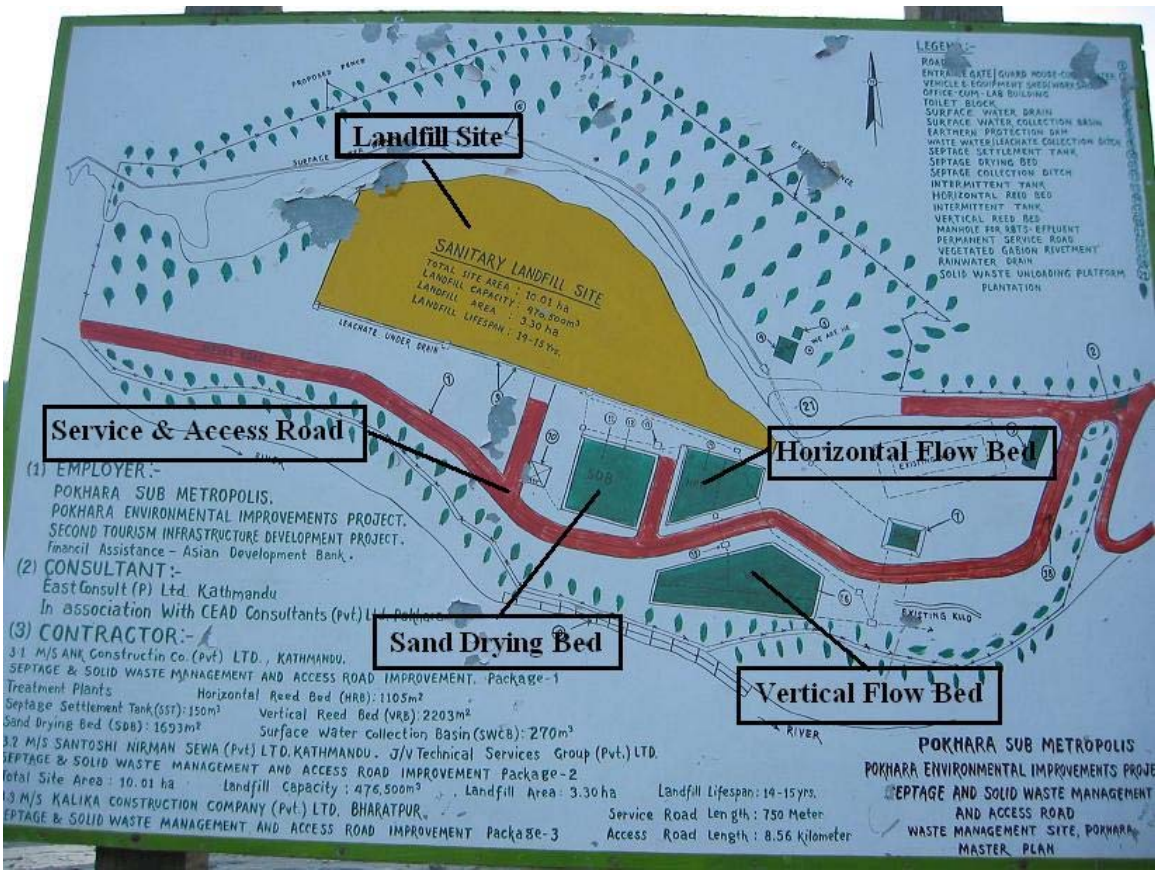


Figure 5.13: **Location of Pokhara Sub-Metropolis.**

The area of Pokhara Sub-Metropolis is about 52.5 km^2 with an estimated of 200,000 people inhabiting in it. The sub-metropolis is 827 meters above sea level and is about 250 km west of Kathmandu city.

5.5.1 Design of the Pokhara Sub Metropolis Constructed Wetland System

The proposed septage and solid waste leachate treatment system for Pokhara Sub-Metropolis is shown in Figure 5.14.



<u>Figure 5.14</u>: Proposed Septage and Solid Waste Leachate Treatment System for Pokhara Sub-Metropolis.

The constructed wetlads system is designed to treat 100 m^3/day of septage and 40 m^3/dayof landfill leachate from Pokhara Sub Metropolis . The septage, collected from Pokhara Sub-Metropolis, will be brought to the site and pumped into the septage settlement tank with a capacity of 200 m^3 (Figure 5.15).

Figure 5.15: Septage Settlement Tank

The septage settlement tank will provide a holding tank, here the septage will undergo anaerobic digestion. Next, the septage will be transferred to the sand drying bed that is designed to have an area of 1,849 m^2 by gravity (Figure 5.16).

Figure 5.16: Sand Drying Bed

The dried sludge on the sand drying bed will be manually disposed of to the landfill site (Figure 5.17).

Figure 5.17: Proposed Landfill Site

The effluent of the sand drying bed will be channeled into an intermitted tank with a capacity of 36.0 m^3 (Figure 5.18).

Figure 5.18: Intermitted Feeding Tank for Horizontal Bed.

The system does not need any electric energy as the wastewater is fed hydro-mechanically by gravity into the horizontal bed with an area of 1,105 m^2 (Figure 5.19).

Figure 5.19: Horizontal Flow Bed

Next, the effluent from the horizontal bed will enter another intermittent tank before flowing into the vertical flow bed with an area of 2203 m^2 (Figure 5.20).

Figure 5.20: Vertical Flow Bed at Kathmandu

The effluent of the vertical flow bed will finally pass into a surface water collection basin to dilute it before discharging into the Seti River.

Table 5.9: Overview Designed Details of Septage and Solid Waste Leachate Treatment System for Pokhara Sub-Metropolis.

Type of Flow Bed	Length (Estimated) (m)	Width (Estimated) (m)	Required Area (m^2)
Sand Drying Bed	61.6	30.0	1849.0
Horizontal	47.0	22.0	1105.0
Vertical	71.0	41.0	2203.0
Septage Settlement Tank		200.0	m^3
Intermitted Feeding Tank Capacity (Each)		36.0	m^3
Designed Septage Capacity		100	m^3/day
Designed Landfill Leachate Capacity		40	m^3/day

Chapter 6 TRACER TEST

6.1 Monitoring the Hydraulic Characteristics of Constructed Wetland

To improve the treatment efficiency of the wetland system, the wetland's hydraulic characteristics must be determined. A common method for determining the hydraulic characteristics is by conducting a tracer test. The tracer test revels the actual flow of the water within the wetland system. In addition, the removal efficiency of the wetland system for a non-conservative constituent can be also estimated. The constructed wetland systems in Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital and Dhulikhel Hospital were chosen to conduct tracer tests.

6.2 Theoretical Background

Most of the literature on wetland systems defines the mean hydraulic detention time (also called nominal residence time) to be the ratio of the volume of water in the wetland over the influent flow rate of water into the system:

$$\tau = \frac{\mathbf{ndA}}{\mathbf{Q}} \qquad \textbf{(6.1)}$$

Where,

τ = Mean hydraulic detention time, [T]

n = Porosity

d= Wetland depth, [L]

A= Wetland surface area, [L^2]

Q= Average flow rate, [L^3/T]

The value of the mean hydraulic detention time is often not known with a high degree of accuracy, as it is rarely possible to perform a quantitative fill or drain experiment to quantify the water volume (Kadlec 1996). By performing a tracer test, the actual mean detention time for the wetland can be determined. These tests provide insight into the actual hydrology of the wetland. In addition, the removal performance of the wetland for specific constituent can be estimated, as will be discuss later in this chapter.

Since wetlands are classified as reactor vessels, basic chemical reaction engineering principles can be applied to the system (Kadlec 1996). Since the wetland systems do not fit the Plug-Flow or Stirred Reactor models flawlessly, a more specific method to describe the transport through the constructed wetland system is needed. By using the theory of residence time distribution (RTD), it will provide a good approximation of the time each parcel of fluid remain in the system.

The residence time distribution function, RTD (t), represents the time various fractions of water spend in the wetland system. It is the probability density function for the residence times in the system. The time function is shown as the following:

RTD (t)*Δt = fraction of the incoming water which stays in the wetland for a period of time between t and t+Δt. **(6.2)**

Where,

RTD (t)= residence time distribution function, [1/T]

Δt = time interval, [T]

The RTD (t) function for a given system can be determined by releasing an instantaneous slug of dissolved conservative tracer at the inlet of the wetland and measuring the tracer concentration as a function of time at the outlet of the system. With the time of release at t = 0, the RTD (t) function is then defined as:

$$\mathbf{RTD(t) = \frac{QC(t)}{\int_0^\infty QC(t)dt}} \qquad \mathbf{(6.3)}$$

Where,

Q = Flow rate of water out of the wetland, $[L^3/T]$

C(t) = Concentration of tracer at the outlet of the wetland, $[M/L^3]$

The numerator represents the mass flow rate of the tracer out of the wetland at a given time after the release. The integral in the denominator represents the summation of all the tracer collected and thus should be equal to the total mass of the tracer input in the wetland, M:

$$\mathbf{M = \int_0^\infty QC(t)dt} \tag{6.4}$$

The recovery of the tracer mass is an important quality check for the measured RTD (t). However some percent of the tracer injected may be lost due to adsorption to the roots of the plants and to the soil, or entrapment in the stagnant regions of the wetland (‘dead zones’). Thus the failure to recovery one hundred percent of the tracer mass results an inaccurate measurement of the RTD (t).
If the flow rate is constant, the RTD (t) is simplified to:

$$\mathbf{RTD(t) = \frac{C(t)}{\int_0^\infty C(t)dt}} \tag{6.5}$$

The moments of the RTD (t) define the transport characteristic of the wetland system. The nth moment is defined by:

$$\mathbf{Mn = \int_0^\infty t^n RTD(t)dt} \tag{6.6}$$

The zeroth moment is one by definition.

$$\mathbf{\int_0^\infty RTD(t)dt = 1} \tag{6.7}$$

The first moment of the RTD (t) is the detention time. It is the average time that a tracer particle spends in the wetland system. This average time is also called the effective residence time:

$$\mathbf{T_{det} = \int_0^\infty tRTD(t)dt} \qquad \textbf{(6.8)}$$

Where,

T_{det} = Tracer detention time, [T]

A wetland system may have internal regions that do not interact with the flow of the water, such as the regions that are occupied by stagnant water bodies. With the existences of these excluded zones, the tracer detention time, T_{det} will be shorter than the mean hydraulic detention time, τ. If a non-conservative tracer is used, it will produce an incorrectly short detention time, which may lead to an erroneous presumption that an excluded zone existed in the system. In a steady state system without excluded zones, the tracer detention time, T_{det} will be equal to the mean hydraulic detention time, τ. This is true for all flow patterns and all degree of mixing in the wetland system.
The second moment of the RTD (t) is the variance, σ^2. It characterizes the spread of the tracer response curve around the tracer detention time, T_{det} (Figure 6.1).

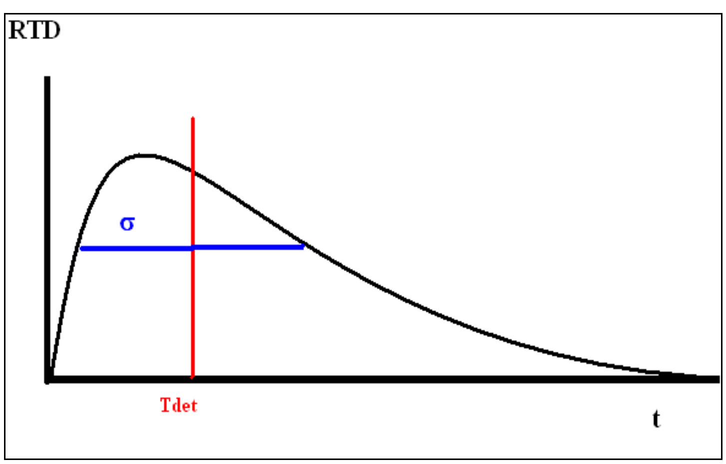


Figure 6.1: Plot of Residence Time Distribution function, RTD (t) Vs. Time.

If the standard deviation, σ approaches zero, it is a case where there is no mixing in the reactor and is considered as a plug flow reactor. Similarly, if the standard deviation, σ approaches infinity, it is considered as a fully mixed reactor.

The variance, σ^2 of the RTD (t) is created by mixing or by a distribution of flow paths and flow speeds within the wetland system. The second moment of the RTD (t) is defined as:

$$\sigma^2 = \int_0^\infty (t - T_{det})^2 \, RTD(t)dt \tag{6.9}$$

Where,

σ^2 = Variance of the RTD (t) function, $[T^2]$

The tracer curves and moment calculations can be used to compare the efficiency of ideal and non-ideal chemical reactors (Kadlec 1996). The chemical reactions in wetlands can be modeled as first order, homogeneous reactions (Kadlec 1996). This produces a decay in concentration that is exponential:

$$\frac{C(t)}{C_o} = \exp(-k_r t) \tag{6.10}$$

Where,

C (t) = Concentration of pollutant at a given time, t, $[M/L^3]$

C_o = Concentration of pollutant at time, t=0, $[M/L^3]$

k_r = Reaction rate coefficient, [1/T]

Elements of water entering a flow-through wetland system are presumed to move through the system as individual, non-interacting ‘packets’ (Kadlec 1996). Since a given packet of fluid has a distinct residence time, it will also have a different effluent concentration. The

RTD (t) can be used to describe the length of time any packet spends in the wetlands before exiting, thus providing the respective residence time for the given packet.
Given steady state conditions, and an inlet concentration, C_o, the average concentration of pollutant at the exit is then defined as:

$$\frac{\overline{C_e}}{C_o} = \int_0^\infty RTD(t)\exp(k_r t)dt \qquad (6.11)$$

Where,

$\overline{C_e}$ = Average concentration of pollutant at outlet, $[M/L^3]$

C_o = Concentration of pollutant at inlet, $[M/L^3]$

.

Thus the fraction of the average concentration of pollution that is removed by the wetland system, RF, is then defined as:

$$RF = 1 - \frac{\overline{C_e}}{C_o} \qquad (6.12)$$

6.3 Methodology

Tracer tests were conducted on the constructed wetland systems in Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital and Dhulikhel Hospital. The detected bromide concentration in the sample collected was analyzed using the method of moments (Chapter 6.1.1). The moments provide information needed to determine the tracer detention time, $T_{det,}$ the variance, σ^2 of the RTD (t), the reaction rate coefficient, k_r, and the fraction of the average concentration of pollution that is removed by the wetland system, RF (Chapter 7).

6.3.1 Flowrate Measurement

Due to the design of the outlet of the wetland systems, it was not possible to use a flow meter to measure the flowrate of the effluent. Therefore the conservative method of discharge measurement, *bucket method* was used. A plastic bucket, with a volume of 8 liters or 10 liters, is placed under the effluent pipe to collect the water discharge from the system. The time for the bucket to be filled was recorded. Thus the flowrate of the effluent, Q at that instance is given as:

$$\mathbf{Q = \frac{V_b}{T_f}} \qquad \mathbf{(6.13)}$$

Where,

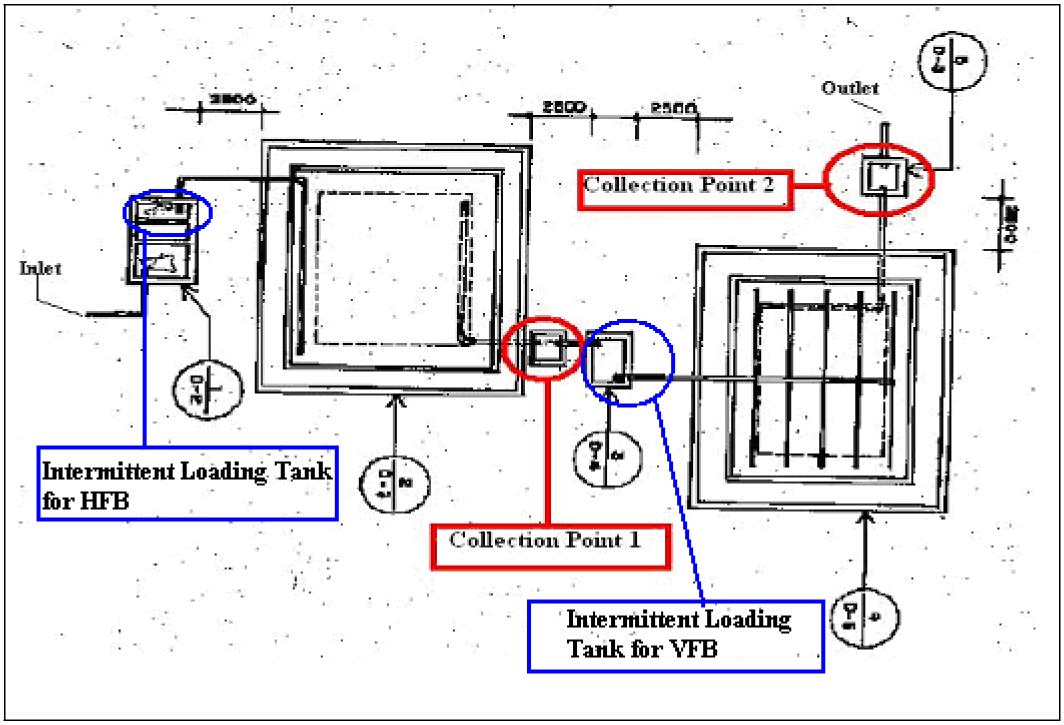
Q = Effluent flow rate, $[L^3/T]$

V_b = Volume of the bucket used, $[L^3]$

T_f = Time taken to fill the bucket, [T]

To obtain the entire flowrate of the discharge during the course of the experiment, the number of flushes, which is fed into the wetland beds, is recorded (Appendix A). The volume of the wastewater in the feeding tank can be estimated by measuring the depth of the water as the dimension of the tank is given. Thus, the volume of the wastewater discharging into the wetland system can be determined. The effluent flowrate during a flush is recorded almost continuously to estimate the overall flowrate for the system.

The collection points to determine the flowrates for Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital is shown in Figure 6.2.



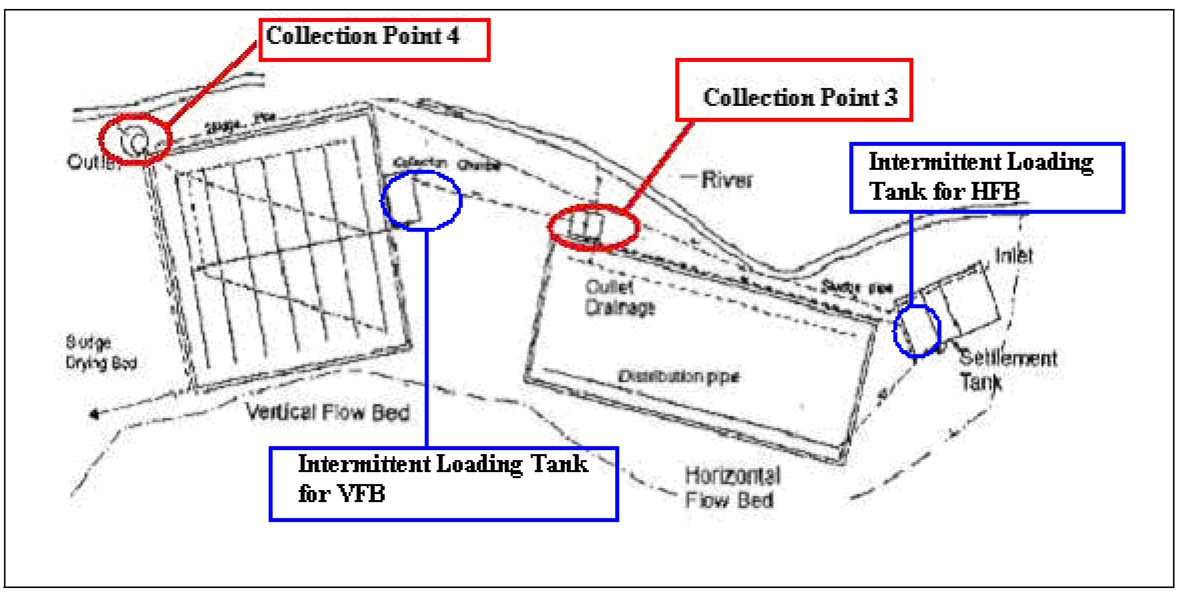
<u>Figure 6.2</u>: Collection Points for Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital (ENPHO 2002).

Collection Point 1 and Collection Point 2 are the locations at which the flowrate for the effluent for the horizontal flow bed and the vertical flow bed respectively. The collection point 1 and collection point 2 are shown in Figure 6.3 and Figure 6.4 respectively.

<u>Figure 6.3</u>: Collection Point 1 at Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital (Effluent of HFB)

<u>Figure 6.4</u>: Collection Point 2 at Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital (Effluent of VFB)

The collection points to determine the flowrates for Dhulikhel Hospital is shown in Figure 6.5.



<u>Figure 6.5</u>: Collection Points for Dhulikhel Hospital (ENPHO, 1997).

Collection Point 3 and Collection Point 4 are the locations to measure the flowrate for the effluent for the horizontal flow bed and the vertical flow bed respectively.

The collection point 3 and collection point 4 are shown in Figure 6.6 and Figure 6.7 respectively.

Figure 6.6: Collection Point 3 at Dhulikhel Hospital (Effluent of HFB)

Figure 6.7: Collection Point 4 at Dhulikhel Hospital (Effluent of VFB)

6.3.2 Tracer Experiments

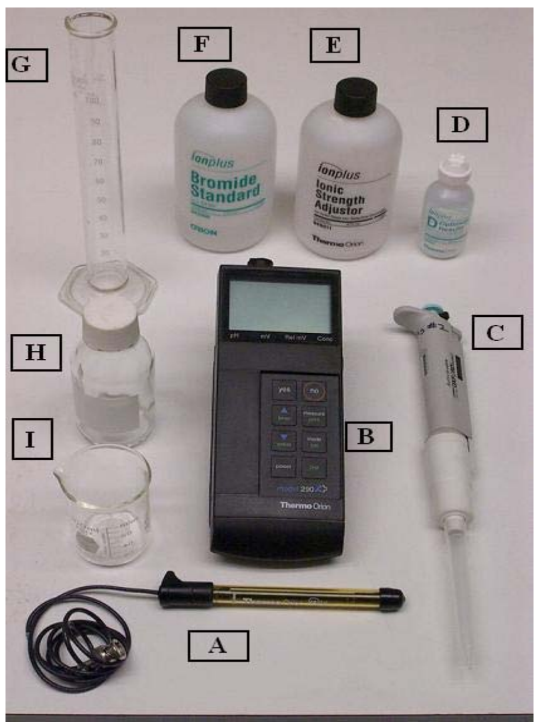
The number of tracer tests conducted on the constructed wetland systems in Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital and Dhulikhel Hospital were two for each system. The two tracer tests for each wetland system were performed on the vertical and horizontal flow bed.

6.3.2.1 Sodium Bromide Tracer Tests

Bromide was chosen as the tracer as it is conservative in most environments, has low background concentration, is easy to analyze and has low toxicity. It was obtained in the form of reagent grade Sodium Bromide, NaBr.

Equipment Used:

The Thermo Orion Model 9635 *ionplus*® Series Bromide Electrode and Thermo Orion Model 290Aplus Portable Meter were used to measure the bromide ions, which were used as tracers (Figure 6.8).



<u>Figure 6.8</u>: Equipments Used for NaBr Tracer Test: A) Thermo Orion Model 9635 *ionplus*® Series Bromide Electrode. B) Thermo Orion Model 290Aplus Portable Meter. C) Automatic Pipette. D) Optimum Results D Filling Solution. E) Ionic Strength Adjustor (ISA). F) Bromide Standard Solution. G) 100ml Graduated Cylinder. H) Sampling Bottle I) 100 ml Measuring Beaker.

The Optimum Results D Filling Solution was used to fill the chamber of the electrode to prevent the electrode potentials from erratic behavior. The Bromide Standard Solution was used for calibrating the electrode, while the Ionic Strength Adjustor (ISA) was used to adjust the sample to a constant background ionic strength. Automatic Pipette, 100ml Graduated Cylinder, 100 ml Volumetric Flask and metal stirrer were also included for measurement and preparation for standard solutions. The list of equipments required is shown in Table 6.1.

Table 6.1: List of Equipment for NaBr Tracer Test

Quantity	Item	Company	Catalog No.	Unit Price	Price	Note
1	Portable Meter Reader	Thermo Orion	0290A0	$ 655.00	$ 655.00	
1	Bromide Ionplus Sure-Flow Electrode	Thermo Orion	9635BN	$ 592.00	$ 592.00	
1	Ion Selective Calibration Standards	Thermo Orion	943506	$ 64.00	$ 64.00	
1	Ionic Strength Adjustors	Thermo Orion	940011	$ 59.00	$ 59.00	
1	Optimum Results D Filling Solution	Thermo Orion	900063	$ 67.00	$ 67.00	Pack of 5 bottles
1	Automatic Pipette, autoclave 1-5 ml	Oxford	53502-440		$ -	
100	Pipette tips 250 /pk	VRW	53503-826	$ 0.09	$ 8.79	
1	100ml Graduated Cylinder				$ -	
2	100 ml Volumetric Flask	VRW	14216236	$ 22.49	$ 44.98	
1	Metal stirrer				$ -	

Tracer Amount Added:

The detection range for the electrode was from 10^{-6} to 10^{3} moles per liter (mol/L)
By assuming a well-mixed condition in the wetland with a concentration of 0.0001 mol/L in the wetland, the minimum amount of NaBr required for Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital and Dhulikhel Hospital wetland systems are 654 g and 162 g respectively (Calculation shown in Appendix A(xi) and Appendix B(ix) respectively). Therefore the effluent of the systems was estimated within the detection range for the electrode, which ranges from 10^{-6} to 10^{3} moles per liter (mol/L). The exact amount of NaBr added to the wetland system is summarized in Table 6.2.

Table 6.2: Amount of Sodium Bromide Added in Wetland System.

Hospital	Type of Flow Bed	Amount of NaBr (g)
Sushma Koirala Memorial	Horizontal	700
Sushma Koirala Memorial	Vertical	200
Dhulikhel	Horizontal	1200
Dhulikhel	Vertical	1150

Method of Feeding Tracer into the Wetland System:

The tracer solution was prepared by mixing the amount of NaBr with water in a bucket with a capacity of 15 liter. To ensure that all the solution would flushed into the flow beds, the solution was fed directing into the feeding bucket of the intermittent loading tank when the wastewater was about to flush into the wetland system (Figure 6.9).

Figure 6.9: Feeding Bucket of Intermittent Loading Tank

This method was used for all the tests, as the intermittent loading tanks for all systems were similar in design. The location of the intermittent loading tanks for the Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's and Dhulikhel Hospital's constructed wetland systems are shown in Figure 6.2 and Figure 6.5 respectively.

The tracer tests for the vertical flow bed and the horizontal flow bed of Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's wetland systems were conducted on January 12, 2003 and January 13, 2003 respectively. While the tracer tests for the vertical flow bed and the horizontal flow bed of Dhulikhel Hospital's wetland systems were conducted on January 19, 2003 and January 21, 2003 respectively.

Sample Collection and Analysis:

After the injection, the effluent of the beds was collected for at 15-30 minutes intervals for a maximum duration of 24 hours. The sample collection points for Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital are shown in Figure 6.2. Collection Point 1 and Collection Point 2 are the locations to collect the sample for the effluent for the horizontal flow bed and the vertical flow bed respectively. The collection point 1 and collection point 2 are shown in Figure 6.3 and Figure 6.4 respectively. The sample collection points for Dhulikhel Hospital are shown in Figure 6.3. Collection Point 3 and Collection Point 4 are the locations to collect the sample for the effluent for the horizontal flow bed and the vertical flow bed respectively. The collection point 3 and collection point 4 are shown in Figure 6.6 and Figure 6.7 respectively.

A plastic bucket that was tied with a piece of rope was placed below the effluent pipe to collect the effluent (Figure 6.10).

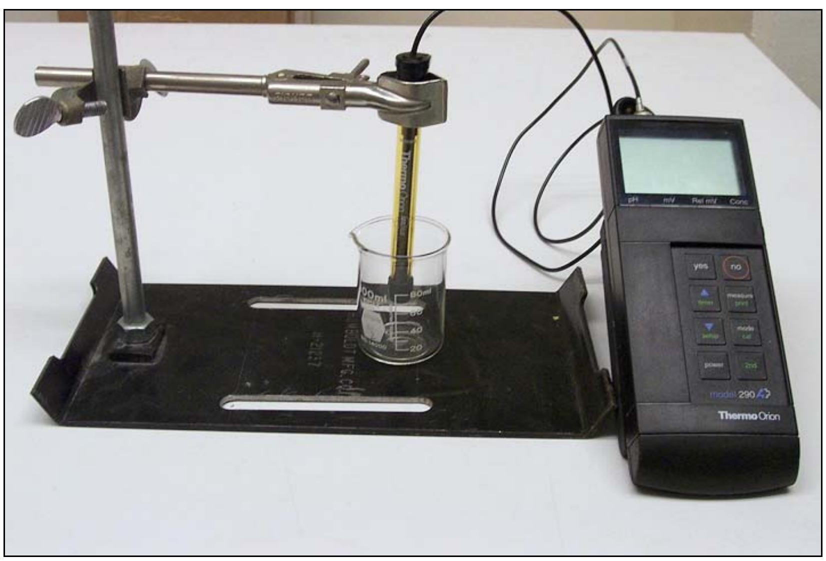
<u>Figure 6.10</u>: Sample Collection

The samples were collected in plastic bottles with a capacity of 150 milliliters (mL). The plastic bottle was flushed with the effluent collected in the bucket for three times before the final sample was collected.

The Thermo Orion Model 9635 *ionplus*® Series Bromide Electrode was calibrated as described in the electrode instruction manual. The method for preparation of standards is by serial dilution using the 0.1 M Bromide Standard Solution where the Ionic Strength Adjustor (ISA) was used to adjust the sample to a constant background ionic strength. This procedure involves preparing an initial standard that is diluted, using volumetric glassware, to prepare a second standard solution. The second standard solution is similarly diluted to prepare a third standard, and so on, until the desired range of 10^{-4} to 10^{-1} moles per liter (mol/L) has been prepared.

The sample was measured using the *Direct Measurement* procedures (Full procedure is found in the Thermo Orion Model 9635 *ionplus*® Series Bromide Electrode instruction manual):

1. Measure 100 mL of each sample collected and pour the sample into separate 150 mL beakers.
2. Add 2 mL of the Ionic Strength Adjustor (ISA) to each beaker.
3. Stir the sample solution thoroughly.
4. Rinse the electrode with distilled water and blot it dry.
5. Place the electrode into the sample with the assistant of a stand (Figure 6.11).



<u>Figure 6.11</u>: Sample Taking

6. Wait for a stable reading and the concentration of the bromide will be displayed on the meter.

Chapter 7 RESULTS

7.1 Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's Constructed Wetland System

7.1.1 Vertical Flow Bed

On January 12, 2003 at 4:20 P.M, 200 g of sodium bromide (NaBr) was introduced as tracer into the vertical flow bed of the Sushma Koirala Memorial (SKM) Plastic and Reconstructive Surgery Hospital's constructed wetland system. The collection of sample started when the tracer was introduced and the last sample was collected on January 13,2003 at 11:30 A.M (Appendix Ai). The concentration found was plot against time starting from t = 0 as the first sample was taken (Figure 7.1).

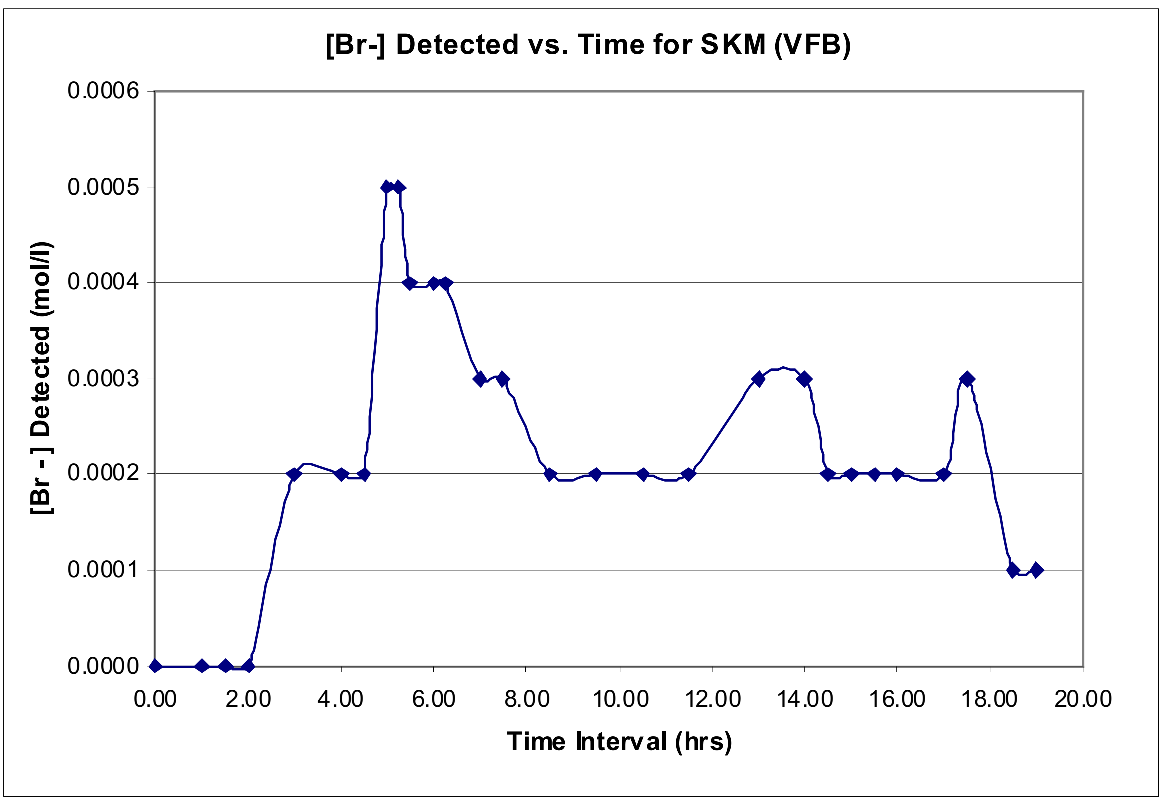


Figure 7.1: Plot of Bromide Concentration Detected against Time for SKM (Vertical Flow Bed).

Flowrates:

To obtain the flowrate for the entire experiment, the numbers of flushes into the vertical flow bed from the intermittent loading tank was recorded (Appendix A (ii)). It was observed that during the flushing, the effluent flowrate was higher. With the recorded effluent flow rate during a single flush (Appendix A (iii)), the effluent flowrate for the vertical bed was estimated for the entire duration of the tracer test (Appendix A (iv)). The plot of the estimated effluent flowrate during the duration of the experiment was shown in Figure 7.2 (where time =0 is the time the tracer was introduced).

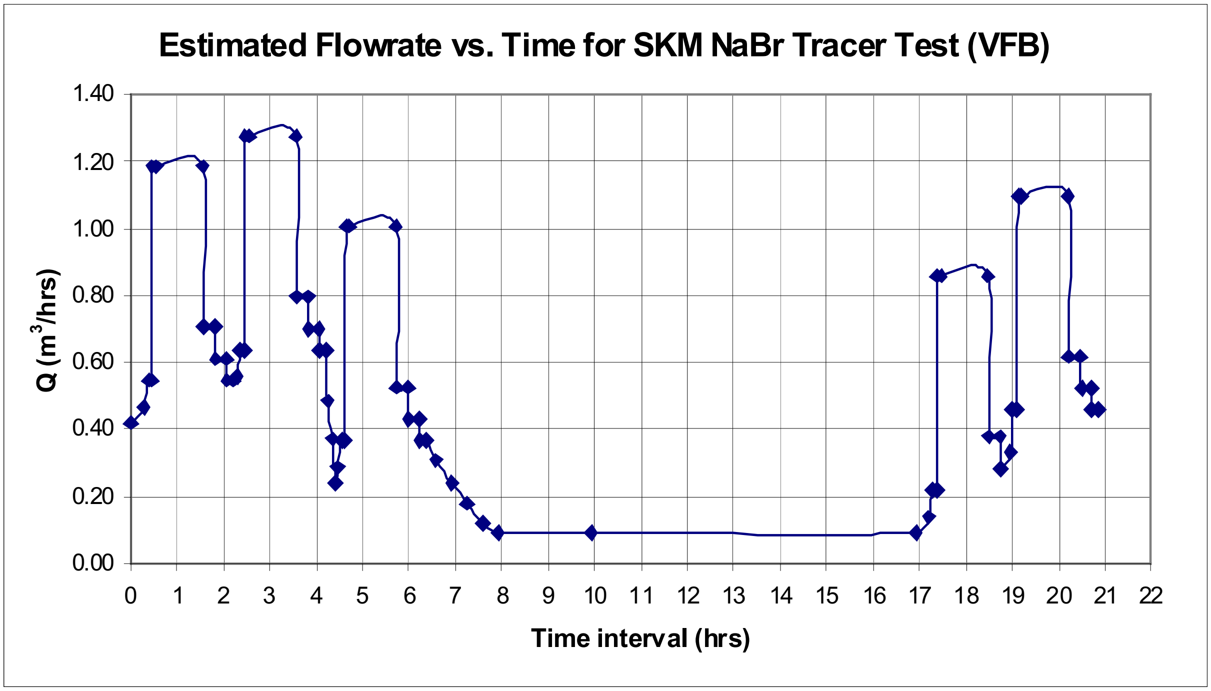


Figure 7.2: Plot of Estimated Flowrate vs. Time for SKM Hospital (Vertical Flow Bed).

The data collected were analyzed using the method of moments (Chapter 6.1.1). The moments provide information needed to determine the tracer detention time, T_{det}, residence time distribution function, RTD (t) and the variance, σ^2 of the RTD (t). By assigning a reaction rate coefficient, k_r, and the average concentration of pollution that is removed by the wetland system, RF can be found.

Tracer Detention Time:

Under the assumption that the effluent flowrate was constant, the tracer detention time was calculated at 10.1 hours using Equation 6.8. The integral was solved numerically by applying the trapezoid rule method. The calculations could be found in Appendix A (v). However since the actual effluent flowrate of the constructed wetland vary during the test, the tracer detention time was computed with the estimated flowrate was found to be 7.8 hours Appendix A (vi).

Mass of Sodium Bromide Recovered:

The total mass of sodium bromide recovered was calculated at 153.2 g using Equation 6.4. This showed that almost 77% of the chemical was recovered during the entire experiment.

Residence Time Distribution, RTD (t):

The residence time distribution, RTD (t) was computed using Equation 6.3 (Appendix A (vii)). The variance, σ^2 of the RTD (t) was found to be 27.0 hours^2 (Using Equation 6.9). The RTD (t) function was plotted against the number of detention time, shown in Figure 7.3.

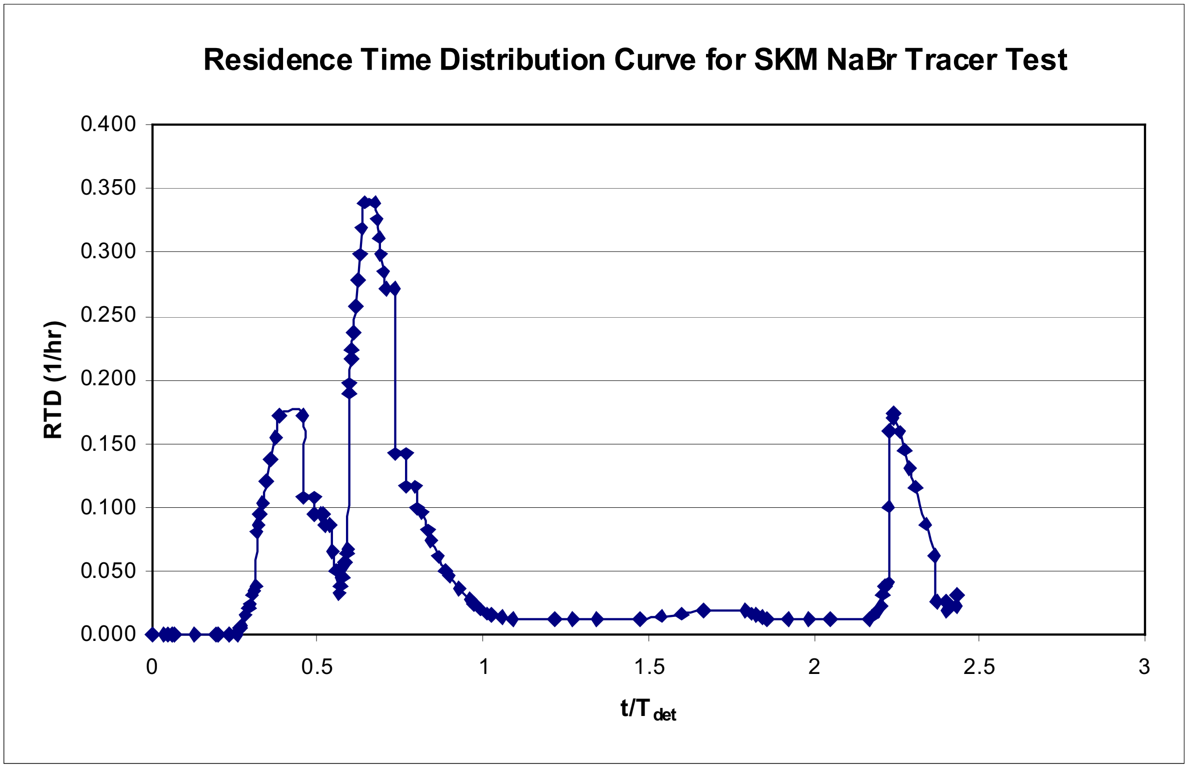


Figure 7.3: Residence Time Distribution Curve for SKM Hospital Tracer Test (Vertical Flow Bed).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

By assigning a reaction rate coefficient, k_r, and the average concentration of pollution that is removed by the wetland system, RF was be found using Equation 6.12. The range of the computed values compare to the respective assigned k_r was shown in Table 7.1.

Table 7.1: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for SKM Hospital Tracer Test (Vertical Flow Bed).

k_r (1/day)	7.0	8.0	10.0	12.0	17.0	22.0	25.0
R.F (%)	80.5	83.8	88.7	92.0	96.4	98.3	98.9

7.1.2 Horizontal Flow Bed

On January 13, 2003 at 12:45 P.M, 700 g of sodium bromide (NaBr) was introduced as tracer into the horizontal flow bed of the Sushma Koirala Memorial (SKM) Plastic and Reconstructive Surgery Hospital's constructed wetland system. The collection of sample started when the tracer was introduced and the last sample was collected on January 14,2003 at 10:45 A.M (Appendix Ai). The concentration found was plot against the time with t = 0 as when the tracer is released (Figure 7.4).

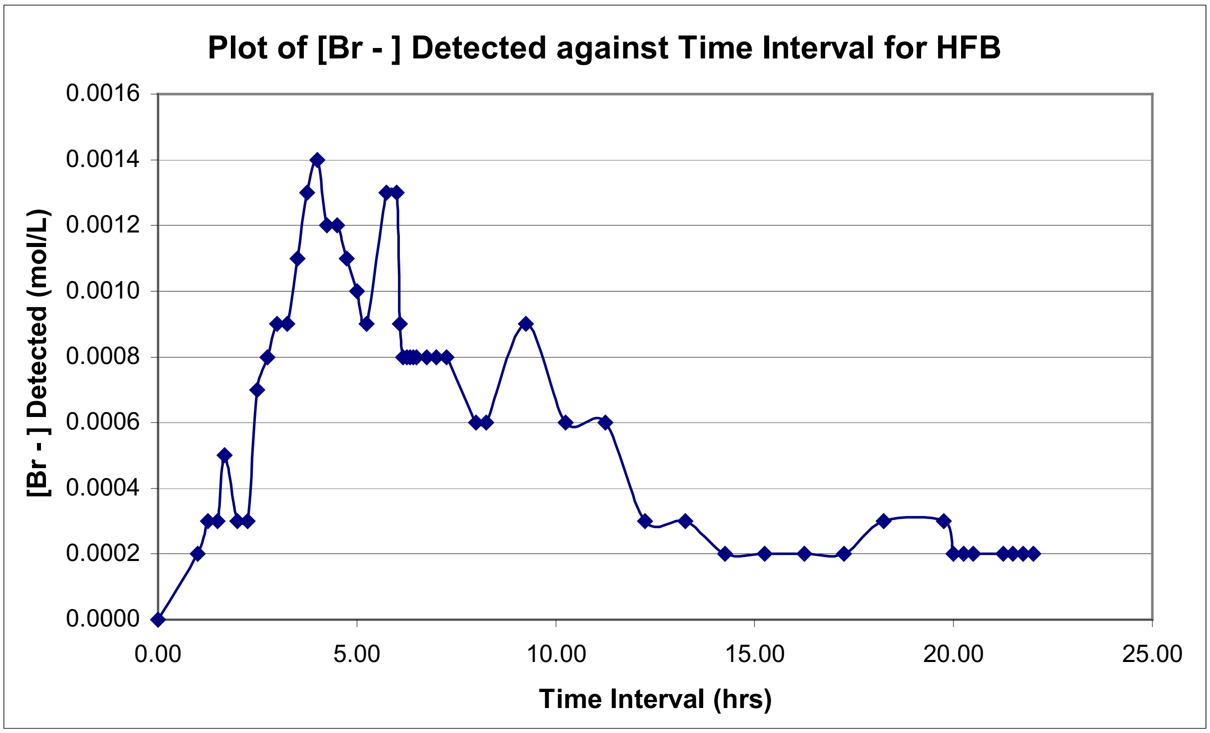


Figure 7.4: Plot of Bromide Concentration Detected against Time for SKM Hospital Horizontal Flow Bed).

Flowrates:

The plot of the estimated effluent flowrate during the duration of the experiment was shown in Figure 7.5 (where time=0 is when the tracer is introduced into the system).

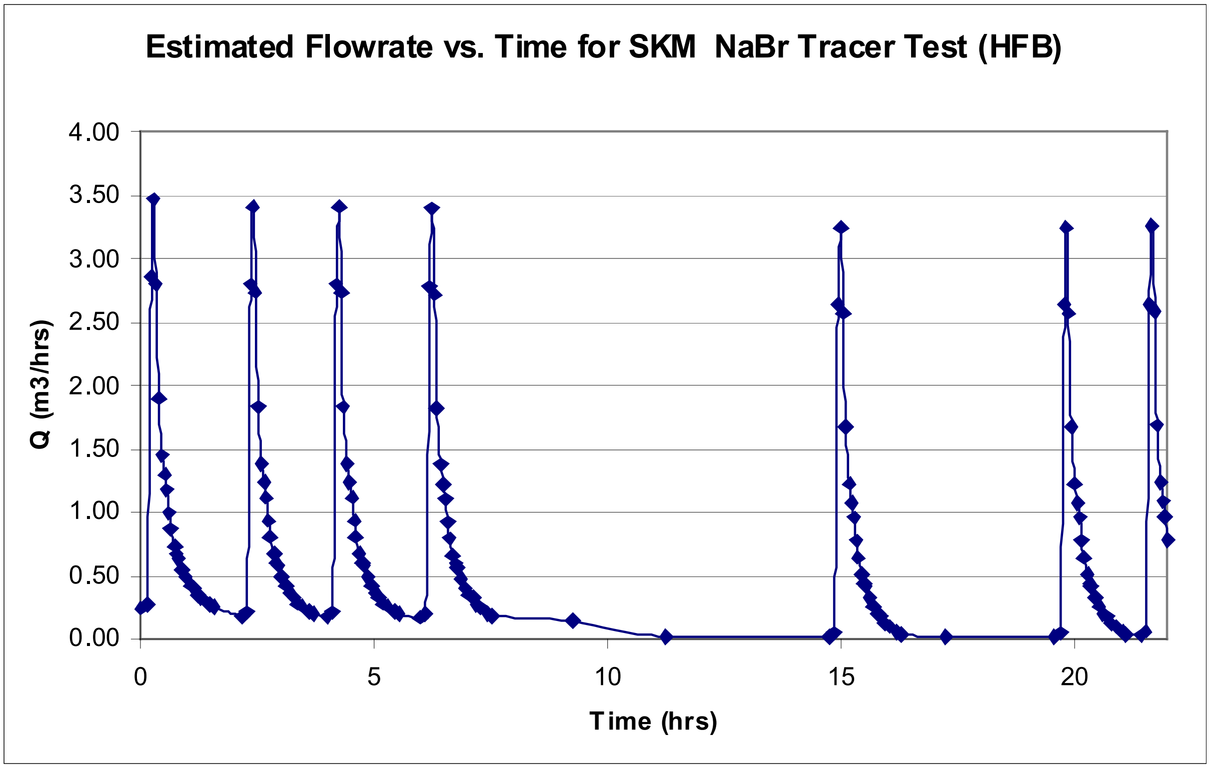


Figure 7.5: Plot of Estimated Flowrate vs. Time for SKM Hospital Tracer Test (Horizontal Flow Bed).

Tracer Detention Time:

The tracer detention time was calculated at 8.6 hours by assuming the effluent flowrate was constant (Appendix A (v)). The tracer detention time was computed with the estimated flowrate, was found to be 6.7 hours (Appendix A (vi)).

Mass of Sodium Bromide Recovered:

The total mass of sodium bromide recovered was calculated at 489.0 g using Equation 6.4. This showed that almost 70% of the chemical was recovered during the entire experiment.

Residence Time Distribution, RTD (t):

The variance, σ^2 of the RTD (t) was found to be 27.1 hours^2 (Using Equation 6.9). The RTD (t) function, found using Equation 6.3, was plotted against the number of detention time, shown in Figure 7.6.

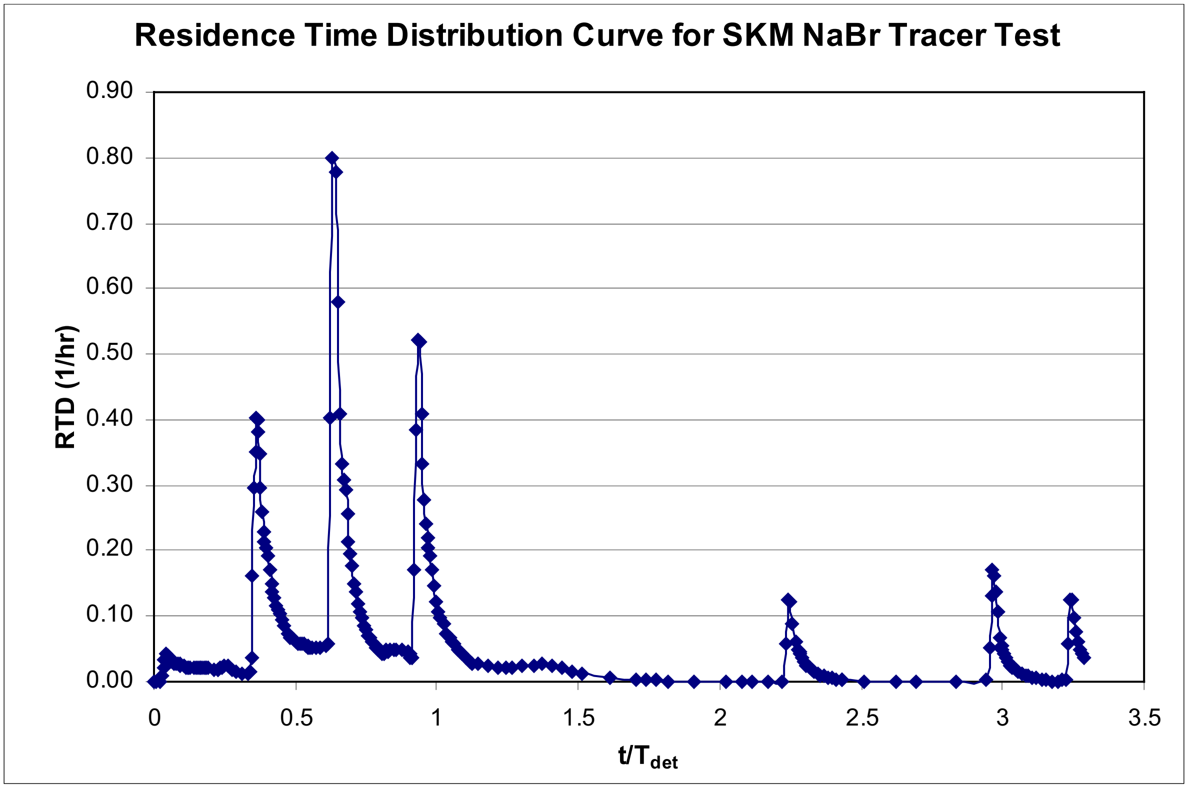


Figure 7.6: Residence Time Distribution Curve for SKM Hospital Tracer Test (Horizontal Flow Bed).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

The range of the computed values compare to the respective assigned k_r was shown in Table 7.2.

Table 7.2: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for SKM Hospital (Horizontal Flow Bed).

k_r (1/day)	9.0	11.0	14.0	17.0	20.0	28.0	38.0
R.F (%)	81.5	86.0	90.5	93.2	95.0	97.4	98.5

7.1.3 Simulation of Day Flow and Night Flow for Horizontal Flow Bed

Estimated Hourly Flowrate :

It was observed that the both the influent and effluent discharge was higher in the day than the night. The effluent flowrate for the horizontal bed in a day was estimated (Appendix A (iv)). The plot of the estimated hourly effluent flowrate in a day was shown in Figure 7.7 (where time =0 and time= 24 represents 12:00 A.M).

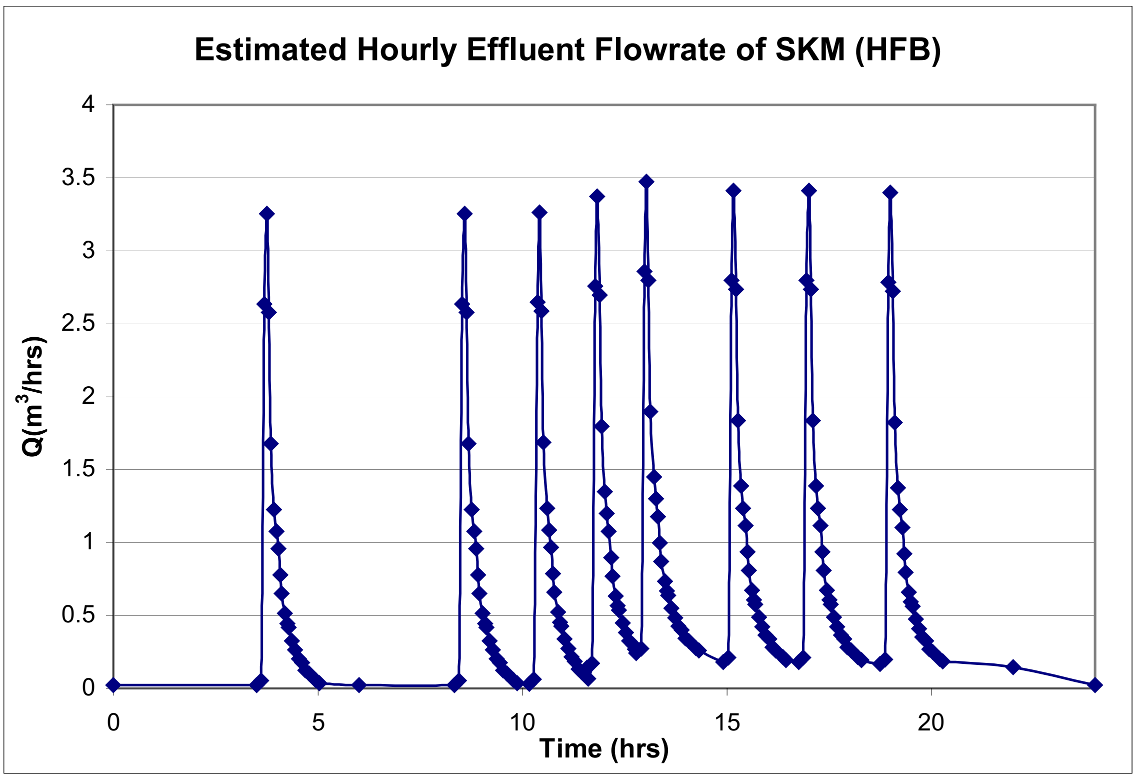
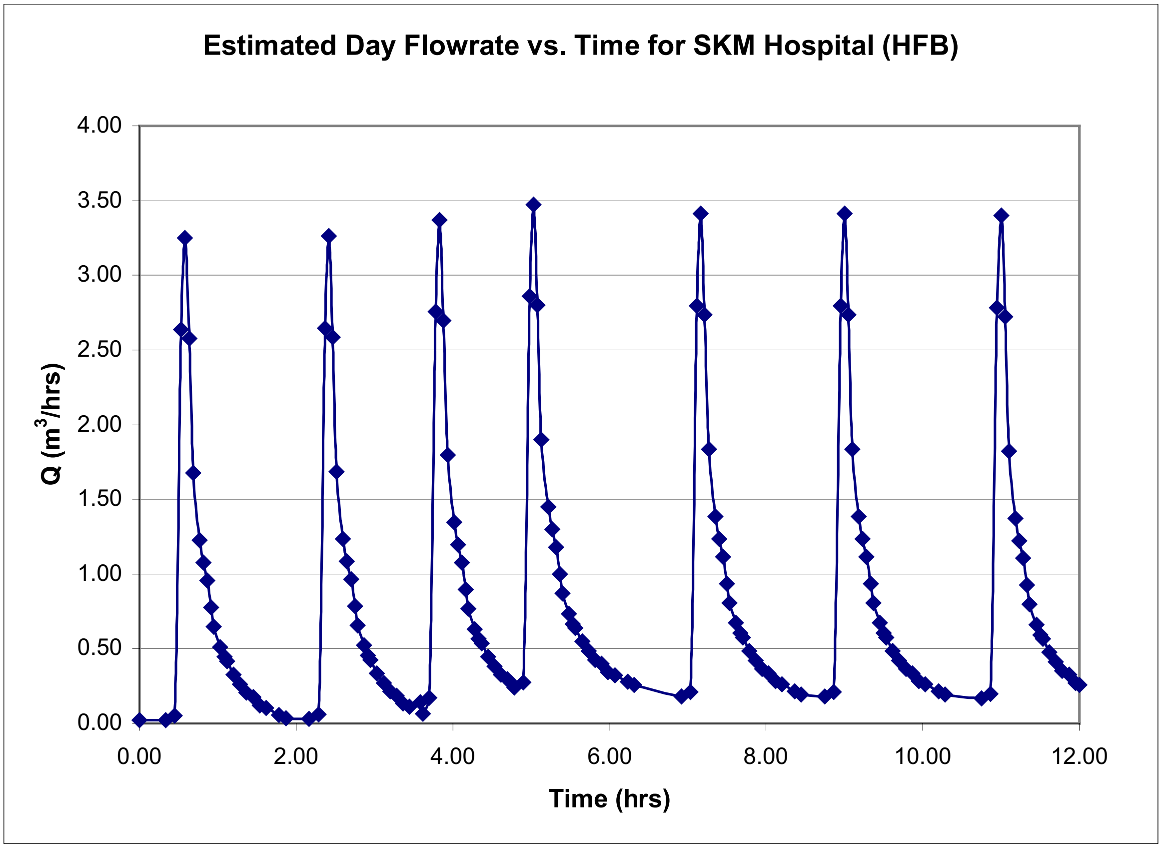


Figure 7.7: Plot of Estimated Hourly Flowrate against Time for SKM Horizontal Flow Bed In A Day.

Simulation of Day Flow and Night Flow:

The model was simulated for two diurnal variations, during the high flow period and the low flow period. These flow period were represented as the day flow and the night flow respectively. The hours selected for the day and night flows were 8:00 A.M to 8:00 P.M and 8:00 P.M to 8:00 A.M. The estimated day flowrate was shown in Figure 7.8 (where time =0 and time= 12 represents 8:00 A.M and 8:00 P.M respectively).



<u>Figure 7.8</u>: Plot of Estimated Day Flowrate Against Time for SKM Hospital (Horizontal Flow Bed).

The estimated night flowrate was shown in Figure 7.9 (where time =0 and time= 12 represents 8:00 P.M and 8:00 A.M and respectively).

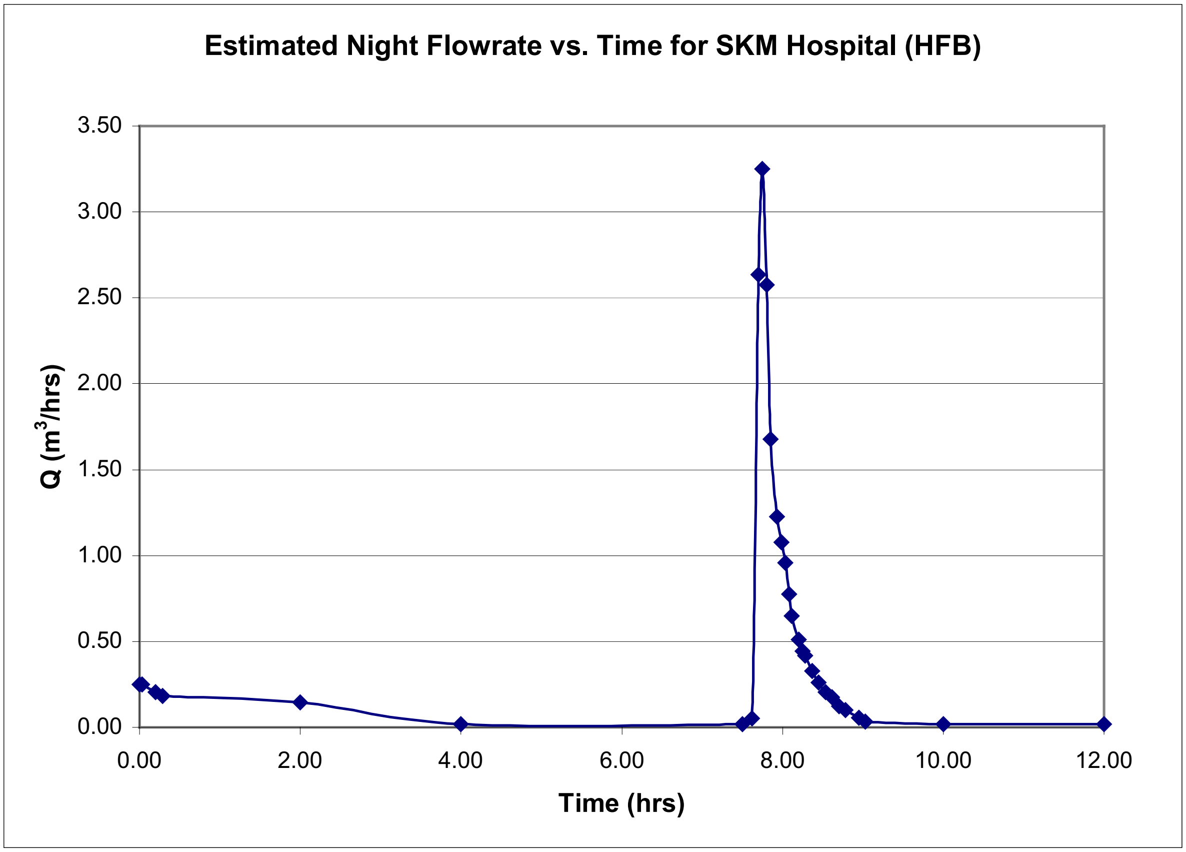


Figure 7.9: Plot of Estimated Night Flowrate Against Time for SKM Hospital (Horizontal Flow Bed).

The average flowrates for the high flow period and the low flow period were found to be 0.72 m^3/hr and 0.16 m^3/hr respectively (Appendix A (viii)).

Tracer Detention Time:

Although the physical design volume of the horizontal flow bed was 17.0 m^3, effective volume used during the tracer test was found to be 2.2 m^3 using the T_{det} found in Chapter 7.11 and the estimated flowrate for the experiment ($T_{det} = V/Q$) .

For analysis purpose, the volume of the flow bed was set as 17.0 m^3, the day and the night detention times were calculated to be 23.6 hours and 105.7 hours respectively (Appendix A (viii)).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

By assuming plug flow in the system, the average concentration of pollutant remained in the wetland can be defined as:

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right) \qquad \textbf{(7.1)}$$

Where,

$\frac{\overline{C_e}}{C_o} =$ Average concentration of pollutant remained in system

k_r = Reaction rate coefficient, [1/L]

T_{det}= Tracer detention time, [T]

Therefore by assigning a reaction rate coefficient, k_r, and the average concentration of pollution that is removed by the wetland system, RF was found using Equation 7.1 and 6.12 (Appendix A (viii)). The range of the computed values compare to the respective assigned k_r for day and night flows were shown in Table 7.3 and Table 7.4 respectively.

<u>Table 7.3</u>: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for SKM Hospital with Day Flow (Horizontal Flow Bed).

k_r (1/day)	0.4	0.44	0.5	0.6	0.7	0.8	1
R.F (%)	35.2	35.2	38.9	44.6	49.8	54.5	62.6

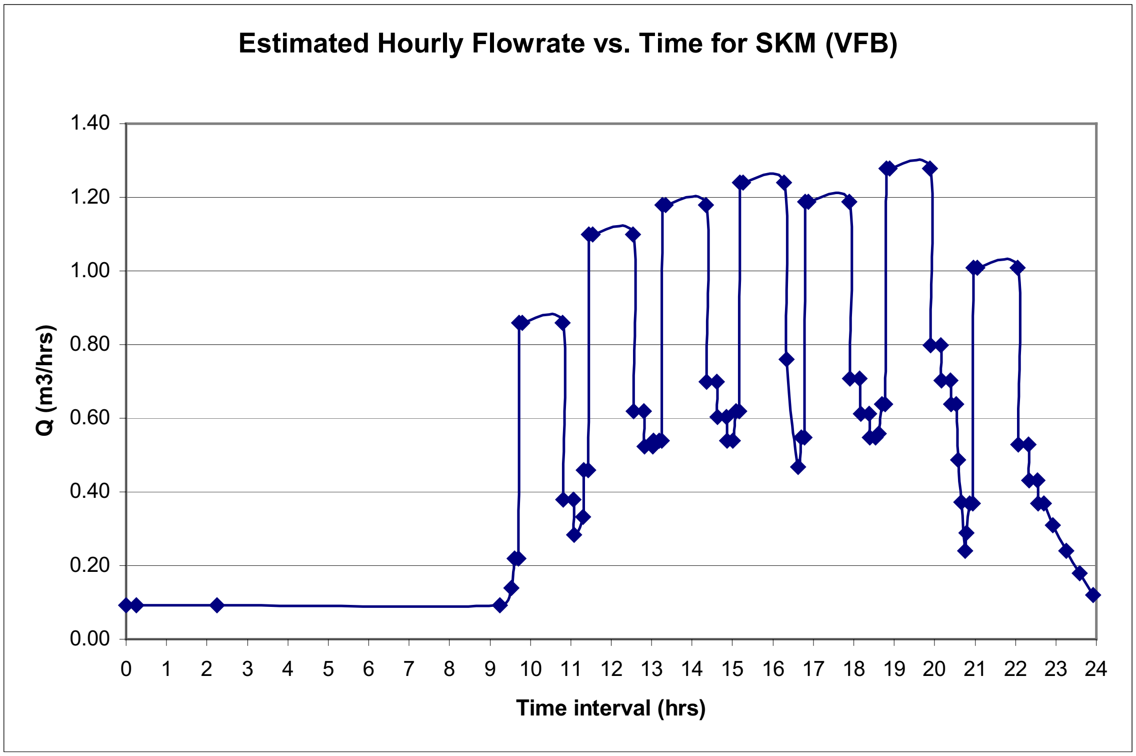
<u>Table 7.4</u>: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for SKM Hospital with Night Flow (Horizontal Flow Bed).

k_r (1/day)	0.4	0.44	0.5	0.6	0.7	0.8	1
R.F (%)	82.8	85.6	88.9	92.9	95.4	97.0	98.8

7.1.4 Simulation of Day Flow and Night Flow for Vertical Flow Bed

Estimated Hourly Flowrate :

The effluent flowrate for the vertical flow bed in a day was estimated (Appendix A (iv)). The plot of the estimated hourly effluent flowrate was shown in Figure 7.10 (where time =0 and time= 24 represents 12:00 A.M).



<u>Figure 7.10</u>: Plot of Estimated Hourly Flowrate Against Time for SKM Hospital In a Day (Vertical Flow Bed).

Simulation of Day Flow and Night Flow :

The hours selected for the day and night flows were 8:00 A.M to 8:00 P.M and 8:00 P.M to 8:00 A.M. The estimated day flowrate was shown in Figure 7.11 (where time =0 and time= 12 represents 8:00 A.M and 8:00 P.M respectively).

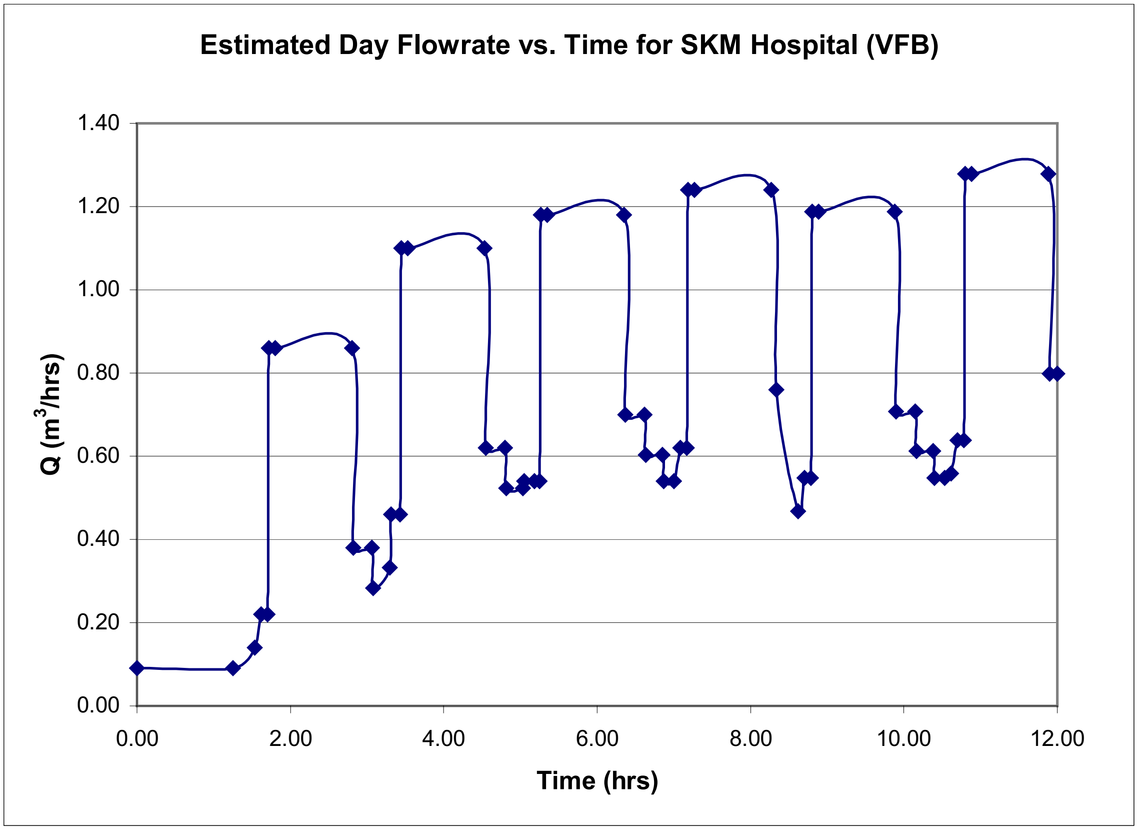
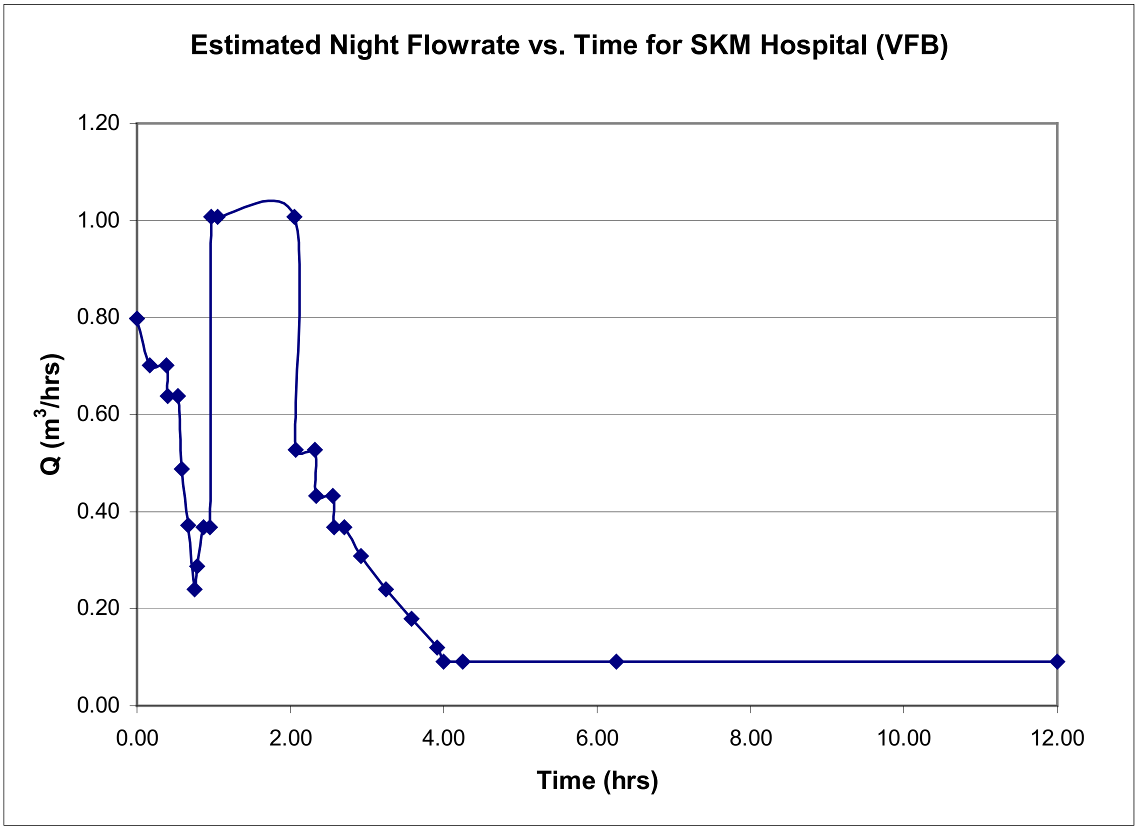


Figure 7.11: Plot of Estimated Day Flowrate Against Time for SKM Hospital (Vertical Flow Bed).

The estimated night flowrate was shown in Figure 7.12 (where time =0 and time= 12 represents 8:00 P.M and 8:00 A.M and respectively).



<u>Figure 7.12</u>: Plot of Estimated Night Flowrate Against Time for SKM Hospital (Vertical Flow Bed)

The average flowrates for the high flow period and the low flow period were found to be 0.97 m^3/hr and 0.14 m^3/hr respectively (Appendix A (viii)).

Tracer Detention Time:

Although the physical design volume of the vertical flow bed was 18.2 m^3, effective volume used during the tracer test was found to be 2.2 m^3, using the T_{det} found in Chapter 7.12 and the estimated flowrate for the experiment.

For analysis purpose, the volume of the flow bed was set as 18.2 m^3, the day and the night detention times were calculated to be 18.8 hours and 133.0 hours (Appendix A (viii)).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

The range of the computed values compare to the respective assigned k_r for day and night flows were shown in Table 7.5 and Table 7.6 respectively.

Table 7.5: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for SKM Hospital with Day Flow (Vertical Flow Bed).

k_r (1/day)	0.3	0.35	0.4	0.45	0.5	0.6	0.9
R.F (%)	20.9	24.0	26.9	29.7	32.4	37.5	50.6

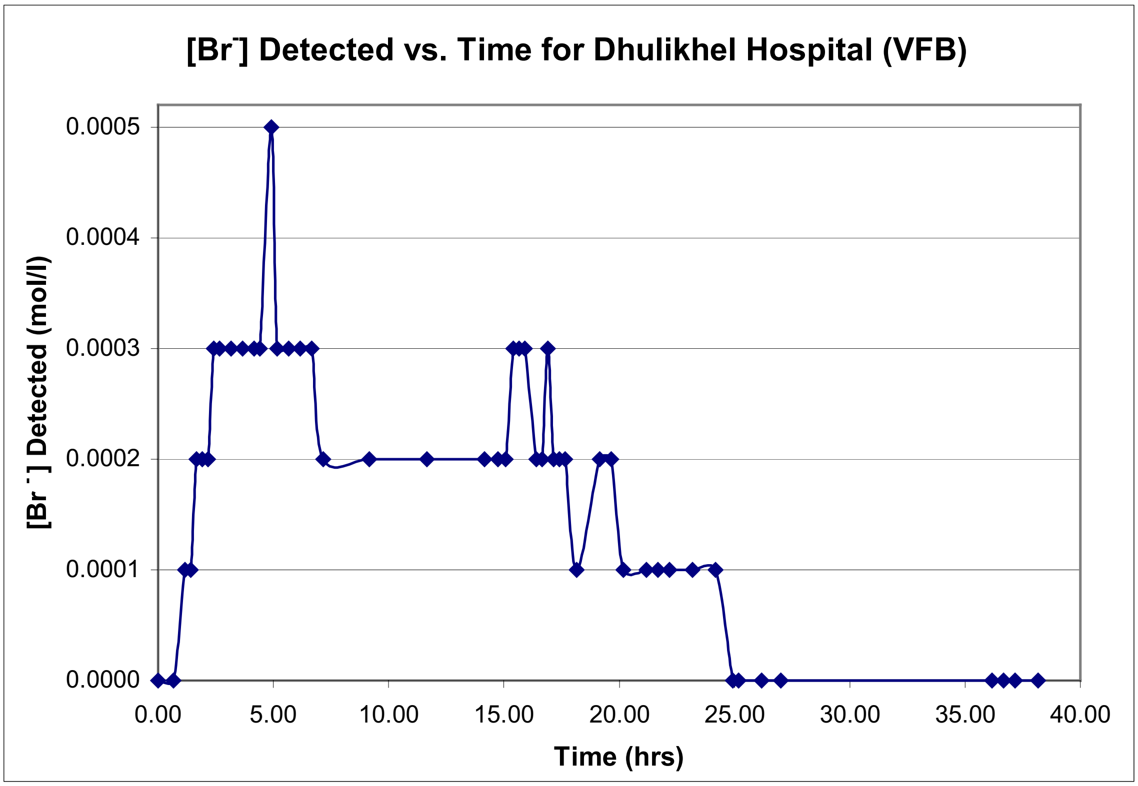
Table 7.6: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital with Night Flow (Vertical Flow Bed).

k_r (1/day)	0.3	0.35	0.4	0.45	0.5	0.6	0.9
R.F (%)	81.0	85.6	89.1	91.7	93.7	96.4	99.3

7.2 Dhulikhel Hospital's Constructed Wetland System

7.2.1 Vertical Flow Bed

On January 19, 2003 at 5:50 P.M, 1150 g of sodium bromide (NaBr) was introduced as tracer into the vertical flow bed of Dhulikhel Hospital's constructed wetland system. The collection of sample started when the tracer was introduced and the last sample was collected on January 21,2003 at 8:00 A.M (Appendix Bi). The concentration found was plot against time starting from t = 0 as the first sample was taken (Figure 7.13).



<u>Figure 7.13</u>: Plot of Bromide Concentration Detected against Time for Dhulikhel Hospital (Vertical Flow Bed).

Flowrates:

To obtain the flowrate for the entire experiment, the numbers of flushes into the vertical flow bed from the intermittent loading tank was recorded (Appendix B (ii)). It was observed that during the flushing, the effluent flowrate was higher. With the recorded volume of wastewater discharging during a single flush (Appendix B (iii)), the effluent flowrate for the vertical bed was estimated for the entire duration tracer test (Appendix B (iv)). The plot of the estimated effluent flowrate during the duration of the experiment was shown in Figure 7.14 (where time =0 is the time the tracer was introduced).

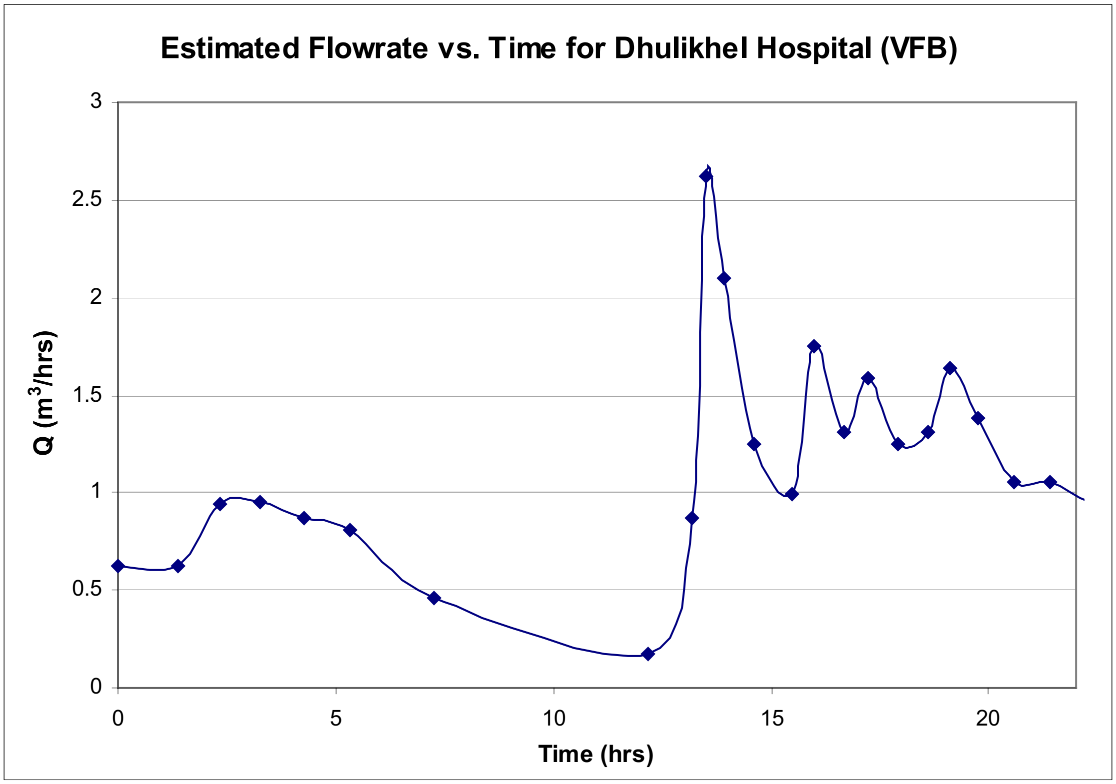


Figure 7.14: Plot of Estimated Flowrate vs. Time Dhulikhel Tracer Test (Vertical Flow Bed)

Tracer Detention Time:

The tracer detention time was calculated at 11.0 hours by assuming the effluent flowrate was constant (Appendix B (v)). The tracer detention time was computed with the estimated flowrate, was found to be 12.2 hours (Appendix B (vi)).

Mass of Sodium Bromide Recovered:

The total mass of sodium bromide recovered was calculated at 527.5 g using Equation 6.4. This showed that only 46% of the chemical was recovered during the entire experiment.

Residence Time Distribution, RTD (t):

The residence time distribution, RTD (t) was computed using Equation 6.3 (Appendix B (vii)). The variance, σ^2 of the RTD (t) was found to be 41.4 hours^2 (Using Equation 6.9). The RTD (t) function was plotted against the number of detention time, shown in Figure 7.15.

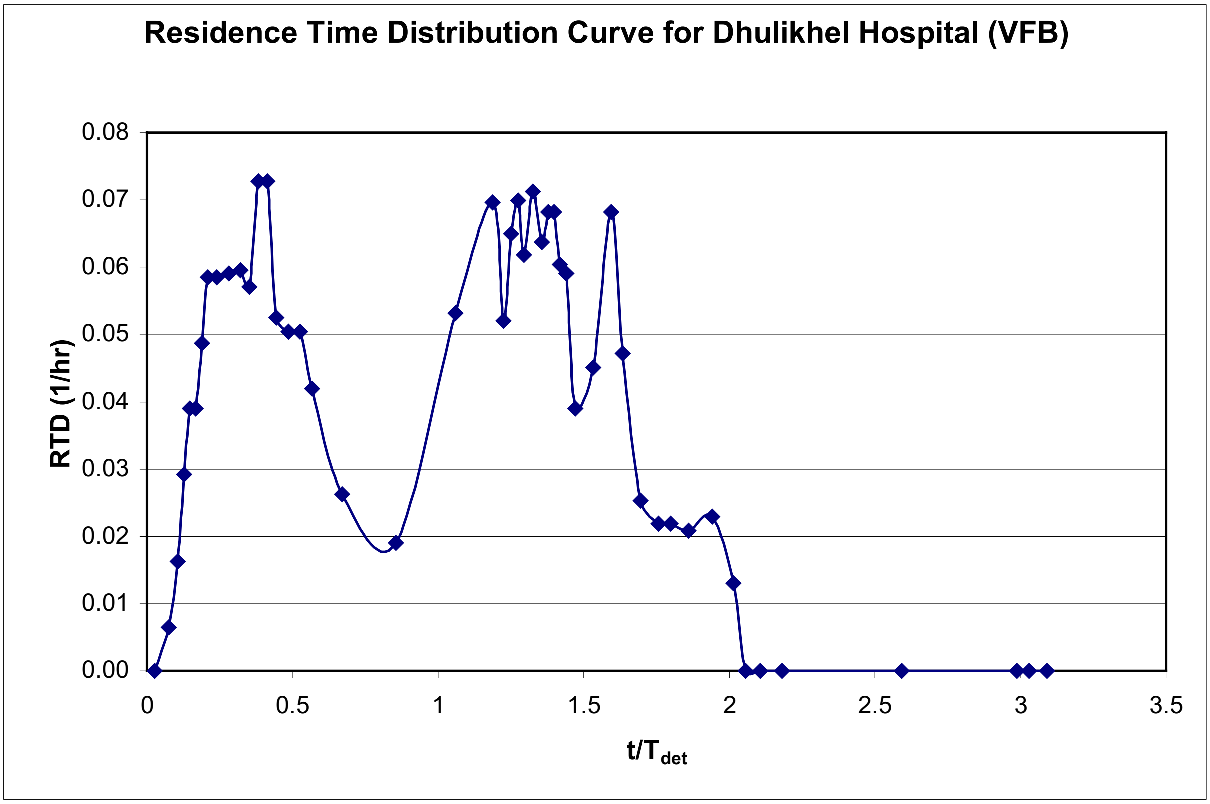


Figure 7.15: Residence Time Distribution Curve for Dhulikhel Hospital Tracer Test (Vertical Flow Bed)

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

The range of the computed values compare to the respective assigned k_r was shown in Table 7.7.

Table 7.7: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital Tracer Test (Vertical Flow Bed).

k_r (1/day)	5.0	7.0	9.0	11.0	13.0	20.0	25.0
R.F (%)	82.7	88.6	92.0	94.0	95.4	98.0	98.8

7.2.2 Horizontal Flow Bed

On January 21, 2003 at 6:50 A.M, 1200 g of sodium bromide (NaBr) was introduced as tracer into the horizontal flow bed of Dhulikhel Hospital's constructed wetland system. The collection of sample started when the tracer was introduced and the last sample was collected on January 22,2003 at 10:00 A.M (Appendix Bi). The concentration found was plot against the time with t = 0 as when the tracer is released (Figure 7.16).

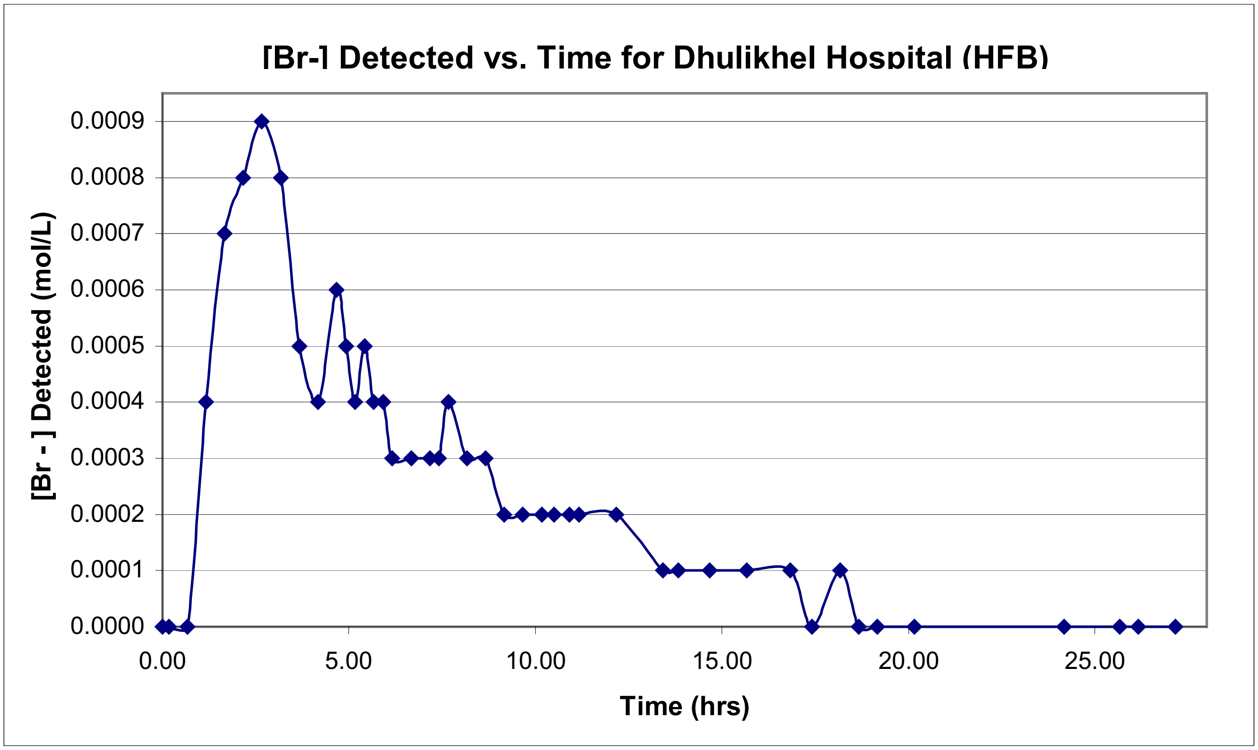


Figure 7.16: Plot of Bromide Concentration Detected Vs. Time for Dhulikhel Hospital (Horizontal Flow Bed).

Flowrates:

The plot of the estimated effluent flowrate during the duration of the experiment was shown in Figure 7.17 (where time =0 is the time the tracer was introduced).

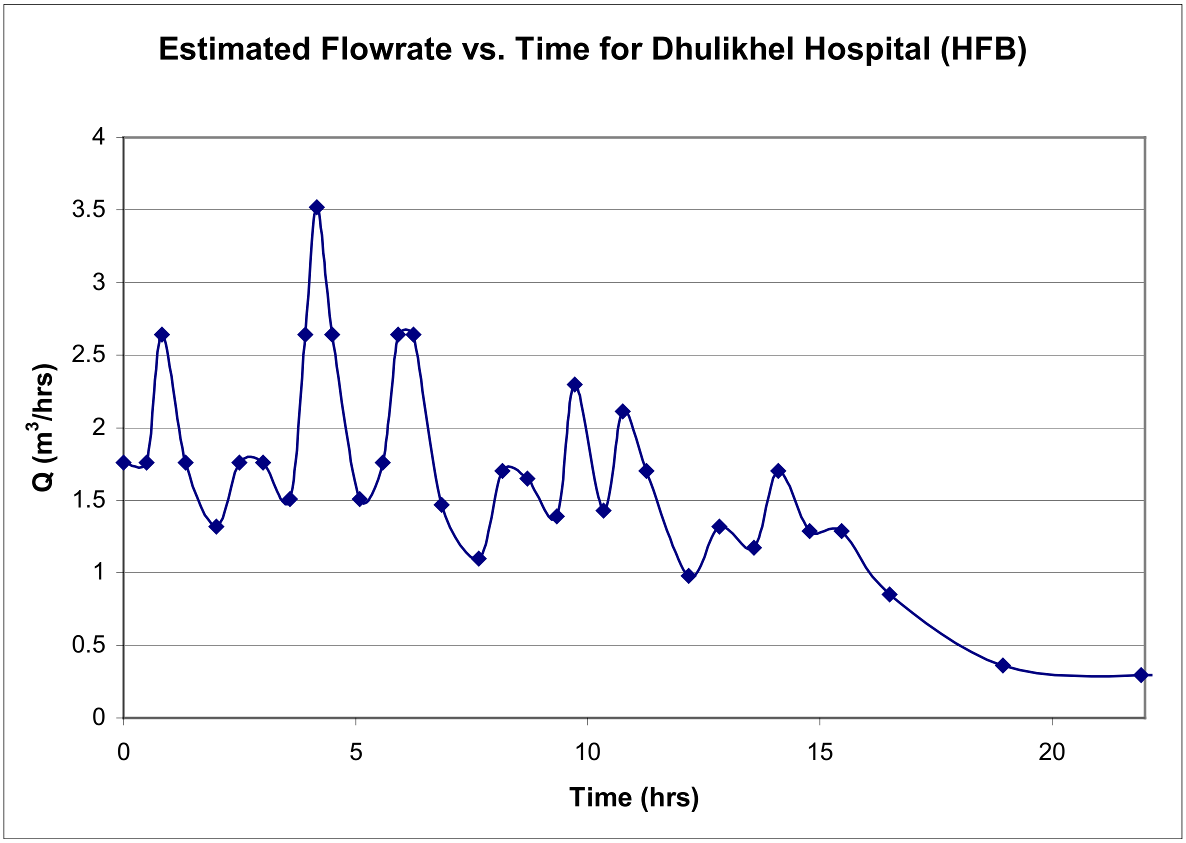


Figure 7.17: Plot of Estimated Flowrate Vs. Time Dhulikhel Tracer Test (Vertical Flow Bed).

Tracer Detention Time:

The tracer detention time was calculated at 6.3 hours by assuming the effluent flowrate was constant (Appendix B (v)). The tracer detention time was computed with the estimated flowrate, was found to be 5.6 hours (Appendix B (vi)).

Mass of Sodium Bromide Recovered:

The total mass of sodium bromide recovered was calculated at 921.9 g using Equation 6.4. This showed that only 77% of the chemical was recovered during the entire experiment.

Residence Time Distribution, RTD (t):

The variance, σ^2 of the RTD (t) was found to be 13.4 hours^2 (Using Equation 6.9). The RTD (t) function, found by using Equation 6.3, was plotted against the number of detention time, shown in Figure 7.18.

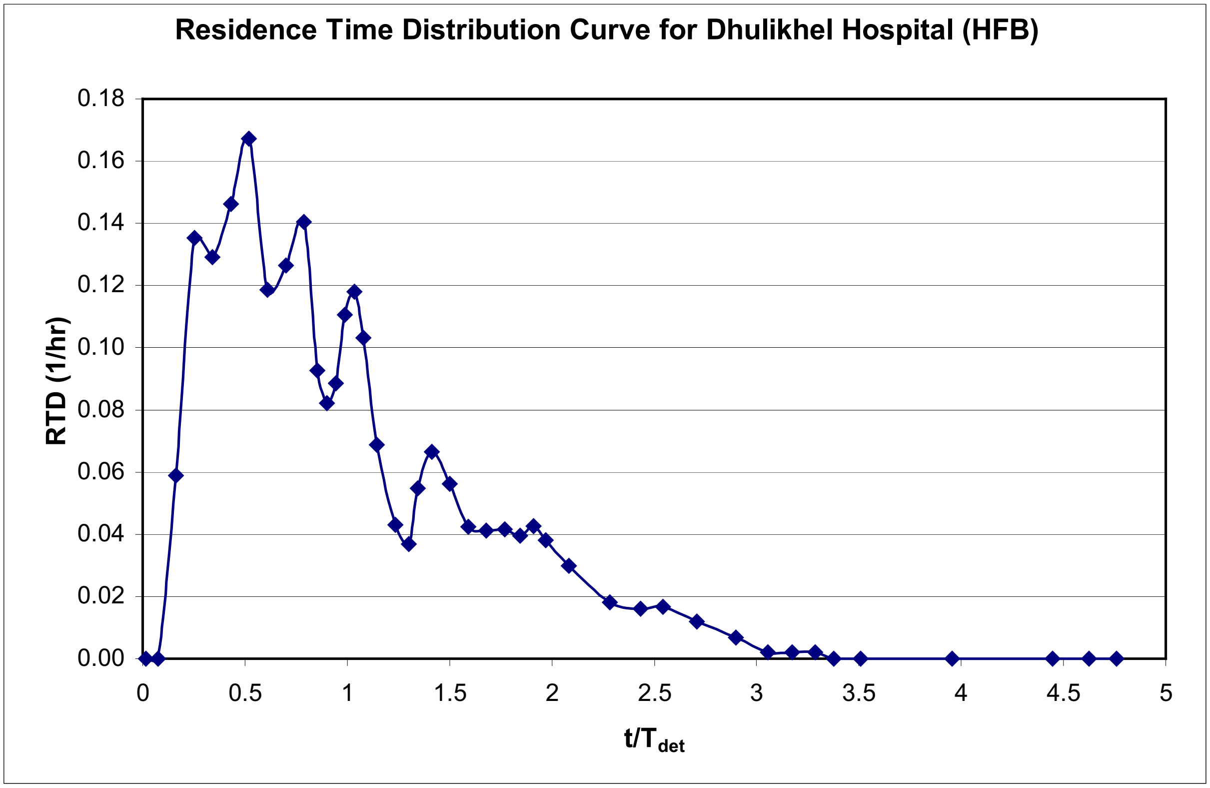


Figure 7.18: Residence Time Distribution Curve for Dhulikhel Hospital Tracer Test (Horizontal Flow Bed).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

The range of the computed values compare to the respective assigned k_r was shown in Table 7.8.

Table 7.8: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital Tracer Test (Horizontal Flow Bed).

k_r (1/day)	10.0	12.0	15.0	18.0	22.0	30	40.0
R.F (%)	80.0	84.0	88.3	91.1	93.7	96.6	98.2

7.2.3 Simulation of Day Flow and Night Flow for Horizontal Flow Bed

Estimated Hourly Flowrate :

The effluent flowrate for the horizontal bed in a day was estimated (Appendix B (iv)). The plot of the estimated hourly effluent flowrate in a day was shown in Figure 7.19 (where time =0 and time= 24 represents 12:00 A.M).

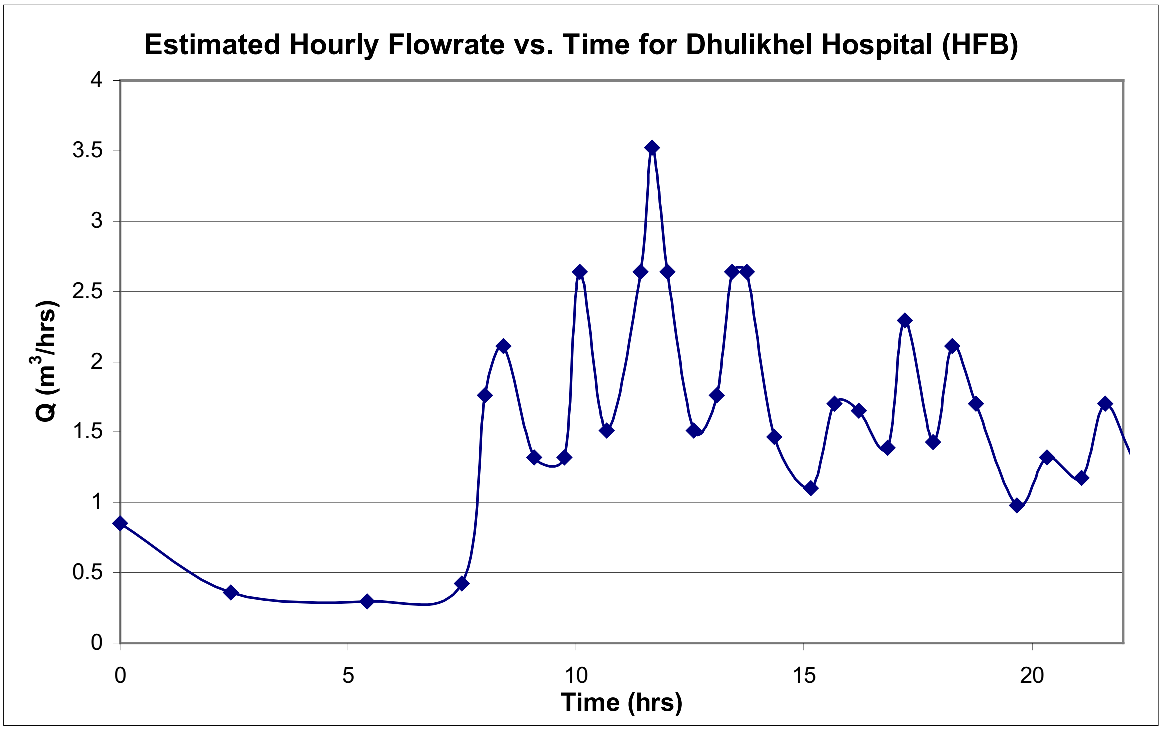


Figure 7.19: Plot of Estimated Hourly Flowrate Against Time for Dhulikhel Hospital In A Day (Horizontal Flow Bed).

Simulation of Day Flow and Night Flow:

The hours selected for the day and mean night flow were 8:00 A.M to 8:00 P.M and 8:00 P.M to 8:00 A.M. The estimated day flowrate was shown in Figure 7.20 (where time =0 and time= 12 represents 8:00 A.M and 8:00 P.M respectively).

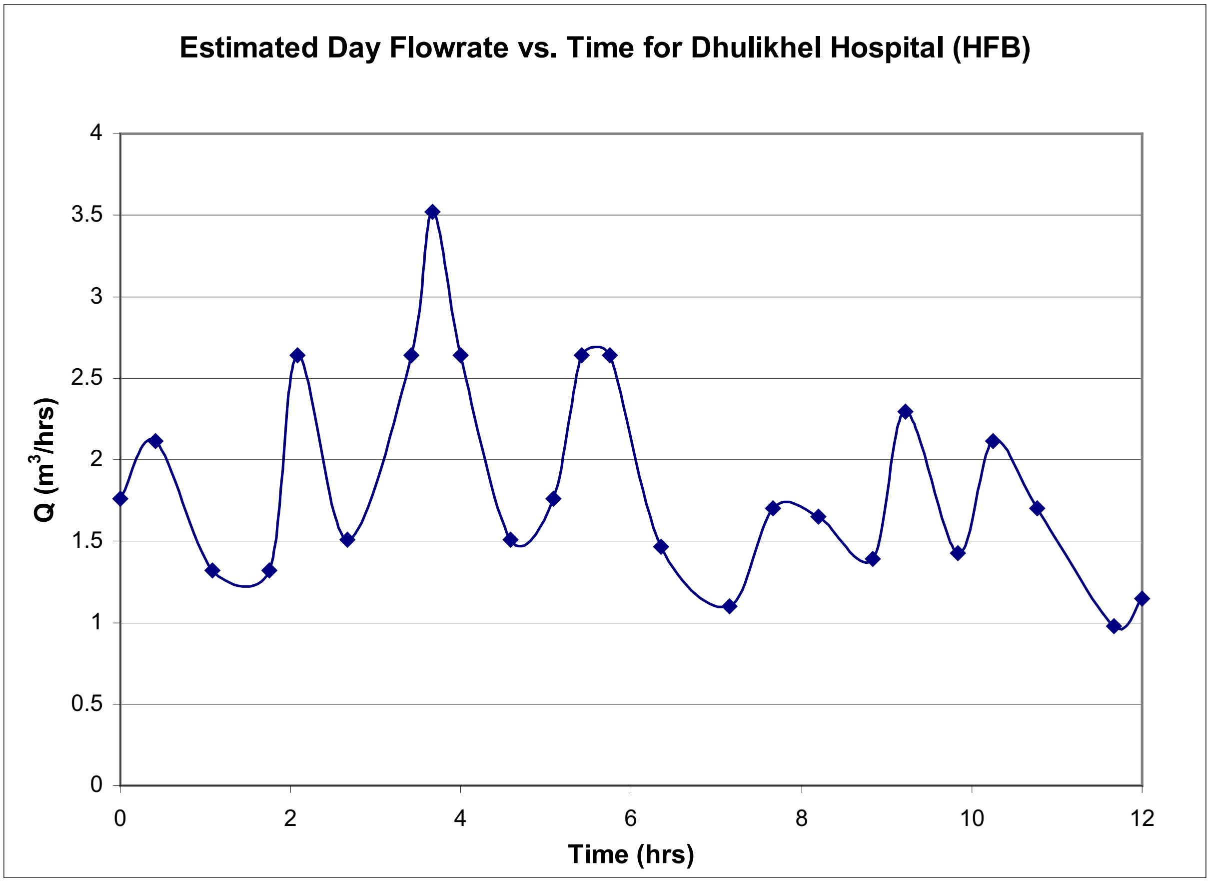


Figure 7.20: Plot of Estimated Day Flowrate Against Time for Dhulikhel Hospital (Horizontal Flow Bed).

The estimated mean night flowrate was shown in Figure 7.21 (where time =0 and time= 12 represents 8:00 P.M and 8:00 A.M and respectively).

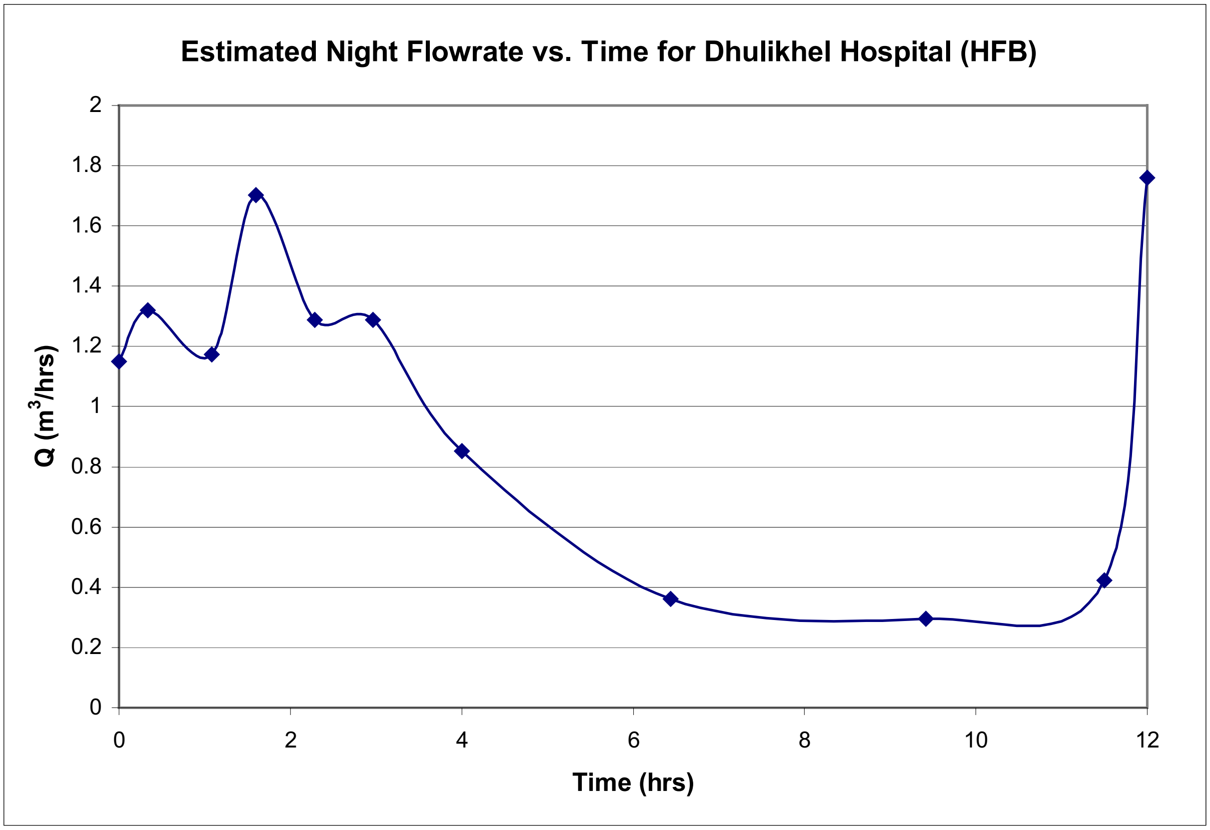


Figure 7.21: Plot of Estimated Night Flowrate Against Time for Dhulikhel Hospital (Horizontal Flow Bed).

The average flowrates for the high flow period and the low flow period were found to be 1.80 m^3/hr and 0.53 m^3/hr (Appendix B (viii)).

Tracer Detention Time:

Although the physical design volume of the horizontal flow bed was 33.0 m^3, effective volume used during the tracer test was found to be 8.5 m^3 using the T_{det} found in Chapter 7.11 and the estimated flowrate for the experiment.

For analysis purpose, the volume of the flow bed was set as 33.0 m^3, the day and the night detention times were calculated to be 18.3 hours and 62.2 hours (Appendix B (viii)).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

By assuming plug flow in the system, the average concentration of pollutant remained in the wetland was defined in Equation 7.1. The range of the computed values compare to the respective assigned k_r for day and night flows were shown in Table 7.9 and Table 7.10 respectively.

<u>Table 7.9</u>: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital with Day Flow (Horizontal Flow Bed).

k_r (1/day)	0.44	0.5	0.65	0.75	0.9	1.2	2
R.F (%)	28.5	31.7	39.1	43.5	49.6	60.0	78.2

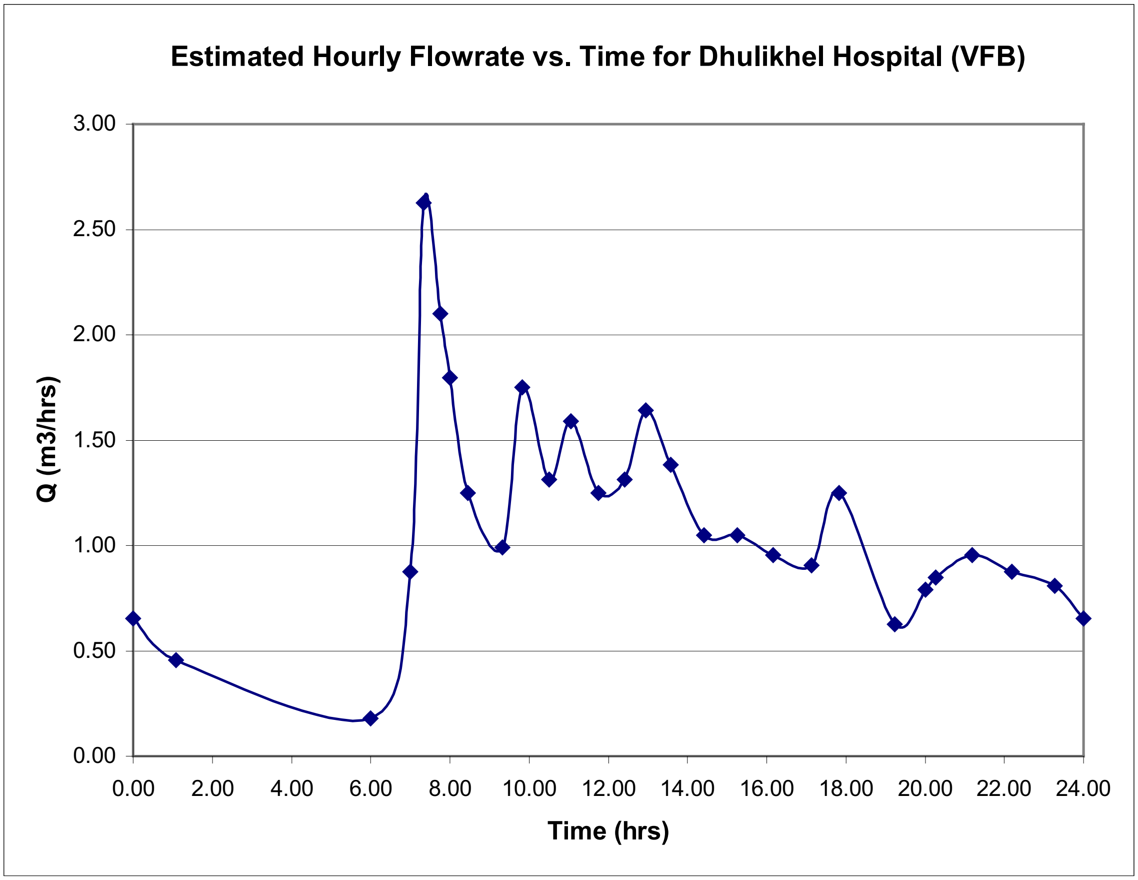
<u>Table 7.10</u>: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital with Night Flow (Horizontal Flow Bed).

k_r (1/day)	0.44	0.5	0.65	0.75	0.9	1.2	2
R.F (%)	68.0	72.7	81.5	85.7	90.3	95.5	99.4

7.2.4 Simulation of Day Flow and Night Flow for Vertical Flow Bed

Estimated Hourly Flowrate :

The effluent flowrate for the vertical flow bed in a day was estimated (Appendix B (iv)). The plot of the estimated daily effluent flowrate was shown in Figure 7.22 (where time =0 and time= 24 represents 12:00 A.M).



<u>Figure 7.22</u>: Plot of Estimated Hourly Flowrate Against Time for Dhulikhel Hospital In A Day (Vertical Flow Bed).

Simulation of Day Flow and Night Flow :

The hours selected for the day and night flows were 8:00 A.M to 8:00 P.M and 8:00 P.M to 8:00 A.M. The estimated day flowrate was shown in Figure 7.23 (where time =0 and time= 12 represents 8:00 A.M and 8:00 P.M respectively).

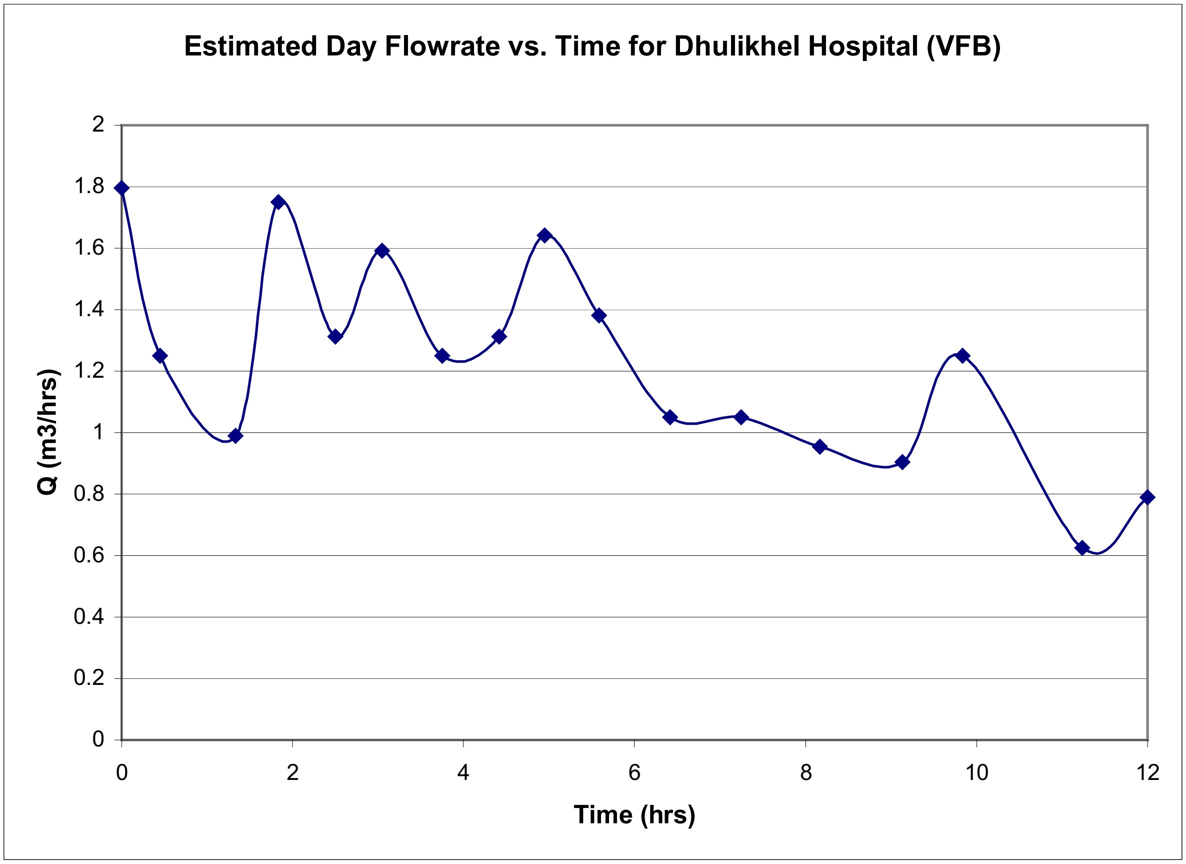


Figure 7.23: Plot of Estimated Day Flowrate Against Time for Dhulikhel Hospital (Vertical Flow Bed).

The estimated night flowrate was shown in Figure 7.24 (where time =0 and time= 12 represents 8:00 P.M and 8:00 A.M and respectively).

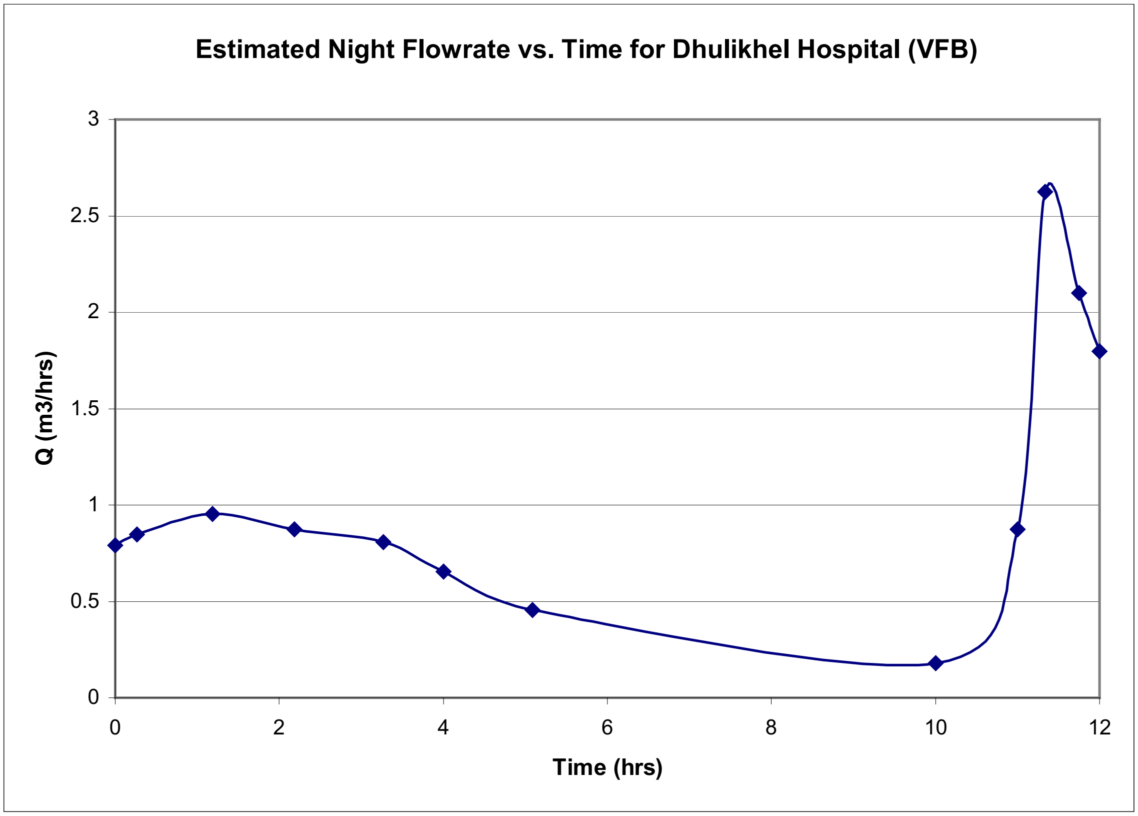


Figure 7.24: Plot of Estimated Night Flowrate Against Time for Dhulikhel Hospital (Vertical Flow Bed).

The average flowrates for the high flow period and the low flow period were found to be 1.11 m^3/hr and 0.76 m^3/hr (Appendix B (iv)).

Tracer Detention Time:

Although the physical design volume of the vertical flow bed was 33.0 m^3, effective volume used during the tracer test was found to be 14.0 m^3, using the T_{det} found in Chapter 7.12 and the estimated flowrate for the experiment.

For analysis purpose, the volume of the flow bed was set as 33.0 m^3, the day and the night detention times were calculated to be 29.6 hours and 43.5 hours respectively (Appendix B (iv)).

Reaction rate coefficient, k_r and Average Concentration of Pollution Removed, RF:

The range of the computed values compare to the respective assigned k_r for day and night flows were shown in Table 7.11 and Table 7.12 respectively.

Table 7.11: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital with Day Flow (Vertical Flow Bed).

k_r (1/day)	0.8	1	1.3	1.5	1.7	2	2.5
R.F (%)	62.7	70.9	79.9	84.3	87.7	91.5	95.4

Table 7.12: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF for Dhulikhel Hospital with Night Flow (Vertical Flow Bed).

k_r (1/day)	0.8	1	1.3	1.5	1.7	2	2.5
R.F (%)	76.5	83.7	90.5	93.4	95.4	97.3	99.0

Chapter 8 DISCUSSION

8.1 Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's Constructed Wetland System

8.1.1 Vertical Flow And Horizontal Flow Bed

The data computed, using the method of moments for the vertical flow and horizontal flow beds of SKM Hospital's constructed wetland system, are summarized in Table 8.1 and Table 8.2 respectively.

Table 8.1: Overview of SKM Hospital (Vertical Flow Bed)

Description	Value	
Theoretical Detention Time	40.8	hrs
Total Volume of Flow Bed	18.2	m^3
Design Flowrate	10	m^3/day
Tracer Detention Time	7.8	hrs
Effective Volume of Flow Bed	2.2	m^3
Mass Recovery	77	%
σ^2 of the RTD (t)	27	hrs^2

Table 8.2: Overview of SKM Hospital (Horizontal Flow Bed)

Description	Value	
Theoretical Detention Time	40.8	hrs
Total Volume of Flow Bed	17	m^3
Design Flowrate	10	m^3/day
Tracer Detention Time	6.7	hrs
Effective Volume of Flow Bed	2.2	m^3
Mass Recovery	70	%
σ^2 of the RTD (t)	27	hrs^2

It was noted that the computed tracer detention time, T_{det} was shorter than the mean hydraulic detention time, τ, which suggested the existences of excluded zones. The difference between the two detention times is due to the fact that the theoretical value assumes a constant flow rate and flow within 100% of the bed volume, which was not the actual case.

It was observed only 12% of the total volume of the vertical flow bed and 13% of the total volume of the horizontal flow bed were covered with water during the tracer test, which suggested that there were low amounts of mixing and dead zones in the flow bed. The residence time distribution function, RTD (t) found will provide a good approximation of the distribution of different parcels of water remain in the system.

8.1.2 Simulation of Day Flow and Night Flow for Constructed Wetland System

The computed detention times, T_{det} (Using Equation 6.1), based on the average flowrates for day and night in the horizontal and vertical flow beds are listed in Table 8.3 and Table 8.4 respectively.

<u>Table 8.3</u>: Computed Detention Time, T_{det} and Average Flowrate of Simulated Flow Period for SKM Hospital (Horizontal Flow Bed).

Flow Period	Description	Values	
SKM HFB	Tracer Detention Time	23.6	hrs
(Day Flow)	Average Flowrate	0.72	m^3/hr
SKM HFB	Tracer Detention Time	105.7	hrs
(Mean Night Flow)	Average Flowrate	0.16	m^3/hr

<u>Table 8.4</u>: Computed Detention Time, T_{det} and Average Flowrate of Simulated Flow Period for SKM Hospital (Vertical Flow Bed).

Flow Period	Description	Values	
SKM VFB	Tracer Detention Time	18.8	hrs
(Day Flow)	Average Flowrate	0.97	m^3/hr
SKM VFB	Tracer Detention Time	133.0	hrs
(Night Flow)	Average Flowrate	0.14	m^3/hr

It was observed the distribution of different parcels of water remained in the system longer during the night flow period than the day flow period.
The average concentration of pollution removed, RF for a range of reasonable k_r the day and night flows are shown in Table 8.5 and Table 8.6 respectively.

Table 8.5: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF of Simulated Flow Period for SKM Hospital (Horizontal Flow Bed).

SKM HFB *(Mean Day Flow)*	**k_r (1/day)**	0.44	1	1.5	2	2.5	3	4
	R.F (%)	35.2	62.6	77.2	86.1	91.5	94.8	98.1
SKM HFB *(Mean Night Flow)*	**k_r (1/day)**	0.4	0.44	0.5	0.6	0.7	0.8	1
	R.F (%)	82.8	85.6	88.9	92.9	95.4	97	98.8

Table 8.6: Range of Reaction Rate Coefficient, k_r Average Concentration of Pollution Removed, RF of Simulated Flow Period for SKM Hospital (Vertical Flow Bed).

SKM VFB *(Mean Day Flow)*	**k_r (1/day)**	2	2.5	3	3.5	4	4.5	6
	R.F (%)	79.1	85.6	90.4	93.5	95.6	97.0	99.1
SKM VFB *(Mean Night Flow)*	**k_r (1/day)**	0.3	0.35	0.4	0.45	0.5	0.6	0.9
	R.F (%)	81.0	85.6	89.1	91.7	93.7	96.4	99.3

It was noted that for a given k_r, a greater pollutant removal is achieved during low flow because the residence time is higher .The designer for the constructed wetland system chose a k_r value of 0.44 1/d (KBOD =0.1 m/d) for the design of the horizontal flow bed (Shrestha, 1999). The values of R.F computed for the day flow and night flow period using this kr value were 35.2% and 85.6% respectively. The comparison of the two R.F was made under the assumption that the dispersion mechanisms were similar at the high and low flow period.

To improve the efficiencies of the wetland system, the flowrate discharging into the beds should be regulated. It was observed that 90% of the discharge happened during the day. By decreasing the flowrate into the loading tank from the settling tank in the day and increasing it in the night with a valve controlling device mechanism, a constant flowrate discharging into the beds can be obtained.

8.2 Dhulikhel Hospital's Constructed Wetland System

8.2.1 Vertical Flow Bed And Horizontal Flow Bed

The data computed, using the method of moments for the vertical flow and horizontal flow beds of Dhulikhel Hospital's constructed wetland system, are summarized in Table 8.7 and Table 8.8 respectively.

Table 8.7: Overview of Dhulikhel Hospital (Vertical Flow Bed)

Description	Value	
Theoretical Detention Time	22.4	hrs
Volume of Flow Bed	33.0	m^3
Design Flowrate	35	m^3/day
Tracer Detention Time	12.2	hrs
Effective Volume of Flow Bed	14.0	m^3
Mass Recovery	46	%
σ^2 of the RTD (t)	41.4	hrs^2

Table 8.8: Overview of Dhulikhel Hospital (Vertical Flow Bed)

Description	Value	
Theoretical Detention Time	22.5	hrs
Volume of Flow Bed	33.0	m^3
Design Flowrate	35	m^3/day
Tracer Detention Time	5.6	hrs
Effective Volume of Flow Bed	8.5	m^3
Mass Recovery	77	%
σ^2 of the RTD (t)	13.4	hrs^2

The computed tracer detention time, T_{det} was shorter than the mean hydraulic detention time, τ, which suggested that the existences of excluded zones. The difference between the two detention times is due to the fact that the theoretical value assumes a constant flow rate and flow within 100% of the bed volume, which was not the actual case.

It was observed only 42% of the total volume of the vertical flow bed and 26% of the total volume of the horizontal flow bed were covered with water during the tracer test, which suggested that there were low amounts of mixing and dead zones in the flow bed.

The mass recovery percentage for the vertical flow bed was particularly low at 46%. The reason might be due to the ponding situation in the flow bed where the water was not able to infiltrated to the bottom of the wetland. Thus suggesting that the measurement period might be inadequate to recover all of the bromide added.

8.2.2 Simulation of Day Flow and Night Flow for Constructed Wetland System

The computed detention times, T_{det} (Using Equation 6.1), based on the average flowrates for day and night in the horizontal and vertical flow beds are listed in Table 8.9 and Table 8.10 respectively.

Table 8.9: Computed Detention Time, T_{det} and Average Flowrate of Simulated Flow Period for Dhulikhel Hospital (Horizontal Flow Bed).

Flow Period	Description	Values	
Dhulikhel HFB	Tracer Detention Time	18.3	hrs
(Day Flow)	Average Flowrate	1.80	m^3/hr
Dhulikhel HFB	Tracer Detention Time	62.2	hrs
(Night Flow)	Average Flowrate	0.53	m^3/hr

Table 8.10: Computed Detention Time, T_{det} and Average Flowrate of Simulated Flow Period for Dhulikhel Hospital (Vertical Flow Bed).

Flow Period	Description	Values	
Dhulikhel VFB	Tracer Detention Time	29.6	hrs
(Day Flow)	Average Flowrate	1.11	m^3/hr
Dhulikhel VFB	Tracer Detention Time	43.5	hrs
(Night Flow)	Average Flowrate	0.76	m^3/hr

It was observed the distribution of different parcels of water remained in the system longer during the night flow period than the day flow period.

The average concentration of pollution removed, RF for a range of reasonable k_r the day and night flows are shown in Table 8.11 and Table 8.12 respectively

Table 8.11: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF of Simulated Flow Period for Dhulikhel Hospital (Horizontal Flow Bed).

SKM HFB	**k_r (1/day)**	0.44	1	2	3	3.5	4	6
(Mean Day Flow)	**R.F (%)**	28.5	53.3	78.2	89.8	93.1	95.3	99.0
SKM HFB	**k_r (1/day)**	0.44	0.5	0.65	0.75	0.9	1.2	2
(Mean Night Flow)	**R.F (%)**	68.0	72.7	81.5	85.7	90.3	95.5	99.4

Table 8.12: Range of Reaction Rate Coefficient, k_r And Resulting Average Concentration of Pollution Removed, RF of Simulated Flow Period for Dhulikhel Hospital (Vertical Flow Bed).

SKM VFB	**k_r (1/day)**	1	1.2	1.3	1.5	2	3	4
(Mean Day Flow)	**R.F (%)**	70.9	77.2	80.0	84.3	91.5	97.5	99.3
SKM VFB	**k_r (1/day)**	0.8	1	1.3	1.5	1.7	2	2.5
(Mean Night Flow)	**R.F (%)**	76.5	83.7	90.5	93.4	95.4	97.3	99.0

It was noted that for a given k_r, a greater pollutant removal is achieved during low flow because the residence time is higher. The designer for the constructed wetland system chose a k_r value of 0.44 1/d (KBOD =0.1 m/d) for the design of the horizontal flow bed (Shrestha, 1999). The values of R.F computed for the day flow and night flow period using this kr value were 28.5% and 68.0% respectively. The comparison of the two R.F was made under the assumption that the dispersion mechanisms were similar at the high and low flow period. Although the original design had a R.F of 85%, due to the increase of flowrate compare to the design value, the removal rate for pollutants were lower.

To improve the efficiencies of the wetland system, the flowrate discharging into the beds should be regulated. It was observed that 90% of the discharge happened during the day. By decreasing the flowrate into the loading tank from the settling tank in the day and increasing it in the night with a value mechanism, a constant flowrate discharging into the beds can be obtained. It was observed that the constructed wetlands were covered with sludge, particularly with the vertical flow bed. Since the original design was for 10 m^3/d and the flowrate coming into the system is about 30-40 m^3/d, the sludge in the settlement tank might not be able to settle to the bottom before discharging into the system. It is recommended to build additional settlement tank to maintain the efficiency of the system.

8.2.3 Conclusion

The actual detention time, residence time distribution function, RTD (t), variance, σ^2 of the RTD (t) found, can be used to predict the actual flow of the water within the wetland system. In addition, the removal efficiency of the wetland system for a non-conservative constituent can be also estimated with the k_r values. The k_r values are usually not known to a certain degree as they depend on the parameter and the different environmental and operational circumstances (Haberl, 1998). Given a range of k_r values and the resulting average concentration of pollution that is removed by the wetland system, RF, the designer will be able to use a more accurate value to size the wetland system flow bed. This will enable a better and more efficient design in future.

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APPENDIX A

Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital's Constructed Wetland System

I. Field Data For SKM

Sushma Koirala Memorial Plastic & Reconstructive Surgery Hospital

Effluent For Vertical Flow Bed

Chemical Used:	NaBr
Amount of Chemical Used:	200 g
Tracer introduced at:	16:20
	4:20 PM
Date:	1/12/2003

No	Time Date	Time (hrs:min)	Time Interval (hr:min)	Time Interval (hrs)	$[Br^-]$ Detected (mol/l)
1	1/12/03 4:30 PM	16:30	0:00	0.00	0.0000
2	1/12/03 5:30 PM	17:30	1:00	1.00	0.0000
3	1/12/03 6:00 PM	18:00	1:30	1.50	0.0000
4	1/12/03 6:30 PM	18:30	2:00	2.00	0.0000
5	1/12/03 7:30 PM	19:30	3:00	3.00	0.0002
6	1/12/03 8:30 PM	20:30	4:00	4.00	0.0002
7	1/12/03 9:00 PM	21:00	4:30	4.50	0.0002
8	1/12/03 9:30 PM	21:30	5:00	5.00	0.0005
9	1/12/03 9:45 PM	21:45	5:15	5.25	0.0005
10	1/12/03 10:00 PM	22:00	5:30	5.50	0.0004
11	1/12/03 10:30 PM	22:30	6:00	6.00	0.0004
12	1/12/03 10:45 PM	22:45	6:15	6.25	0.0004
13	1/12/03 11:30 PM	23:30	7:00	7.00	0.0003
14	1/13/03 12:00 AM	0:00	7:30	7.50	0.0003
15	1/13/03 1:00 AM	1:00	8:30	8.50	0.0002
16	1/13/03 2:00 AM	2:00	9:30	9.50	0.0002
17	1/13/03 3:00 AM	3:00	10:30	10.50	0.0002
18	1/13/03 4:00 AM	4:00	11:30	11.50	0.0002
19	1/13/03 5:30 AM	5:30	13:00	13.00	0.0003
20	1/13/03 6:30 AM	6:30	14:00	14.00	0.0003
21	1/13/03 7:00 AM	7:00	14:30	14.50	0.0002
22	1/13/03 7:30 AM	7:30	15:00	15.00	0.0002
23	1/13/03 8:00 AM	8:00	15:30	15.50	0.0002
24	1/13/03 8:30 AM	8:30	16:00	16.00	0.0002
25	1/13/03 9:30 AM	9:30	17:00	17.00	0.0002
26	1/13/03 10:00 AM	10:00	17:30	17.50	0.0003
27	1/13/03 11:00 AM	11:00	18:30	18.50	0.0001
28	1/13/03 11:30 AM	11:30	19:00	19.00	0.0001

Effluent For Horizontal Flow Bed

Chemical Used:	NaBr	
Amount of Chemical Used:	700	g
Tracer introduced at:	12:45	
	12:45 PM	
Date:	1/13/2003	

No	Time Date	Time (hrs:min)	Time Interval (hr:min)	Time Interval (hrs)	[Br⁻] Detected (mol/l)	Note
1	1/13/03 12:45 PM	12:45	0:00	0.00	0.0000	Flushes (0.95-0.60)m
2	1/13/03 1:45 PM	13:45	1:00	1.00	0.0002	
3	1/13/03 2:00 PM	14:00	1:15	1.25	0.0003	
4	1/13/03 2:15 PM	14:15	1:30	1.50	0.0003	
5	1/13/03 2:30 PM	14:30	1:45	1.67	0.0005	
6	1/13/03 2:45 PM	14:45	2:00	2.00	0.0003	
7	1/13/03 3:00 PM	15:00	2:15	2.25	0.0003	Flushes (3.00 PM)
8	1/13/03 3:15 PM	15:15	2:30	2.50	0.0007	
9	1/13/03 3:30 PM	15:30	2:45	2.75	0.0008	
10	1/13/03 3:45 PM	15:45	3:00	3.00	0.0009	
11	1/13/03 4:00 PM	16:00	3:15	3.25	0.0009	
12	1/13/03 4:15 PM	16:15	3:30	3.50	0.0011	
13	1/13/03 4:30 PM	16:30	3:45	3.75	0.0013	
14	1/13/03 4:45 PM	16:45	4:00	4.00	0.0014	
15	1/13/03 5:00 PM	17:00	4:15	4.25	0.0012	
16	1/13/03 5:15 PM	17:15	4:30	4.50	0.0012	
17	1/13/03 5:30 PM	17:30	4:45	4.75	0.0011	
18	1/13/03 5:45 PM	17:45	5:00	5.00	0.0010	
19	1/13/03 6:00 PM	18:00	5:15	5.25	0.0009	
20	1/13/03 6:30 PM	18:30	5:45	5.75	0.0013	
21	1/13/03 6:45 PM	18:45	6:00	6.00	0.0013	Flushes (6.48 PM)
22	1/13/03 6:50 PM	18:50	6:05	6.08	0.0009	
23	1/13/03 6:55 PM	18:55	6:10	6.17	0.0008	
24	1/13/03 7:00 PM	19:00	6:15	6.25	0.0008	
25	1/13/03 7:05 PM	19:05	6:20	6.33	0.0008	
26	1/13/03 7:10 PM	19:10	6:25	6.42	0.0008	
27	1/13/03 7:15 PM	19:15	6:30	6.50	0.0008	
28	1/13/03 7:30 PM	19:30	6:45	6.75	0.0008	
29	1/13/03 7:45 PM	19:45	7:00	7.00	0.0008	
30	1/13/03 8:00 PM	20:00	7:15	7.25	0.0008	

No	Time Date	Time (hrs:min)	Time Interval (hr:min)	Time Interval (hrs)	[Br$^-$] Detected (mol/l)	Note
31	1/13/03 8:45 PM	20:45	8:00	8.00	0.0006	
32	1/13/03 9:00 PM	21:00	8:15	8.25	0.0006	
33	1/13/03 10:00 PM	22:00	9:15	9.25	0.0009	
34	1/13/03 11:00 PM	23:00	10:15	10.25	0.0006	Flow too slow for
35	1/14/03 12:00 AM	0:00	11:15	11.25	0.0006	data collection
36	1/14/03 1:00 AM	1:00	12:15	12.25	0.0003	
37	1/14/03 2:00 AM	2:00	13:15	13.25	0.0003	
38	1/14/03 3:00 AM	3:00	14:15	14.25	0.0002	Flushes (3.00 AM)
39	1/14/03 4:00 AM	4:00	15:15	15.25	0.0002	
40	1/14/03 5:00 AM	5:00	16:15	16.25	0.0002	
41	1/14/03 6:00 AM	6:00	17:15	17.25	0.0002	
42	1/14/03 7:00 AM	7:00	18:15	18.25	0.0003	
43	1/14/03 8:30 AM	8:30	19:45	19.75	0.0003	Flushes (8.30 AM)
44	1/14/03 8:45 AM	8:45	20:00	20.00	0.0002	
45	1/14/03 9:00 AM	9:00	20:15	20.25	0.0002	
46	1/14/03 9:15 AM	9:15	20:30	20.50	0.0002	
47	1/14/03 10:00 AM	10:00	21:15	21.25	0.0002	
48	1/14/03 10:15 AM	10:15	21:30	21.50	0.0002	Flushes (10.10 AM)
49	1/14/03 10:30 AM	10:30	21:45	21.75	0.0002	
50	1/14/03 10:45 AM	10:45	22:00	22.00	0.0002	

II. Number of Flushes Recorded

Number of Flushes into the VFB

No of Flushes	Time Date	Time (hrs)	Note
1	1/12/03 2:30 PM	14:30	
2	1/12/03 4:30 PM	16:30	
3	1/12/03 6:20 PM	18:20	
4	1/12/03 8:30 PM	20:30	
5	1/13/03 9:15 AM	9:15	
6	1/13/03 11:00 AM	11:00	
7	1/13/03 12:45 PM	12:45	
8	1/13/03 3:15 PM	15:15	
9	1/13/03 5:15 PM	17:15	
10	1/13/03 7:00 PM	19:00	
11	1/14/03 7:30 AM	7:30	
12	1/14/03 10:00 AM	10:00	
13	1/14/03 12:13 PM	12:13	

Number of Flushes into the HFB

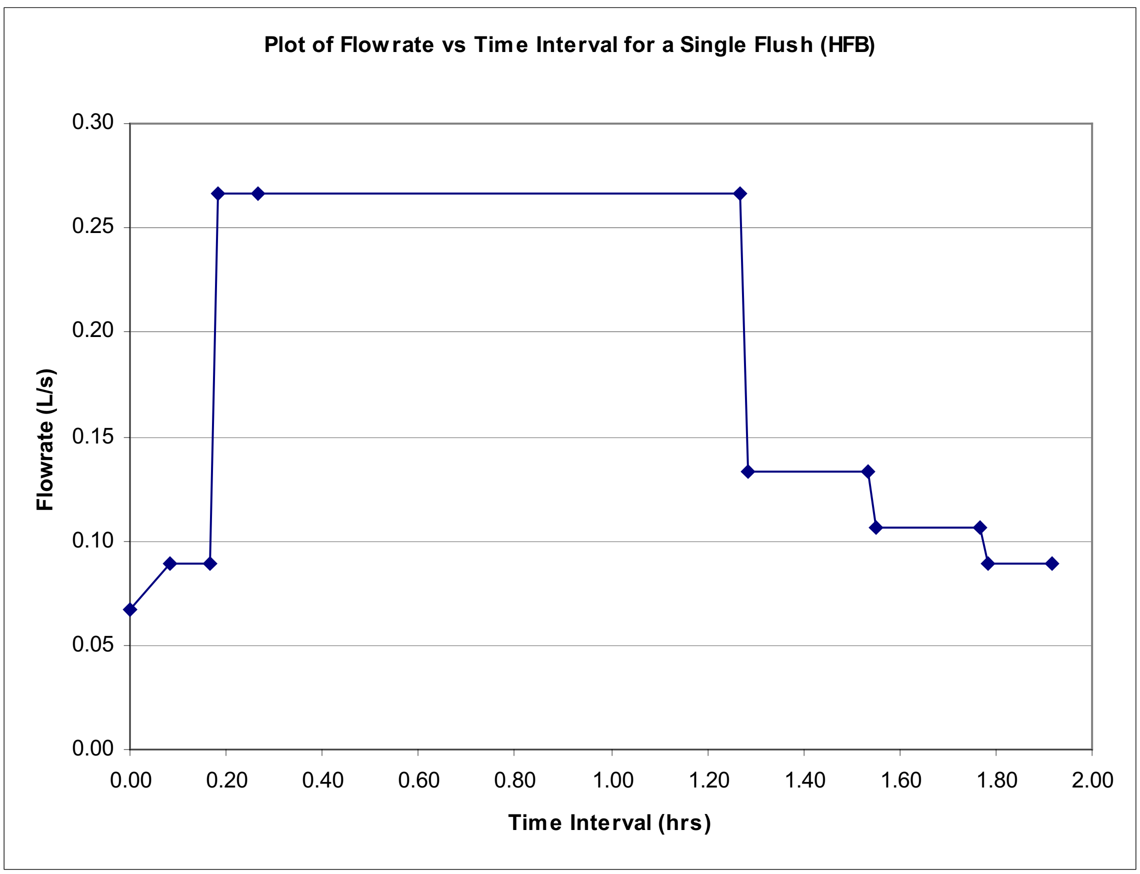
No of Flushes	Time Date	Time (hrs)	Note
1	1/12/03 2:30 PM	14:30	
2	1/12/03 4:30 PM	16:30	
3	1/12/03 6:30 PM	18:30	
4	1/13/03 7:15 AM	7:15	
5	1/13/03 9:45 AM	9:45	
6	1/13/03 11:35 AM	11:35	
7	1/13/03 12:45 PM	12:45	
8	1/13/03 2:55 PM	14:55	
9	1/13/03 4:45 PM	16:45	
10	1/13/03 6:45 PM	18:45	
11	1/14/03 3:30 AM	3:30	
12	1/14/03 8:20 AM	8:20	
13	1/14/03 10:10 AM	10:10	
14	1/14/03 12:13 PM	12:13	

III. Effluent Flowrate Data For A Single Flush

Effluent Flowrate Data for a Single Flush into the Vertical Flow Bed

Date: 1/14/2003 **Time of Flush:** 12:13

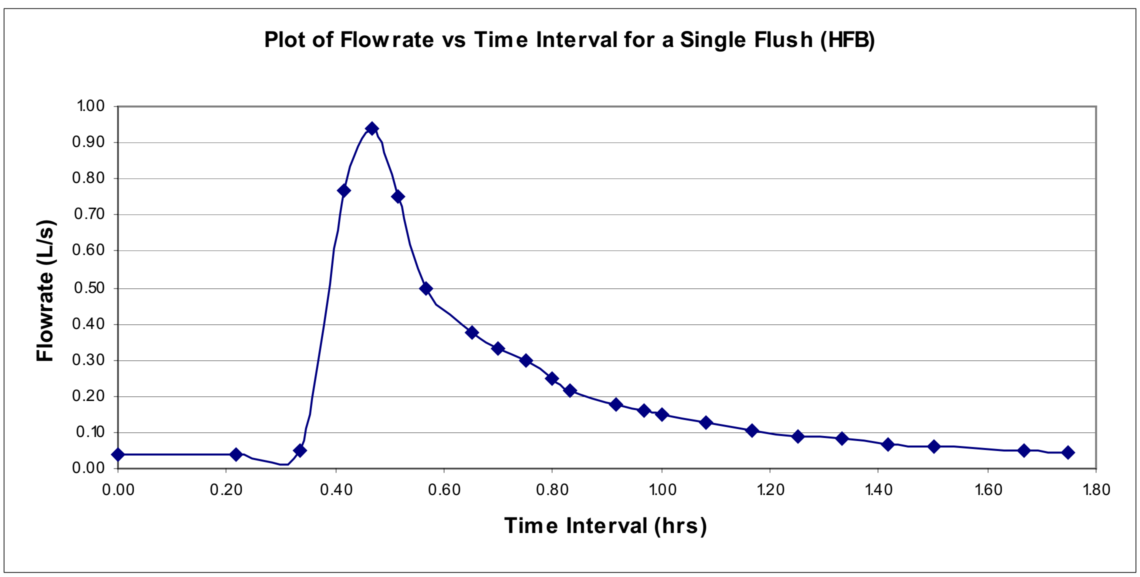
No	Time		Vol. of Bucket	Time Taken		Time Taken	Flowrate	Flowrate	Time Interval
	(hrs:mins)		(L)	(min)	(s)	(s)	(L/s)	(L/min)	(hrs)
1	12	30	8.0	2	0	120	0.07	4.00	0.00
2	12	35	8.0	1	30	90	0.09	5.33	0.08
3	12	40	8.0	1	30	90	0.09	5.33	0.17
4	12	41	8.0	0	30	30	0.27	16.00	0.18
5	12	46	8.0	0	30	30	0.27	16.00	0.27
6	13	46	8.0	0	30	30	0.27	16.00	1.27
7	13	47	8.0	1	0	60	0.13	8.00	1.28
8	14	2	8.0	1	0	60	0.13	8.00	1.53
9	14	3	8.0	1	15	75	0.11	6.40	1.55
10	14	16	8.0	1	15	75	0.11	6.40	1.77
11	14	17	8.0	1	30	90	0.09	5.33	1.78
12	14	25	8.0	1	30	90	0.09	5.33	1.92



Effluent Flowrate Data for a Single Flush into the Horizontal Flow Bed

Date: 1/14/2003 **Time of Flush:** 12:13

No	Time (hrs:mins)		Vol. of Bucket (L)	Time Taken (min)	Time Taken (s)	Time Taken (s)	Flowrate (L/s)	Flowrate (L/min)	Time Interval (hrs)
1	12	0	8.0	3	30	210	0.04	2.29	0.00
2	12	13	8.0	3	20	200	0.04	2.40	0.22
3	12	20	15.0	5	10	310	0.05	2.90	0.33
4	12	25	138.0	3	0	180	0.77	46.00	0.42
5	12	28	15.0	0	16	16	0.94	56.25	0.47
6	12	31	15.0	0	20	20	0.75	45.00	0.52
7	12	34	15.0	0	30	30	0.50	30.00	0.57
8	12	39	15.0	0	40	40	0.38	22.50	0.65
9	12	42	15.0	0	45	45	0.33	20.00	0.70
10	12	45	15.0	0	50	50	0.30	18.00	0.75
11	12	48	15.0	1	0	60	0.25	15.00	0.80
12	12	50	15.0	1	10	70	0.21	12.86	0.83
13	12	55	15.0	1	25	85	0.18	10.59	0.92
14	12	58	15.0	1	35	95	0.16	9.47	0.97
15	13	0	15.0	1	40	100	0.15	9.00	1.00
16	13	5	15.0	2	0	120	0.13	7.50	1.08
17	13	10	15.0	2	20	140	0.11	6.43	1.17
18	13	15	15.0	2	45	165	0.09	5.45	1.25
19	13	20	15.0	3	0	180	0.08	5.00	1.33
20	13	25	15.0	3	40	220	0.07	4.09	1.42
21	13	30	15.0	4	0	240	0.06	3.75	1.50
22	13	40	15.0	5	0	300	0.05	3.00	1.67
22	13	45	15.0	5	40	340	0.04	2.65	1.75



IV. Estimation of Effluent Flowrate

Estimation of Effluent Flowrate into the Vertical Flow Bed for NaBr Tracer Test

No	Time Date	Time (hrs:min)	Flowrate (L/min)	Flowrate (L/hrs)	Flowrate (m^3/hr)	Time (hrs:mins)		Time Int. (hrs)	Time Int. (hrs)
1	1/12/03 4:20 PM	16:20	7.00	420.00	0.42	4	20	4.33	0.00
2	1/12/03 4:37 PM	16:37	7.80	468.00	0.47	4	37	4.62	0.28
3	1/12/03 4:42 PM	16:42	9.13	548.00	0.55	4	42	4.70	0.37
4	1/12/03 4:47 PM	16:47	9.13	548.00	0.55	4	47	4.78	0.45
5	1/12/03 4:48 PM	16:48	19.80	1188.00	1.19	4	48	4.80	0.47
6	1/12/03 4:53 PM	16:53	19.80	1188.00	1.19	4	53	4.88	0.55
7	1/12/03 5:53 PM	17:53	19.80	1188.00	1.19	5	53	5.88	1.55
8	1/12/03 5:54 PM	17:54	11.80	708.00	0.71	5	54	5.90	1.57
9	1/12/03 6:09 PM	18:09	11.80	708.00	0.71	6	9	6.15	1.82
10	1/12/03 6:10 PM	18:10	10.20	612.00	0.61	6	10	6.17	1.83
11	1/12/03 6:23 PM	18:23	10.20	612.00	0.61	6	23	6.38	2.05
12	1/12/03 6:24 PM	18:24	9.13	548.00	0.55	6	24	6.40	2.07
13	1/12/03 6:32 PM	18:32	9.13	548.00	0.55	6	32	6.53	2.20
14	1/12/03 6:37 PM	18:37	9.30	558.00	0.56	6	37	6.62	2.28
15	1/12/03 6:42 PM	18:42	10.63	638.00	0.64	6	42	6.70	2.37
16	1/12/03 6:47 PM	18:47	10.63	638.00	0.64	6	47	6.78	2.45
17	1/12/03 6:48 PM	18:48	21.30	1278.00	1.28	6	48	6.80	2.47
18	1/12/03 6:53 PM	18:53	21.30	1278.00	1.28	6	53	6.88	2.55
19	1/12/03 7:53 PM	19:53	21.30	1278.00	1.28	7	53	7.88	3.55
20	1/12/03 7:54 PM	19:54	13.30	798.00	0.80	7	54	7.90	3.57
21	1/12/03 8:09 PM	20:09	13.30	798.00	0.80	8	9	8.15	3.82
22	1/12/03 8:10 PM	20:10	11.70	702.00	0.70	8	10	8.17	3.83
23	1/12/03 8:23 PM	20:23	11.70	702.00	0.70	8	23	8.38	4.05
24	1/12/03 8:24 PM	20:24	10.63	638.00	0.64	8	24	8.40	4.07
25	1/12/03 8:32 PM	20:32	10.63	638.00	0.64	8	32	8.53	4.20
26	1/12/03 8:35 PM	20:35	8.13	487.80	0.49	8	35	8.58	4.25
27	1/12/03 8:40 PM	20:40	6.20	372.00	0.37	8	40	8.67	4.33
28	1/12/03 8:45 PM	20:45	4.00	240.00	0.24	8	45	8.75	4.42
29	1/12/03 8:47 PM	20:47	4.80	288.00	0.29	8	47	8.78	4.45
30	1/12/03 8:52 PM	20:52	6.13	368.00	0.37	8	52	8.87	4.53
31	1/12/03 8:57 PM	20:57	6.13	368.00	0.37	8	57	8.95	4.62
32	1/12/03 8:58 PM	20:58	16.80	1008.00	1.01	8	58	8.97	4.63
33	1/12/03 9:03 PM	21:03	16.80	1008.00	1.01	9	3	9.05	4.72
34	1/12/03 10:03 PM	22:03	16.80	1008.00	1.01	10	3	10.05	5.72
35	1/12/03 10:04 PM	22:04	8.80	528.00	0.53	10	4	10.07	5.73
36	1/12/03 10:19 PM	22:19	8.80	528.00	0.53	10	19	10.32	5.98
37	1/12/03 10:20 PM	22:20	7.20	432.00	0.43	10	20	10.33	6.00
38	1/12/03 10:33 PM	22:33	7.20	432.00	0.43	10	33	10.55	6.22
39	1/12/03 10:34 PM	22:34	6.13	368.00	0.37	10	34	10.57	6.23

No	Time Date	Time (hrs:min)	Flowrate (L/min)	Flowrate (L/hrs)	Flowrate (m^3/hr)	Time (hrs:	mins)	Time Int. (hrs)	Time Int. (hrs)
40	1/12/03 10:42 PM	22:42	6.13	368.00	0.37	10	42	10.70	6.37
41	1/12/03 10:55 PM	22:55	5.15	309.00	0.31	10	55	10.92	6.58
42	1/12/03 11:15 PM	23:15	4.00	240.00	0.24	11	15	11.25	6.92
43	1/12/03 11:35 PM	23:35	3.00	180.00	0.18	11	35	11.58	7.25
44	1/12/03 11:55 PM	23:55	2.00	120.00	0.12	11	55	11.92	7.58
45	1/13/03 12:15 AM	0:15	1.53	91.53	0.09	12	15	12.25	7.92
46	1/13/03 2:15 AM	2:15	1.53	91.53	0.09	14	15	14.25	9.92
47	1/13/03 9:15 AM	9:15	1.53	91.53	0.09	21	15	21.25	16.92
48	1/13/03 9:32 AM	9:32	2.33	139.53	0.14	21	32	21.53	17.20
49	1/13/03 9:37 AM	9:37	3.66	219.53	0.22	21	37	21.62	17.28
50	1/13/03 9:42 AM	9:42	3.66	219.53	0.22	21	42	21.70	17.37
51	1/13/03 9:43 AM	9:43	14.33	859.53	0.86	21	43	21.72	17.38
52	1/13/03 9:48 AM	9:48	14.33	859.53	0.86	21	48	21.80	17.47
53	1/13/03 10:48 AM	10:48	14.33	859.53	0.86	22	48	22.80	18.47
54	1/13/03 10:49 AM	10:49	6.33	379.53	0.38	22	49	22.82	18.48
55	1/13/03 11:04 AM	11:04	6.33	379.53	0.38	23	4	23.07	18.73
56	1/13/03 11:05 AM	11:05	4.73	283.53	0.28	23	5	23.08	18.75
57	1/13/03 11:18 AM	11:18	5.53	331.80	0.33	23	18	23.30	18.97
58	1/13/03 11:19 AM	11:19	7.66	459.60	0.46	23	19	23.32	18.98
59	1/13/03 11:26 AM	11:26	7.66	459.60	0.46	23	26	23.43	19.10
60	1/13/03 11:27 AM	11:27	18.33	1099.80	1.10	23	27	23.45	19.12
61	1/13/03 11:32 AM	11:32	18.33	1099.80	1.10	23	32	23.53	19.20
62	1/13/03 12:32 PM	12:32	18.33	1099.80	1.10	24	32	24.53	20.20
63	1/13/03 12:33 PM	12:33	10.33	619.80	0.62	24	33	24.55	20.22
64	1/13/03 12:48 PM	12:48	10.33	619.80	0.62	24	48	24.80	20.47
65	1/13/03 12:49 PM	12:49	8.73	523.80	0.52	24	49	24.82	20.48
66	1/13/03 1:02 PM	13:02	8.73	523.80	0.52	25	2	25.03	20.70
67	1/13/03 1:03 PM	13:03	7.66	459.80	0.46	25	3	25.05	20.72
68	1/13/03 1:11 PM	13:11	7.66	459.80	0.46	25	11	25.18	20.85

Estimation of Effluent Flowrate into the Vertical Flow Bed in a day

No	Time (hrs:min)	Flowrate (L/min)	Flowrate (L/hrs)	Flowrate (m^3/hr)	Time (hrs:	mins)	Time Int. (hrs)	Flowrate (L/hrs)
1	0:00	1.53	91.53	0.09	0	0	0.00	91.53
2	0:15	1.53	91.53	0.09	0	15	0.25	91.53
3	2:15	1.53	91.53	0.09	2	15	2.25	91.53
4	9:15	1.53	91.53	0.09	9	15	9.25	91.53
5	9:32	2.33	139.53	0.14	9	32	9.53	139.53
6	9:37	3.66	219.53	0.22	9	37	9.62	219.53
7	9:42	3.66	219.53	0.22	9	42	9.70	219.53
8	9:43	14.33	859.53	0.86	9	43	9.72	859.53
9	9:48	14.33	859.53	0.86	9	48	9.80	859.53
10	10:48	14.33	859.53	0.86	10	48	10.80	859.53
11	10:49	6.33	379.53	0.38	10	49	10.82	379.53
12	11:04	6.33	379.53	0.38	11	4	11.07	379.53
13	11:05	4.73	283.53	0.28	11	5	11.08	283.53
14	11:18	5.53	331.80	0.33	11	18	11.30	331.80
15	11:19	7.66	459.60	0.46	11	19	11.32	459.60
16	11:26	7.66	459.60	0.46	11	26	11.43	459.60
17	11:27	18.33	1099.80	1.10	11	27	11.45	1099.80
18	11:32	18.33	1099.80	1.10	11	32	11.53	1099.80
19	12:32	18.33	1099.80	1.10	12	32	12.53	1099.80
20	12:33	10.33	619.80	0.62	12	33	12.55	619.80
21	12:48	10.33	619.80	0.62	12	48	12.80	619.80
22	12:49	8.73	523.80	0.52	12	49	12.82	523.80
23	13:02	8.73	523.80	0.52	13	2	13.03	523.80
24	13:03	9.00	539.80	0.54	13	3	13.05	539.80
25	13:11	9.00	539.80	0.54	13	11	13.18	539.80
26	13:15	9.00	539.80	0.54	13	15	13.25	539.80
27	13:16	19.66	1179.80	1.18	13	16	13.27	1179.80
28	13:21	19.66	1179.80	1.18	13	21	13.35	1179.80
29	14:21	19.66	1179.80	1.18	14	21	14.35	1179.80
30	14:22	11.66	699.78	0.70	14	22	14.37	699.78
31	14:37	11.66	699.78	0.70	14	37	14.62	699.78
32	14:38	10.06	603.60	0.60	14	38	14.63	603.60
33	14:51	10.06	603.60	0.60	14	51	14.85	603.60
34	14:52	9.00	539.80	0.54	14	52	14.87	539.80
35	15:00	9.00	539.80	0.54	15	0	15.00	539.80
36	15:05	10.33	620.00	0.62	15	5	15.08	620.00
37	15:10	10.33	620.00	0.62	15	10	15.17	620.00
38	15:11	20.66	1239.80	1.24	15	11	15.18	1239.80
39	15:16	20.66	1239.80	1.24	15	16	15.27	1239.80
40	16:16	20.66	1239.80	1.24	16	16	16.27	1239.80
41	16:20	12.66	759.60	0.76	16	20	16.33	759.60

No	Time	Flowrate	Flowrate	Flowrate	Time		Time Int.	Flowrate
	(hrs:min)	(L/min)	(L/hrs)	(m^3/hr)	(hrs:	mins)	(hrs)	(L/hrs)
42	16:37	7.80	468.00	0.47	16	37	16.62	468.00
43	16:42	9.13	548.00	0.55	16	42	16.70	548.00
44	16:47	9.13	548.00	0.55	16	47	16.78	548.00
45	16:48	19.80	1188.00	1.19	16	48	16.80	1188.00
46	16:53	19.80	1188.00	1.19	16	53	16.88	1188.00
47	17:53	19.80	1188.00	1.19	17	53	17.88	1188.00
48	17:54	11.80	708.00	0.71	17	54	17.90	708.00
49	18:09	11.80	708.00	0.71	18	9	18.15	708.00
50	18:10	10.20	612.00	0.61	18	10	18.17	612.00
51	18:23	10.20	612.00	0.61	18	23	18.38	612.00
52	18:24	9.13	548.00	0.55	18	24	18.40	548.00
53	18:32	9.13	548.00	0.55	18	32	18.53	548.00
54	18:37	9.30	558.00	0.56	18	37	18.62	558.00
55	18:42	10.63	638.00	0.64	18	42	18.70	638.00
56	18:47	10.63	638.00	0.64	18	47	18.78	638.00
57	18:48	21.30	1278.00	1.28	18	48	18.80	1278.00
58	18:53	21.30	1278.00	1.28	18	53	18.88	1278.00
59	19:53	21.30	1278.00	1.28	19	53	19.88	1278.00
60	19:54	13.30	798.00	0.80	19	54	19.90	798.00
61	20:09	13.30	798.00	0.80	20	9	20.15	798.00
62	20:10	11.70	702.00	0.70	20	10	20.17	702.00
63	20:23	11.70	702.00	0.70	20	23	20.38	702.00
64	20:24	10.63	638.00	0.64	20	24	20.40	638.00
65	20:32	10.63	638.00	0.64	20	32	20.53	638.00
66	20:35	8.13	487.80	0.49	20	35	20.58	487.80
67	20:40	6.20	372.00	0.37	20	40	20.67	372.00
68	20:45	4.00	240.00	0.24	20	45	20.75	240.00
69	20:47	4.80	288.00	0.29	20	47	20.78	288.00
70	20:52	6.13	368.00	0.37	20	52	20.87	368.00
71	20:57	6.13	368.00	0.37	20	57	20.95	368.00
72	20:58	16.80	1008.00	1.01	20	58	20.97	1008.00
73	21:03	16.80	1008.00	1.01	21	3	21.05	1008.00
74	22:03	16.80	1008.00	1.01	22	3	22.05	1008.00
75	22:04	8.80	528.00	0.53	22	4	22.07	528.00
76	22:19	8.80	528.00	0.53	22	19	22.32	528.00
77	22:20	7.20	432.00	0.43	22	20	22.33	432.00
78	22:33	7.20	432.00	0.43	22	33	22.55	432.00
79	22:34	6.13	368.00	0.37	22	34	22.57	368.00
80	22:42	6.13	368.00	0.37	22	42	22.70	368.00
81	22:55	5.15	309.00	0.31	22	55	22.92	309.00
82	23:15	4.00	240.00	0.24	23	15	23.25	240.00
83	23:35	3.00	180.00	0.18	23	35	23.58	180.00
84	23:55	2.00	120.00	0.12	23	55	23.92	120.00

Estimation of Effluent Flowrate into the Horizontal Flow Bed for NaBr Test

No	Time Date	Time (hrs:min)	Flowrate (L/min)	Flowrate (m^3/hr)
1	1/13/03 11:35 AM	11:35	2.34	0.14
2	1/13/03 11:42 AM	11:42	2.85	0.17
3	1/13/03 11:47 AM	11:47	45.94	2.76
4	1/13/03 11:50 AM	11:50	56.19	3.37
5	1/13/03 11:53 AM	11:53	44.94	2.70
6	1/13/03 11:56 AM	11:56	29.94	1.80
7	1/13/03 12:01 PM	12:01	22.44	1.35
8	1/13/03 12:04 PM	12:04	19.94	1.20
9	1/13/03 12:07 PM	12:07	17.94	1.08
10	1/13/03 12:10 PM	12:10	14.94	0.90
11	1/13/03 12:12 PM	12:12	12.80	0.77
12	1/13/03 12:17 PM	12:17	10.53	0.63
13	1/13/03 12:20 PM	12:20	9.42	0.57
14	1/13/03 12:22 PM	12:22	8.94	0.54
15	1/13/03 12:27 PM	12:27	7.44	0.45
16	1/13/03 12:32 PM	12:32	6.37	0.38
17	1/13/03 12:37 PM	12:37	5.40	0.32
18	1/13/03 12:42 PM	12:42	4.94	0.30
19	1/13/03 12:47 PM	12:47	4.03	0.24
20	1/13/03 12:54 PM	12:54	4.54	0.27
21	1/13/03 12:59 PM	12:59	47.63	2.86
22	1/13/03 1:02 PM	13:02	57.88	3.47
23	1/13/03 1:05 PM	13:05	46.63	2.80
24	1/13/03 1:08 PM	13:08	31.63	1.90
25	1/13/03 1:13 PM	13:13	24.13	1.45
26	1/13/03 1:16 PM	13:16	21.63	1.30
27	1/13/03 1:19 PM	13:19	19.63	1.18
28	1/13/03 1:22 PM	13:22	16.63	1.00
29	1/13/03 1:24 PM	13:24	14.49	0.87
30	1/13/03 1:29 PM	13:29	12.22	0.73
31	1/13/03 1:32 PM	13:32	11.11	0.67
32	1/13/03 1:34 PM	13:34	10.63	0.64
33	1/13/03 1:39 PM	13:39	9.13	0.55
34	1/13/03 1:44 PM	13:44	8.06	0.48
35	1/13/03 1:49 PM	13:49	7.09	0.43
36	1/13/03 1:54 PM	13:54	6.63	0.40
37	1/13/03 1:59 PM	13:59	5.73	0.34
38	1/13/03 2:04 PM	14:04	5.38	0.32
39	1/13/03 2:14 PM	14:14	4.63	0.28
40	1/13/03 2:19 PM	14:19	4.28	0.26

No	Time	Time	Flowrate	Flowrate
	Date	(hrs:min)	(L/min)	(m^3/hr)
41	1/13/03 2:55 PM	14:55	3.00	0.18
42	1/13/03 3:02 PM	15:02	3.50	0.21
43	1/13/03 3:07 PM	15:07	46.60	2.80
44	1/13/03 3:10 PM	15:10	56.85	3.41
45	1/13/03 3:13 PM	15:13	45.60	2.74
46	1/13/03 3:16 PM	15:16	30.60	1.84
47	1/13/03 3:21 PM	15:21	23.10	1.39
48	1/13/03 3:24 PM	15:24	20.60	1.24
49	1/13/03 3:27 PM	15:27	18.60	1.12
50	1/13/03 3:30 PM	15:30	15.60	0.94
51	1/13/03 3:32 PM	15:32	13.46	0.81
52	1/13/03 3:37 PM	15:37	11.19	0.67
53	1/13/03 3:40 PM	15:40	10.07	0.60
54	1/13/03 3:42 PM	15:42	9.60	0.58
55	1/13/03 3:47 PM	15:47	8.10	0.49
56	1/13/03 3:52 PM	15:52	7.03	0.42
57	1/13/03 3:57 PM	15:57	6.05	0.36
58	1/13/03 4:02 PM	16:02	5.60	0.34
59	1/13/03 4:07 PM	16:07	4.69	0.28
60	1/13/03 4:12 PM	16:12	4.35	0.26
61	1/13/03 4:22 PM	16:22	3.60	0.22
62	1/13/03 4:27 PM	16:27	3.25	0.19
63	1/13/03 4:45 PM	16:45	3.00	0.18
64	1/13/03 4:52 PM	16:52	3.50	0.21
65	1/13/03 4:57 PM	16:57	46.60	2.80
66	1/13/03 5:00 PM	17:00	56.85	3.41
67	1/13/03 5:03 PM	17:03	45.60	2.74
68	1/13/03 5:06 PM	17:06	30.60	1.84
69	1/13/03 5:11 PM	17:11	23.10	1.39
70	1/13/03 5:14 PM	17:14	20.60	1.24
71	1/13/03 5:17 PM	17:17	18.60	1.12
72	1/13/03 5:20 PM	17:20	15.60	0.94
73	1/13/03 5:22 PM	17:22	13.46	0.81
74	1/13/03 5:27 PM	17:27	11.19	0.67
75	1/13/03 5:30 PM	17:30	10.07	0.60
76	1/13/03 5:32 PM	17:32	9.60	0.58
77	1/13/03 5:37 PM	17:37	8.10	0.49
78	1/13/03 5:42 PM	17:42	7.03	0.42
79	1/13/03 5:47 PM	17:47	6.05	0.36
80	1/13/03 5:52 PM	17:52	5.60	0.34
81	1/13/03 5:57 PM	17:57	4.69	0.28
82	1/13/03 6:02 PM	18:02	4.35	0.26
83	1/13/03 6:12 PM	18:12	3.60	0.22
84	1/13/03 6:17 PM	18:17	3.25	0.19
85	1/13/03 6:45 PM	18:45	2.80	0.17

No	Time	Time	Flowrate	Flowrate
	Date	(hrs:min)	(L/min)	(m^3/hr)
86	1/13/03 6:52 PM	18:52	3.30	0.20
87	1/13/03 6:57 PM	18:57	46.40	2.78
88	1/13/03 7:00 PM	19:00	56.65	3.40
89	1/13/03 7:03 PM	19:03	45.40	2.72
90	1/13/03 7:06 PM	19:06	30.40	1.82
91	1/13/03 7:11 PM	19:11	22.90	1.37
92	1/13/03 7:14 PM	19:14	20.40	1.22
93	1/13/03 7:17 PM	19:17	18.40	1.10
94	1/13/03 7:20 PM	19:20	15.40	0.92
95	1/13/03 7:22 PM	19:22	13.26	0.80
96	1/13/03 7:27 PM	19:27	10.99	0.66
97	1/13/03 7:30 PM	19:30	9.87	0.59
98	1/13/03 7:32 PM	19:32	9.40	0.56
99	1/13/03 7:37 PM	19:37	7.90	0.47
100	1/13/03 7:42 PM	19:42	6.83	0.41
101	1/13/03 7:47 PM	19:47	5.85	0.35
102	1/13/03 7:52 PM	19:52	5.40	0.32
103	1/13/03 7:57 PM	19:57	4.49	0.27
104	1/13/03 8:02 PM	20:02	4.15	0.25
105	1/13/03 8:12 PM	20:12	3.40	0.20
106	1/13/03 8:17 PM	20:17	3.05	0.18
107	1/13/03 10:00 PM	22:00	2.40	0.14
108	1/14/03 12:00 AM	0:00	0.34	0.02
109	1/14/03 3:30 AM	3:30	0.34	0.02
110	1/14/03 3:37 AM	3:37	0.84	0.05
111	1/14/03 3:42 AM	3:42	43.94	2.64
112	1/14/03 3:45 AM	3:45	54.19	3.25
113	1/14/03 3:48 AM	3:48	42.94	2.58
114	1/14/03 3:51 AM	3:51	27.94	1.68
115	1/14/03 3:56 AM	3:56	20.44	1.23
116	1/14/03 3:59 AM	3:59	17.94	1.08
117	1/14/03 4:02 AM	4:02	15.94	0.96
118	1/14/03 4:05 AM	4:05	12.94	0.78
119	1/14/03 4:07 AM	4:07	10.80	0.65
120	1/14/03 4:12 AM	4:12	8.53	0.51
121	1/14/03 4:15 AM	4:15	7.41	0.44
122	1/14/03 4:17 AM	4:17	6.94	0.42
123	1/14/03 4:22 AM	4:22	5.44	0.33
124	1/14/03 4:27 AM	4:27	4.37	0.26
125	1/14/03 4:32 AM	4:32	3.39	0.20
126	1/14/03 4:37 AM	4:37	2.94	0.18
127	1/14/03 4:42 AM	4:42	2.03	0.12
128	1/14/03 4:47 AM	4:47	1.69	0.10
129	1/14/03 4:57 AM	4:57	0.94	0.06
130	1/14/03 5:02 AM	5:02	0.59	0.04

No	Time Date	Time (hrs:min)	Flowrate (L/min)	Flowrate (m^3/hr)
131	1/14/03 6:00 AM	6:00	0.34	0.02
132	1/14/03 8:20 AM	8:20	0.34	0.02
133	1/14/03 8:27 AM	8:27	0.84	0.05
134	1/14/03 8:32 AM	8:32	43.94	2.64
135	1/14/03 8:35 AM	8:35	54.19	3.25
136	1/14/03 8:38 AM	8:38	42.94	2.58
137	1/14/03 8:41 AM	8:41	27.94	1.68
138	1/14/03 8:46 AM	8:46	20.44	1.23
139	1/14/03 8:49 AM	8:49	17.94	1.08
140	1/14/03 8:52 AM	8:52	15.94	0.96
141	1/14/03 8:55 AM	8:55	12.94	0.78
142	1/14/03 8:57 AM	8:57	10.80	0.65
143	1/14/03 9:02 AM	9:02	8.53	0.51
144	1/14/03 9:05 AM	9:05	7.41	0.44
145	1/14/03 9:07 AM	9:07	6.94	0.42
146	1/14/03 9:12 AM	9:12	5.44	0.33
147	1/14/03 9:17 AM	9:17	4.37	0.26
148	1/14/03 9:22 AM	9:22	3.39	0.20
149	1/14/03 9:27 AM	9:27	2.94	0.18
150	1/14/03 9:32 AM	9:32	2.03	0.12
151	1/14/03 9:37 AM	9:37	1.69	0.10
152	1/14/03 9:47 AM	9:47	0.94	0.06
153	1/14/03 9:52 AM	9:52	0.59	0.04
154	1/14/03 10:10 AM	10:10	0.50	0.03
155	1/14/03 10:17 AM	10:17	1.00	0.06
156	1/14/03 10:22 AM	10:22	44.10	2.65
157	1/14/03 10:25 AM	10:25	54.35	3.26
158	1/14/03 10:28 AM	10:28	43.10	2.59
159	1/14/03 10:31 AM	10:31	28.10	1.69
160	1/14/03 10:36 AM	10:36	20.60	1.24
161	1/14/03 10:39 AM	10:39	18.10	1.09
162	1/14/03 10:42 AM	10:42	16.10	0.97
163	1/14/03 10:45 AM	10:45	13.10	0.79
164	1/14/03 10:47 AM	10:47	10.96	0.66
165	1/14/03 10:52 AM	10:52	8.69	0.52
166	1/14/03 10:55 AM	10:55	7.57	0.45
167	1/14/03 10:57 AM	10:57	7.10	0.43
168	1/14/03 11:02 AM	11:02	5.60	0.34
169	1/14/03 11:07 AM	11:07	4.53	0.27
170	1/14/03 11:12 AM	11:12	3.55	0.21
171	1/14/03 11:17 AM	11:17	3.10	0.19
172	1/14/03 11:22 AM	11:22	2.19	0.13
173	1/14/03 11:27 AM	11:27	1.85	0.11
174	1/14/03 11:37 AM	11:37	1.10	0.07
175	1/14/03 11:42 AM	11:42	0.75	0.04

Estimation of Effluent Flowrate into the Horizontal Flow Bed in a day

Time (hrs)	Flowrate (L/min)	Flowrate (m^3/hr)	Time (hrs)	Flowrate (L/min)	Flowrate (m^3/hr)
0.00	20.40	0.02	9.62	101.40	0.10
3.50	20.40	0.02	9.78	56.40	0.06
3.62	50.59	0.05	9.87	35.22	0.04
3.70	2636.40	2.64	10.17	30.00	0.03
3.75	3251.40	3.25	10.28	60.19	0.06
3.80	2576.40	2.58	10.37	2646.00	2.65
3.85	1676.40	1.68	10.42	3261.00	3.26
3.93	1226.40	1.23	10.47	2586.00	2.59
3.98	1076.40	1.08	10.52	1686.00	1.69
4.03	956.40	0.96	10.60	1236.00	1.24
4.08	776.40	0.78	10.65	1086.00	1.09
4.12	647.83	0.65	10.70	966.00	0.97
4.20	511.69	0.51	10.75	786.00	0.79
4.25	444.82	0.44	10.78	657.43	0.66
4.28	416.40	0.42	10.87	521.29	0.52
4.37	326.40	0.33	10.92	454.42	0.45
4.45	262.11	0.26	10.95	426.00	0.43
4.53	203.67	0.20	11.03	336.00	0.34
4.62	176.40	0.18	11.12	271.71	0.27
4.70	121.85	0.12	11.20	213.27	0.21
4.78	101.40	0.10	11.28	186.00	0.19
4.95	56.40	0.06	11.37	131.45	0.13
5.03	35.22	0.04	11.45	111.00	0.11
6.00	20.40	0.02	11.58	140.60	0.14
8.33	20.40	0.02	11.62	66.00	0.07
8.45	50.59	0.05	11.70	170.80	0.17
8.53	2636.40	2.64	11.78	2756.60	2.76
8.58	3251.40	3.25	11.83	3371.60	3.37
8.63	2576.40	2.58	11.88	2696.60	2.70
8.68	1676.40	1.68	11.93	1796.60	1.80
8.77	1226.40	1.23	12.02	1346.60	1.35
8.82	1076.40	1.08	12.07	1196.60	1.20
8.87	956.40	0.96	12.12	1076.60	1.08
8.92	776.40	0.78	12.17	896.60	0.90
8.95	647.83	0.65	12.20	768.03	0.77
9.03	511.69	0.51	12.28	631.90	0.63
9.08	444.82	0.44	12.33	565.02	0.57
9.12	416.40	0.42	12.37	536.60	0.54
9.20	326.40	0.33	12.45	446.60	0.45
9.28	262.11	0.26	12.53	382.32	0.38
9.37	203.67	0.20	12.62	323.88	0.32
9.45	176.40	0.18	12.70	296.60	0.30
9.53	121.85	0.12	12.75	269.33	0.27

Time (hrs)	Flowrate (L/min)	Flowrate (m^3/hr)	Time (hrs)	Flowrate (L/min)	Flowrate (m^3/hr)
12.78	242.06	0.24	16.87	210.19	0.21
12.90	272.25	0.27	16.95	2796.00	2.80
12.98	2858.06	2.86	17.00	3411.00	3.41
13.03	3473.06	3.47	17.05	2736.00	2.74
13.08	2798.06	2.80	17.10	1836.00	1.84
13.13	1898.06	1.90	17.18	1386.00	1.39
13.22	1448.06	1.45	17.23	1236.00	1.24
13.27	1298.06	1.30	17.28	1116.00	1.12
13.32	1178.06	1.18	17.33	936.00	0.94
13.37	998.06	1.00	17.37	807.43	0.81
13.40	869.49	0.87	17.45	671.29	0.67
13.48	733.35	0.73	17.50	604.42	0.60
13.53	666.48	0.67	17.53	576.00	0.58
13.57	638.06	0.64	17.62	486.00	0.49
13.65	548.06	0.55	17.70	421.71	0.42
13.73	483.77	0.48	17.78	363.27	0.36
13.82	425.33	0.43	17.87	336.00	0.34
13.90	398.06	0.40	17.95	281.45	0.28
13.98	343.51	0.34	18.03	261.00	0.26
14.07	323.06	0.32	18.20	216.00	0.22
14.23	278.06	0.28	18.28	194.82	0.19
14.32	256.88	0.26	18.75	168.00	0.17
14.92	180.00	0.18	18.87	198.19	0.20
15.03	210.19	0.21	18.95	2784.00	2.78
15.12	2796.00	2.80	19.00	3399.00	3.40
15.17	3411.00	3.41	19.05	2724.00	2.72
15.22	2736.00	2.74	19.10	1824.00	1.82
15.27	1836.00	1.84	19.18	1374.00	1.37
15.35	1386.00	1.39	19.23	1224.00	1.22
15.40	1236.00	1.24	19.28	1104.00	1.10
15.45	1116.00	1.12	19.33	924.00	0.92
15.50	936.00	0.94	19.37	795.43	0.80
15.53	807.43	0.81	19.45	659.29	0.66
15.62	671.29	0.67	19.50	592.42	0.59
15.67	604.42	0.60	19.53	564.00	0.56
15.70	576.00	0.58	19.62	474.00	0.47
15.78	486.00	0.49	19.70	409.71	0.41
15.87	421.71	0.42	19.78	351.27	0.35
15.95	363.27	0.36	19.87	324.00	0.32
16.03	336.00	0.34	19.95	269.45	0.27
16.12	281.45	0.28	20.03	249.00	0.25
16.20	261.00	0.26	20.20	204.00	0.20
16.37	216.00	0.22	20.28	182.82	0.18
16.45	194.82	0.19	22.00	144.00	0.14
16.75	180.00	0.18	24.00	20.40	0.02

V. Detention Time Calculations for Flow Beds (Constant Q)

Detention Time For Vertical Flow Bed Using Trapezoidal Rule

Assume : Flowrate is constant

Detention Time= 10.1 hrs

No	Time (hrs:min)	Time Int. (hr:min)	Time Int. (hrs)	$[Br^-]$ Det. (mol/l)	Δt (hrs)	*[Br-]* bar (mol/l)	*t bar* (hrs)	*Δt * [Br⁻]*t*	*Δt * [Br⁻]*
1	16:30	0:00	0.00	0.0000	1.00	0.0000	0.50	0.00000	0.00000
2	17:30	1:00	1.00	0.0000	0.50	0.0000	1.25	0.00000	0.00000
3	18:00	1:30	1.50	0.0000	0.50	0.0000	1.75	0.00000	0.00000
4	18:30	2:00	2.00	0.0000	1.00	0.0001	2.50	0.00025	0.00010
5	19:30	3:00	3.00	0.0002	1.00	0.0002	3.50	0.00070	0.00020
6	20:30	4:00	4.00	0.0002	0.50	0.0002	4.25	0.00043	0.00010
7	21:00	4:30	4.50	0.0002	0.50	0.0004	4.75	0.00083	0.00018
8	21:30	5:00	5.00	0.0005	0.25	0.0005	5.13	0.00064	0.00013
9	21:45	5:15	5.25	0.0005	0.25	0.0005	5.38	0.00060	0.00011
10	22:00	5:30	5.50	0.0004	0.50	0.0004	5.75	0.00115	0.00020
11	22:30	6:00	6.00	0.0004	0.25	0.0004	6.13	0.00061	0.00010
12	22:45	6:15	6.25	0.0004	0.75	0.0004	6.63	0.00174	0.00026
13	23:30	7:00	7.00	0.0003	0.50	0.0003	7.25	0.00109	0.00015
14	0:00	7:30	7.50	0.0003	1.00	0.0003	8.00	0.00200	0.00025
15	1:00	8:30	8.50	0.0002	1.00	0.0002	9.00	0.00180	0.00020
16	2:00	9:30	9.50	0.0002	1.00	0.0002	10.00	0.00200	0.00020
17	3:00	10:30	10.50	0.0002	1.00	0.0002	11.00	0.00220	0.00020
18	4:00	11:30	11.50	0.0002	1.50	0.0003	12.25	0.00459	0.00038
19	5:30	13:00	13.00	0.0003	1.00	0.0003	13.50	0.00405	0.00030
20	6:30	14:00	14.00	0.0003	0.50	0.0003	14.25	0.00178	0.00013
21	7:00	14:30	14.50	0.0002	0.50	0.0002	14.75	0.00148	0.00010
22	7:30	15:00	15.00	0.0002	0.50	0.0002	15.25	0.00153	0.00010
23	8:00	15:30	15.50	0.0002	0.50	0.0002	15.75	0.00158	0.00010
24	8:30	16:00	16.00	0.0002	1.00	0.0002	16.50	0.00330	0.00020
25	9:30	17:00	17.00	0.0002	0.50	0.0003	17.25	0.00216	0.00013
26	10:00	17:30	17.50	0.0003	1.00	0.0002	18.00	0.00360	0.00020
27	11:00	18:30	18.50	0.0001	0.50	0.0001	18.75	0.00094	0.00005
28	11:30	19:00	19.00	0.0001			Σ	0.04103	0.00405

Detention Time For Horizontal Flow Bed

Assume : Flowrate is constant

Detention Time= 8.5846744 hrs

No	Time Int. (hrs)	[Br⁻] Detected (mol/l)	Δt (hrs)	*[Br-]* bar (mol/l)	*t bar* (hrs)	*Δt * [Br⁻]*t*	*Δt * [Br⁻]*
1	0.00	0.0000	1.00	0.0001	0.5	0.00005	0.0001
2	1.00	0.0002	0.25	0.00025	1.125	7.03E-05	6.25E-05
3	1.25	0.0003	0.25	0.0003	1.375	0.000103	0.000075
4	1.50	0.0003	0.17	0.0004	1.583333	0.000106	6.67E-05
5	1.67	0.0005	0.33	0.0004	1.833333	0.000244	0.000133
6	2.00	0.0003	0.25	0.0003	2.125	0.000159	0.000075
7	2.25	0.0003	0.25	0.0005	2.375	0.000297	0.000125
8	2.50	0.0007	0.25	0.00075	2.625	0.000492	0.000188
9	2.75	0.0008	0.25	0.00085	2.875	0.000611	0.000213
10	3.00	0.0009	0.25	0.0009	3.125	0.000703	0.000225
11	3.25	0.0009	0.25	0.001	3.375	0.000844	0.00025
12	3.50	0.0011	0.25	0.0012	3.625	0.001088	0.0003
13	3.75	0.0013	0.25	0.00135	3.875	0.001308	0.000338
14	4.00	0.0014	0.25	0.0013	4.125	0.001341	0.000325
15	4.25	0.0012	0.25	0.0012	4.375	0.001313	0.0003
16	4.50	0.0012	0.25	0.00115	4.625	0.00133	0.000288
17	4.75	0.0011	0.25	0.00105	4.875	0.00128	0.000263
18	5.00	0.0010	0.25	0.00095	5.125	0.001217	0.000238
19	5.25	0.0009	0.50	0.0011	5.5	0.003025	0.00055
20	5.75	0.0013	0.25	0.0013	5.875	0.001909	0.000325
21	6.00	0.0013	0.08	0.0011	6.041667	0.000554	9.17E-05
22	6.08	0.0009	0.08	0.00085	6.125	0.000434	7.08E-05
23	6.17	0.0008	0.08	0.0008	6.208333	0.000414	6.67E-05
24	6.25	0.0008	0.08	0.0008	6.291667	0.000419	6.67E-05
25	6.33	0.0008	0.08	0.0008	6.375	0.000425	6.67E-05
26	6.42	0.0008	0.08	0.0008	6.458333	0.000431	6.67E-05
27	6.50	0.0008	0.25	0.0008	6.625	0.001325	0.0002
28	6.75	0.0008	0.25	0.0008	6.875	0.001375	0.0002
29	7.00	0.0008	0.25	0.0008	7.125	0.001425	0.0002
30	7.25	0.0008	0.75	0.0007	7.625	0.004003	0.000525
31	8.00	0.0006	0.25	0.0006	8.125	0.001219	0.00015
32	8.25	0.0006	1.00	0.00075	8.75	0.006563	0.00075
33	9.25	0.0009	1.00	0.00075	9.75	0.007313	0.00075
34	10.25	0.0006	1.00	0.0006	10.75	0.00645	0.0006
35	11.25	0.0006	1.00	0.00045	11.75	0.005288	0.00045
36	12.25	0.0003	1.00	0.0003	12.75	0.003825	0.0003
37	13.25	0.0003	1.00	0.00025	13.75	0.003438	0.00025
38	14.25	0.0002	1.00	0.0002	14.75	0.00295	0.0002

No	Time Int.	[Br⁻] Detected	Δt	*[Br-]* bar	*t bar*	*Δt * [Br⁻]*t*	*Δt * [Br⁻]*
	(hrs)	(mol/l)	(hrs)	(mol/l)	(hrs)		
39	15.25	0.0002	1.00	0.0002	15.75	0.00315	0.0002
40	16.25	0.0002	1.00	0.0002	16.75	0.00335	0.0002
41	17.25	0.0002	1.00	0.00025	17.75	0.004438	0.00025
42	18.25	0.0003	1.50	0.0003	19	0.00855	0.00045
43	19.75	0.0003	0.25	0.00025	19.875	0.001242	6.25E-05
44	20.00	0.0002	0.25	0.0002	20.125	0.001006	0.00005
45	20.25	0.0002	0.25	0.0002	20.375	0.001019	0.00005
46	20.50	0.0002	0.75	0.0002	20.875	0.003131	0.00015
47	21.25	0.0002	0.25	0.0002	21.375	0.001069	0.00005
48	21.50	0.0002	0.25	0.0002	21.625	0.001081	0.00005
49	21.75	0.0002	0.25	0.0002	21.875	0.001094	0.00005
50	22.00	0.0002			Σ	0.094467	0.011004

VI. Detention Time Calculations for Flow Beds with Q Factor

Detention Time For Vertical Flow Bed Using Trapezoidal Rule

Detention Time= 7.78 hrs

No	Time Int.	Q	[Br⁻] Det.	Δt	*Q bar*	*[Br-]* bar	*t bar*	*Δt * [Br⁻]*t*Q*	*Δt * [Br⁻]*Q*
	(hrs)	(L/hrs)	(mol/l)	(hrs)	(L/hrs)	(mol/l)	(hrs)		
1	0.00	420.00	0.000000	0.28	444.00	0.0000	0.14	0.00000	0.00000
2	0.28	468.00	0.000000	0.08	508.00	0.0000	0.33	0.00000	0.00000
3	0.37	548.00	0.000000	0.08	548.00	0.0000	0.41	0.00000	0.00000
4	0.45	548.00	0.000000	0.02	868.00	0.0000	0.46	0.00000	0.00000
5	0.47	1188.00	0.000000	0.08	1188.00	0.0000	0.51	0.00000	0.00000
6	0.55	1188.00	0.000000	0.45	1188.00	0.0000	0.78	0.00000	0.00000
7	1.00	1188.00	0.000000	0.50	1188.00	0.0000	1.25	0.00000	0.00000
8	1.50	1188.00	0.000000	0.05	1188.00	0.0000	1.53	0.00000	0.00000
9	1.55	1188.00	0.000000	0.02	948.00	0.0000	1.56	0.00000	0.00000
10	1.57	708.00	0.000000	0.25	708.00	0.0000	1.69	0.00000	0.00000
11	1.82	708.00	0.000000	0.02	660.00	0.0000	1.83	0.00000	0.00000
12	1.83	612.00	0.000000	0.17	612.00	0.0000	1.92	0.00000	0.00000
13	2.00	612.00	0.000000	0.05	612.00	0.0000	2.03	0.00031	0.00015
14	2.05	612.00	0.000010	0.02	580.00	0.0000	2.06	0.00023	0.00011
15	2.07	548.00	0.000013	0.03	548.00	0.0000	2.08	0.00063	0.00030
16	2.10	548.00	0.000020	0.10	548.00	0.0000	2.15	0.00353	0.00164
17	2.20	548.00	0.000040	0.08	553.00	0.0000	2.24	0.00499	0.00223
18	2.28	558.00	0.000057	0.02	566.00	0.0001	2.29	0.00126	0.00055
19	2.30	574.00	0.000060	0.07	606.00	0.0001	2.33	0.00628	0.00269
20	2.37	638.00	0.000073	0.03	638.00	0.0001	2.38	0.00389	0.00163
21	2.40	638.00	0.000080	0.05	638.00	0.0001	2.43	0.00658	0.00271
22	2.45	638.00	0.000090	0.02	958.00	0.0001	2.46	0.00360	0.00146
23	2.47	1278.00	0.000093	0.03	1278.00	0.0001	2.48	0.01023	0.00412
24	2.50	1278.00	0.000100	0.05	1278.00	0.0001	2.53	0.01694	0.00671
25	2.55	1278.00	0.000110	0.05	1278.00	0.0001	2.58	0.01892	0.00735
26	2.60	1278.00	0.000120	0.10	1278.00	0.0001	2.65	0.04403	0.01661
27	2.70	1278.00	0.000140	0.10	1278.00	0.0002	2.75	0.05272	0.01917
28	2.80	1278.00	0.000160	0.10	1278.00	0.0002	2.85	0.06192	0.02173
29	2.90	1278.00	0.000180	0.10	1278.00	0.0002	2.95	0.07163	0.02428
30	3.00	1278.00	0.000200	0.55	1278.00	0.0002	3.28	0.46040	0.14058
31	3.55	1278.00	0.000200	0.02	1038.00	0.0002	3.56	0.01231	0.00346
32	3.57	798.00	0.000200	0.25	798.00	0.0002	3.69	0.14730	0.03990
33	3.82	798.00	0.000200	0.02	750.00	0.0002	3.83	0.00956	0.00250
34	3.83	702.00	0.000200	0.17	702.00	0.0002	3.92	0.09165	0.02340
35	4.00	702.00	0.000200	0.05	702.00	0.0002	4.03	0.02826	0.00702
36	4.05	702.00	0.000200	0.02	670.00	0.0002	4.06	0.00906	0.00223
37	4.07	638.00	0.000200	0.13	638.00	0.0002	4.13	0.07032	0.01701
38	4.20	638.00	0.000200	0.05	562.90	0.0002	4.23	0.02378	0.00563
39	4.25	487.80	0.000200	0.08	429.90	0.0002	4.29	0.03075	0.00716

No	Time Int.	Q	[Br⁻] Det.	Δt	*Q bar*	*[Br-]* bar	*t bar*	*Δt * [Br-]*t*Q*	*Δt * [Br-]*Q*
	(hrs)	(L/hrs)	(mol/l)	(hrs)	(L/hrs)	(mol/l)	(hrs)		
40	4.33	372.00	0.000200	0.08	306.00	0.0002	4.38	0.02231	0.00510
41	4.42	240.00	0.000200	0.03	264.00	0.0002	4.43	0.00780	0.00176
42	4.45	288.00	0.000200	0.05	312.00	0.0002	4.48	0.01396	0.00312
43	4.50	336.00	0.000200	0.03	352.00	0.0002	4.52	0.01113	0.00246
44	4.53	368.00	0.000220	0.02	368.00	0.0002	4.54	0.00627	0.00138
45	4.55	368.00	0.000230	0.05	368.00	0.0002	4.58	0.02062	0.00451
46	4.60	368.00	0.000260	0.02	368.00	0.0003	4.61	0.00749	0.00163
47	4.62	368.00	0.000270	0.02	688.00	0.0003	4.63	0.01458	0.00315
48	4.63	1008.00	0.000280	0.02	1008.00	0.0003	4.64	0.02222	0.00479
49	4.65	1008.00	0.000290	0.05	1008.00	0.0003	4.68	0.07186	0.01537
50	4.70	1008.00	0.000320	0.02	1008.00	0.0003	4.71	0.02571	0.00546
51	4.72	1008.00	0.000330	0.03	1008.00	0.0003	4.73	0.05407	0.01142
52	4.75	1008.00	0.000350	0.05	1008.00	0.0004	4.78	0.08784	0.01840
53	4.80	1008.00	0.000380	0.05	1008.00	0.0004	4.83	0.09606	0.01991
54	4.85	1008.00	0.000410	0.05	1008.00	0.0004	4.88	0.10442	0.02142
55	4.90	1008.00	0.000440	0.05	1008.00	0.0005	4.93	0.11294	0.02293
56	4.95	1008.00	0.000470	0.05	1008.00	0.0005	4.98	0.12161	0.02444
57	5.00	1008.00	0.000500	0.25	1008.00	0.0005	5.13	0.64575	0.12600
58	5.25	1008.00	0.000500	0.05	1008.00	0.0005	5.28	0.13027	0.02470
59	5.30	1008.00	0.000480	0.05	1008.00	0.0005	5.33	0.12614	0.02369
60	5.35	1008.00	0.000460	0.05	1008.00	0.0005	5.38	0.12191	0.02268
61	5.40	1008.00	0.000440	0.05	1008.00	0.0004	5.43	0.11757	0.02167
62	5.45	1008.00	0.000420	0.05	1008.00	0.0004	5.48	0.11314	0.02066
63	5.50	1008.00	0.000400	0.22	1008.00	0.0004	5.61	0.48994	0.08736
64	5.72	1008.00	0.000400	0.02	768.00	0.0004	5.73	0.02931	0.00512
65	5.73	528.00	0.000400	0.25	528.00	0.0004	5.86	0.30932	0.05280
66	5.98	528.00	0.000400	0.02	480.00	0.0004	5.99	0.01917	0.00320
67	6.00	432.00	0.000400	0.22	432.00	0.0004	6.11	0.22870	0.03744
68	6.22	432.00	0.000400	0.02	400.00	0.0004	6.23	0.01660	0.00267
69	6.23	368.00	0.000400	0.02	368.00	0.0004	6.24	0.01531	0.00245
70	6.25	368.00	0.000400	0.12	368.00	0.0004	6.31	0.10623	0.01684
71	6.37	368.00	0.000384	0.13	349.85	0.0004	6.43	0.11270	0.01752
72	6.50	331.69	0.000367	0.08	320.35	0.0004	6.54	0.06306	0.00964
73	6.58	309.00	0.000356	0.17	291.75	0.0003	6.67	0.11166	0.01675
74	6.75	274.50	0.000333	0.17	257.25	0.0003	6.83	0.09440	0.01382
75	6.92	240.00	0.000311	0.08	232.50	0.0003	6.96	0.04119	0.00592
76	7.00	225.00	0.000300	0.25	202.50	0.0003	7.13	0.10821	0.01519
77	7.25	180.00	0.000300	0.25	157.50	0.0003	7.38	0.08712	0.01181
78	7.50	135.00	0.000300	0.08	127.50	0.0003	7.54	0.02371	0.00314
79	7.58	120.00	0.000292	0.17	112.88	0.0003	7.67	0.04087	0.00533
80	7.75	105.76	0.000275	0.17	98.64	0.0003	7.83	0.03434	0.00438
81	7.92	91.53	0.000258	0.08	91.53	0.0003	7.96	0.01543	0.00194
82	8.00	91.53	0.000250	0.25	91.53	0.0002	8.13	0.04415	0.00543
83	8.25	91.53	0.000225	0.25	91.53	0.0002	8.38	0.04072	0.00486
84	8.50	91.53	0.000200	1.00	91.53	0.0002	9.00	0.16475	0.01831

No	Time Int.	Q	[Br⁻] Det.	Δt	*Q bar*	*[Br-]* bar	*t bar*	*Δt * [Br⁻]*t*Q*	*Δt * [Br⁻]*Q*
	(hrs)	(L/hrs)	(mol/l)	(hrs)	(L/hrs)	(mol/l)	(hrs)		
85	9.50	91.53	0.000200	0.42	91.53	0.0002	9.71	0.07405	0.00763
86	9.92	91.53	0.000200	0.58	91.53	0.0002	10.21	0.10900	0.01068
87	10.50	91.53	0.000200	1.00	91.53	0.0002	11.00	0.20136	0.01831
88	11.50	91.53	0.000200	0.50	91.53	0.0002	11.75	0.11650	0.00992
89	12.00	91.53	0.000233	0.50	91.53	0.0003	12.25	0.14015	0.01144
90	12.50	91.53	0.000267	0.50	91.53	0.0003	12.75	0.16532	0.01297
91	13.00	91.53	0.000300	1.00	91.53	0.0003	13.50	0.37068	0.02746
92	14.00	91.53	0.000300	0.13	91.53	0.0003	14.06	0.04625	0.00329
93	14.13	91.53	0.000275	0.13	91.53	0.0003	14.19	0.04261	0.00300
94	14.25	91.53	0.000250	0.13	91.53	0.0002	14.31	0.03889	0.00272
95	14.38	91.53	0.000225	0.13	91.53	0.0002	14.44	0.03510	0.00243
96	14.50	91.53	0.000200	0.50	91.53	0.0002	14.75	0.13500	0.00915
97	15.00	91.53	0.000200	0.50	91.53	0.0002	15.25	0.13958	0.00915
98	15.50	91.53	0.000200	0.50	91.53	0.0002	15.75	0.14415	0.00915
99	16.00	91.53	0.000200	0.92	91.53	0.0002	16.46	0.27617	0.01678
100	16.92	91.53	0.000200	0.08	98.58	0.0002	16.96	0.02786	0.00164
101	17.00	105.64	0.000200	0.13	116.23	0.0002	17.06	0.05268	0.00309
102	17.13	126.82	0.000225	0.07	133.17	0.0002	17.16	0.03985	0.00232
103	17.20	139.53	0.000240	0.05	163.53	0.0002	17.23	0.03450	0.00200
104	17.25	187.53	0.000250	0.03	203.53	0.0003	17.27	0.02968	0.00172
105	17.28	219.53	0.000257	0.08	219.53	0.0003	17.33	0.08399	0.00485
106	17.37	219.53	0.000273	0.01	379.53	0.0003	17.37	0.01506	0.00087
107	17.38	539.53	0.000275	0.01	699.53	0.0003	17.38	0.02794	0.00161
108	17.38	859.53	0.000277	0.08	859.53	0.0003	17.43	0.35571	0.02041
109	17.47	859.53	0.000293	0.03	859.53	0.0003	17.48	0.14860	0.00850
110	17.50	859.53	0.000300	0.13	859.53	0.0003	17.56	0.54249	0.03089
111	17.63	859.53	0.000275	0.13	859.53	0.0003	17.69	0.49884	0.02820
112	17.75	859.53	0.000250	0.13	859.53	0.0002	17.81	0.45452	0.02552
113	17.88	859.53	0.000225	0.13	859.53	0.0002	17.94	0.40953	0.02283
114	18.00	859.53	0.000200	0.25	859.53	0.0002	18.13	0.68158	0.03760
115	18.25	859.53	0.000150	0.22	859.53	0.0001	18.36	0.43876	0.02390
116	18.47	859.53	0.000107	0.02	619.53	0.0001	18.48	0.02003	0.00108
117	18.48	379.53	0.000103	0.02	379.53	0.0001	18.49	0.01189	0.00064
118	18.50	379.53	0.000100	0.23	379.53	0.0001	18.62	0.16486	0.00886
119	18.73	379.53	0.000100	0.02	331.53	0.0001	18.74	0.01036	0.00055
120	18.75	283.53	0.000100	0.22	307.66	0.0001	18.86	0.12571	0.00667
121	18.97	331.80	0.000100	0.02	395.70	0.0001	18.98	0.01251	0.00066
122	18.98	459.60	0.000100	0.02	459.60	0.0001	18.99	0.01455	0.00077
123	19.00	459.60	0.000100				Σ	11.67999	1.50018

Detention Time For Horizontal Flow Bed Using Trapezoidal Rule

Detention Time= 6.68 hrs

No	Time Int. (hrs)	[Br⁻] Det. (mol/l)	Q (L/hrs)	Δ t (hrs)	*[Br⁻] bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
1	0.00	0.000	269.3	0.033	0.000	0.017	255.7	0.000	0.000
2	0.033	0.000	242.1	0.067	0.000	0.067	250.7	0.000	0.000
3	0.10	0.000	259.3	0.050	0.000	0.125	265.8	0.000	0.000
4	0.150	0.000	272.3	0.050	0.000	0.175	1048.0	0.000	0.002
5	0.20	0.000	1823.7	0.033	0.000	0.217	2340.9	0.001	0.003
6	0.233	0.000	2858.1	0.050	0.000	0.258	3165.6	0.002	0.008
7	0.283	0.000	3473.1	0.017	0.000	0.292	3360.6	0.001	0.003
8	0.30	0.000	3248.1	0.033	0.000	0.317	3023.1	0.002	0.006
9	0.333	0.000	2798.1	0.050	0.000	0.358	2348.1	0.003	0.008
10	0.383	0.000	1898.1	0.017	0.000	0.392	1853.1	0.001	0.002
11	0.40	0.000	1808.1	0.067	0.000	0.433	1628.1	0.004	0.009
12	0.467	0.000	1448.1	0.050	0.000	0.492	1373.1	0.003	0.007
13	0.517	0.000	1298.1	0.050	0.000	0.542	1238.1	0.004	0.007
14	0.567	0.000	1178.1	0.033	0.000	0.583	1118.1	0.003	0.004
15	0.60	0.000	1058.1	0.017	0.000	0.608	1028.1	0.001	0.002
16	0.617	0.000	998.1	0.033	0.000	0.633	933.8	0.002	0.004
17	0.650	0.000	869.5	0.083	0.000	0.692	801.4	0.006	0.009
18	0.733	0.000	733.4	0.050	0.000	0.758	699.9	0.004	0.005
19	0.783	0.000	666.5	0.017	0.000	0.792	659.4	0.001	0.002
20	0.80	0.000	652.3	0.017	0.000	0.808	645.2	0.001	0.002
21	0.817	0.000	638.1	0.083	0.000	0.858	593.1	0.007	0.008
22	0.900	0.000	548.1	0.083	0.000	0.942	515.9	0.008	0.008
23	0.983	0.000	483.8	0.017	0.000	0.992	477.9	0.002	0.002
24	1.00	0.000	472.1	0.063	0.000	1.031	450.2	0.006	0.006
25	1.06	0.000	428.3	0.004	0.000	1.065	426.8	0.000	0.000
26	1.067	0.000	425.3	0.058	0.000	1.096	415.8	0.006	0.006
27	1.13	0.000	406.2	0.025	0.000	1.138	402.1	0.003	0.003
28	1.150	0.000	398.1	0.038	0.000	1.169	385.8	0.005	0.004
29	1.19	0.000	373.5	0.046	0.000	1.210	358.5	0.006	0.005
30	1.233	0.000	343.5	0.017	0.000	1.242	341.5	0.002	0.002
31	1.25	0.000	339.4	0.067	0.000	1.283	331.2	0.009	0.007
32	1.317	0.000	323.1	0.167	0.000	1.400	300.6	0.021	0.015
33	1.483	0.000	278.1	0.017	0.000	1.492	275.9	0.002	0.001
34	1.50	0.000	273.8	0.050	0.000	1.525	267.5	0.007	0.004
35	1.55	0.000	261.1	0.017	0.000	1.558	259.0	0.002	0.002
36	1.567	0.000	256.9	0.033	0.000	1.583	254.7	0.005	0.003
37	1.60	0.000	252.6	0.067	0.000	1.633	248.3	0.012	0.008
38	1.67	0.001	244.1	0.133	0.000	1.733	235.5	0.025	0.014
39	1.80	0.000	227.0	0.100	0.000	1.850	220.6	0.016	0.009
40	1.90	0.000	214.2	0.100	0.000	1.950	207.8	0.013	0.007
41	2.00	0.000	201.4	0.167	0.000	2.083	190.7	0.020	0.010

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
42	2.167	0.000	180.0	0.083	0.000	2.208	190.8	0.011	0.005
43	2.25	0.000	201.6	0.025	0.000	2.263	204.8	0.004	0.002
44	2.28	0.000	208.0	0.008	0.000	2.279	209.1	0.001	0.001
45	2.283	0.000	210.2	0.017	0.000	2.292	468.8	0.007	0.003
46	2.30	0.000	727.4	0.067	0.000	2.333	1761.7	0.119	0.051
47	2.367	0.000	2796.0	0.008	0.000	2.371	2847.3	0.028	0.012
48	2.38	0.001	2898.5	0.038	0.001	2.394	3129.1	0.149	0.062
49	2.41	0.001	3359.8	0.004	0.001	2.415	3385.4	0.019	0.008
50	2.417	0.001	3411.0	0.033	0.001	2.433	3186.0	0.153	0.063
51	2.45	0.001	2961.0	0.017	0.001	2.458	2848.5	0.074	0.030
52	2.467	0.001	2736.0	0.033	0.001	2.483	2436.0	0.136	0.055
53	2.50	0.001	2136.0	0.017	0.001	2.508	1986.0	0.058	0.023
54	2.517	0.001	1836.0	0.046	0.001	2.540	1712.3	0.143	0.056
55	2.56	0.001	1588.5	0.038	0.001	2.581	1487.3	0.105	0.041
56	2.600	0.001	1386.0	0.025	0.001	2.613	1348.5	0.066	0.025
57	2.63	0.001	1311.0	0.025	0.001	2.638	1273.5	0.063	0.024
58	2.650	0.001	1236.0	0.050	0.001	2.675	1176.0	0.121	0.045
59	2.700	0.001	1116.0	0.050	0.001	2.725	1026.0	0.110	0.041
60	2.75	0.001	936.0	0.033	0.001	2.767	871.7	0.065	0.024
61	2.783	0.001	807.4	0.042	0.001	2.804	773.4	0.076	0.027
62	2.83	0.001	739.4	0.042	0.001	2.846	705.3	0.072	0.025
63	2.867	0.001	671.3	0.050	0.001	2.892	637.9	0.080	0.028
64	2.917	0.001	604.4	0.033	0.001	2.933	590.2	0.051	0.017
65	2.950	0.001	576.0	0.050	0.001	2.975	549.0	0.073	0.025
66	3.00	0.001	522.0	0.033	0.001	3.017	504.0	0.046	0.015
67	3.033	0.001	486.0	0.083	0.001	3.075	453.9	0.105	0.034
68	3.117	0.001	421.7	0.083	0.001	3.158	392.5	0.093	0.029
69	3.200	0.001	363.3	0.050	0.001	3.225	355.1	0.052	0.016
70	3.25	0.001	346.9	0.033	0.001	3.267	341.5	0.034	0.010
71	3.283	0.001	336.0	0.042	0.001	3.304	322.4	0.042	0.013
72	3.33	0.001	308.7	0.042	0.001	3.346	295.1	0.040	0.012
73	3.367	0.001	281.5	0.033	0.001	3.383	277.4	0.031	0.009
74	3.40	0.001	273.3	0.050	0.001	3.425	267.1	0.048	0.014
75	3.450	0.001	261.0	0.050	0.001	3.475	254.3	0.048	0.014
76	3.50	0.001	247.5	0.063	0.001	3.531	239.1	0.059	0.017
77	3.56	0.001	230.6	0.054	0.001	3.590	223.3	0.051	0.014
78	3.617	0.001	216.0	0.008	0.001	3.621	214.9	0.008	0.002
79	3.63	0.001	213.9	0.063	0.001	3.656	205.9	0.058	0.016
80	3.69	0.001	198.0	0.013	0.001	3.694	196.4	0.011	0.003
81	3.700	0.001	194.8	0.050	0.001	3.725	193.6	0.046	0.012
82	3.75	0.001	192.4	0.125	0.001	3.813	189.3	0.120	0.031
83	3.88	0.001	186.2	0.125	0.001	3.938	183.1	0.124	0.031
84	4.00	0.001	180.0	0.117	0.001	4.058	195.1	0.125	0.031
85	4.117	0.001	210.2	0.008	0.001	4.121	211.3	0.009	0.002
86	4.13	0.001	212.4	0.075	0.001	4.163	1504.2	0.596	0.143
87	4.200	0.001	2796.0	0.050	0.001	4.225	3103.5	0.800	0.189

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
88	4.25	0.001	3411.0	0.050	0.001	4.275	3073.5	0.788	0.184
89	4.300	0.001	2736.0	0.050	0.001	4.325	2286.0	0.593	0.137
90	4.350	0.001	1836.0	0.083	0.001	4.392	1611.0	0.707	0.161
91	4.433	0.001	1386.0	0.050	0.001	4.458	1311.0	0.351	0.079
92	4.483	0.001	1236.0	0.017	0.001	4.492	1216.0	0.109	0.024
93	4.50	0.001	1196.0	0.033	0.001	4.517	1156.0	0.208	0.046
94	4.533	0.001	1116.0	0.050	0.001	4.558	1026.0	0.275	0.060
95	4.583	0.001	936.0	0.033	0.001	4.600	871.7	0.155	0.034
96	4.617	0.001	807.4	0.008	0.001	4.621	800.6	0.036	0.008
97	4.63	0.001	793.8	0.075	0.001	4.663	732.6	0.291	0.062
98	4.700	0.001	671.3	0.050	0.001	4.725	637.9	0.167	0.035
99	4.75	0.001	604.4	0.033	0.001	4.767	590.2	0.103	0.022
100	4.783	0.001	576.0	0.083	0.001	4.825	531.0	0.228	0.047
101	4.867	0.001	486.0	0.008	0.001	4.871	482.8	0.021	0.004
102	4.88	0.001	479.6	0.075	0.001	4.913	450.6	0.172	0.035
103	4.950	0.001	421.7	0.050	0.001	4.975	404.2	0.102	0.020
104	5.00	0.001	386.6	0.033	0.001	5.017	375.0	0.062	0.012
105	5.033	0.001	363.3	0.083	0.001	5.075	349.6	0.143	0.028
106	5.117	0.001	336.0	0.008	0.001	5.121	333.3	0.014	0.003
107	5.13	0.001	330.5	0.075	0.001	5.163	306.0	0.111	0.021
108	5.200	0.001	281.5	0.050	0.001	5.225	275.3	0.065	0.013
109	5.25	0.001	269.2	0.033	0.001	5.267	265.1	0.043	0.008
110	5.283	0.001	261.0	0.029	0.001	5.298	252.9	0.037	0.007
111	5.31	0.001	244.7	0.063	0.001	5.344	227.3	0.074	0.014
112	5.38	0.001	209.9	0.063	0.001	5.406	192.4	0.067	0.012
113	5.44	0.001	175.0	0.013	0.001	5.444	195.5	0.014	0.003
114	5.450	0.001	216.0	0.050	0.001	5.475	209.6	0.062	0.011
115	5.50	0.001	203.3	0.033	0.001	5.517	199.1	0.041	0.007
116	5.533	0.001	194.8	0.029	0.001	5.548	194.0	0.036	0.006
117	5.56	0.001	193.1	0.063	0.001	5.594	191.4	0.079	0.014
118	5.63	0.001	189.6	0.063	0.001	5.656	187.8	0.081	0.014
119	5.69	0.001	186.0	0.063	0.001	5.719	184.2	0.084	0.015
120	5.75	0.001	182.4	0.250	0.001	5.875	175.2	0.334	0.057
121	6.00	0.001	168.0	0.010	0.001	6.005	169.3	0.013	0.002
122	6.01	0.001	170.6	0.010	0.001	6.015	171.9	0.013	0.002
123	6.02	0.001	173.2	0.010	0.001	6.025	174.5	0.012	0.002
124	6.03	0.001	175.8	0.010	0.001	6.035	177.1	0.012	0.002
125	6.04	0.001	178.4	0.010	0.001	6.045	179.6	0.012	0.002
126	6.05	0.001	180.9	0.010	0.001	6.055	182.2	0.011	0.002
127	6.06	0.001	183.5	0.010	0.001	6.065	184.8	0.011	0.002
128	6.07	0.001	186.1	0.013	0.001	6.077	187.8	0.014	0.002
129	6.08	0.001	189.6	0.033	0.001	6.100	193.9	0.035	0.006
130	6.117	0.001	198.2	0.050	0.001	6.142	973.9	0.248	0.040
131	6.17	0.001	1749.7	0.033	0.001	6.183	2266.8	0.374	0.060
132	6.200	0.001	2784.0	0.050	0.001	6.225	3091.5	0.770	0.124
133	6.25	0.001	3399.0	0.050	0.001	6.275	3061.5	0.768	0.122

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
134	6.300	0.001	2724.0	0.033	0.001	6.317	2424.0	0.408	0.065
135	6.33	0.001	2124.0	0.017	0.001	6.342	1974.0	0.167	0.026
136	6.350	0.001	1824.0	0.067	0.001	6.383	1644.0	0.560	0.088
137	6.42	0.001	1464.0	0.017	0.001	6.425	1419.0	0.122	0.019
138	6.433	0.001	1374.0	0.050	0.001	6.458	1299.0	0.336	0.052
139	6.483	0.001	1224.0	0.017	0.001	6.492	1204.0	0.104	0.016
140	6.50	0.001	1184.0	0.033	0.001	6.517	1144.0	0.199	0.031
141	6.533	0.001	1104.0	0.050	0.001	6.558	1014.0	0.266	0.041
142	6.583	0.001	924.0	0.033	0.001	6.600	859.7	0.151	0.023
143	6.617	0.001	795.4	0.083	0.001	6.658	727.4	0.323	0.048
144	6.700	0.001	659.3	0.050	0.001	6.725	625.9	0.168	0.025
145	6.75	0.001	592.4	0.033	0.001	6.767	578.2	0.104	0.015
146	6.783	0.001	564.0	0.083	0.001	6.825	519.0	0.236	0.035
147	6.867	0.001	474.0	0.083	0.001	6.908	441.9	0.203	0.029
148	6.950	0.001	409.7	0.050	0.001	6.975	392.2	0.109	0.016
149	7.00	0.001	374.6	0.033	0.001	7.017	363.0	0.068	0.010
150	7.033	0.001	351.3	0.083	0.001	7.075	337.6	0.159	0.023
151	7.117	0.001	324.0	0.083	0.001	7.158	296.7	0.142	0.020
152	7.200	0.001	269.5	0.050	0.001	7.225	263.3	0.076	0.011
153	7.25	0.001	257.2	0.033	0.001	7.267	253.1	0.049	0.007
154	7.283	0.001	249.0	0.167	0.001	7.367	226.5	0.214	0.029
155	7.450	0.001	204.0	0.050	0.001	7.475	197.6	0.055	0.007
156	7.50	0.001	191.3	0.033	0.001	7.517	187.1	0.034	0.005
157	7.533	0.001	182.8	0.217	0.001	7.642	180.4	0.208	0.027
158	7.75	0.001	177.9	0.250	0.001	7.875	175.1	0.218	0.028
159	8.00	0.001	172.3	0.250	0.001	8.125	169.4	0.207	0.025
160	8.25	0.001	166.6	0.125	0.001	8.313	165.2	0.106	0.013
161	8.38	0.001	163.8	0.125	0.001	8.438	162.4	0.112	0.013
162	8.50	0.001	161.0	0.375	0.001	8.688	156.7	0.364	0.042
163	8.88	0.001	152.5	0.188	0.001	8.969	150.4	0.199	0.022
164	9.06	0.001	148.2	0.188	0.001	9.156	146.1	0.216	0.024
165	9.25	0.001	144.0	0.250	0.001	9.375	136.3	0.275	0.029
166	9.50	0.001	128.6	0.250	0.001	9.625	120.8	0.229	0.024
167	9.75	0.001	113.1	0.250	0.001	9.875	105.4	0.185	0.019
168	10.00	0.001	97.7	0.250	0.001	10.125	89.9	0.145	0.014
169	10.25	0.001	82.2	1.000	0.001	10.750	51.3	0.331	0.031
170	11.25	0.001	20.4	0.250	0.001	11.375	20.4	0.033	0.003
171	11.50	0.001	20.4	0.250	0.000	11.625	20.4	0.029	0.002
172	11.75	0.000	20.4	0.250	0.000	11.875	20.4	0.025	0.002
173	12.00	0.000	20.4	0.250	0.000	12.125	20.4	0.021	0.002
174	12.25	0.000	20.4	1.000	0.000	12.750	20.4	0.078	0.006
175	13.25	0.000	20.4	0.500	0.000	13.500	20.4	0.038	0.003
176	13.75	0.000	20.4	0.250	0.000	13.875	20.4	0.017	0.001
177	14.00	0.000	20.4	0.250	0.000	14.125	20.4	0.015	0.001
178	14.25	0.000	20.4	0.500	0.000	14.500	20.4	0.030	0.002
179	14.750	0.000	20.4	0.117	0.000	14.808	35.5	0.012	0.001

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
180	14.867	0.000	50.6	0.083	0.000	14.908	1343.5	0.334	0.022
181	14.950	0.000	2636.4	0.050	0.000	14.975	2943.9	0.441	0.029
182	15.000	0.000	3251.4	0.050	0.000	15.025	2913.9	0.438	0.029
183	15.050	0.000	2576.4	0.050	0.000	15.075	2126.4	0.321	0.021
184	15.100	0.000	1676.4	0.083	0.000	15.142	1451.4	0.366	0.024
185	15.183	0.000	1226.4	0.050	0.000	15.208	1151.4	0.175	0.012
186	15.233	0.000	1076.4	0.017	0.000	15.242	1056.4	0.054	0.004
187	15.25	0.000	1036.4	0.033	0.000	15.267	996.4	0.101	0.007
188	15.283	0.000	956.4	0.050	0.000	15.308	866.4	0.133	0.009
189	15.333	0.000	776.4	0.033	0.000	15.350	712.1	0.073	0.005
190	15.367	0.000	647.8	0.083	0.000	15.408	579.8	0.149	0.010
191	15.450	0.000	511.7	0.050	0.000	15.475	478.3	0.074	0.005
192	15.500	0.000	444.8	0.033	0.000	15.517	430.6	0.045	0.003
193	15.533	0.000	416.4	0.083	0.000	15.575	371.4	0.096	0.006
194	15.617	0.000	326.4	0.083	0.000	15.658	294.3	0.077	0.005
195	15.700	0.000	262.1	0.083	0.000	15.742	232.9	0.061	0.004
196	15.783	0.000	203.7	0.083	0.000	15.825	190.0	0.050	0.003
197	15.867	0.000	176.4	0.083	0.000	15.908	149.1	0.040	0.002
198	15.950	0.000	121.9	0.083	0.000	15.992	111.6	0.030	0.002
199	16.033	0.000	101.4	0.167	0.000	16.117	78.9	0.042	0.003
200	16.200	0.000	56.4	0.050	0.000	16.225	50.0	0.008	0.001
201	16.25	0.000	43.7	0.033	0.000	16.267	39.5	0.004	0.000
202	16.283	0.000	35.2	0.967	0.000	16.767	27.8	0.090	0.005
203	17.25	0.000	20.4	0.500	0.000	17.500	20.4	0.040	0.002
204	17.75	0.000	20.4	0.500	0.000	18.000	20.4	0.050	0.003
205	18.25	0.000	20.4	1.333	0.000	18.917	20.4	0.154	0.008
206	19.583	0.000	20.4	0.117	0.000	19.642	35.5	0.024	0.001
207	19.700	0.000	50.6	0.050	0.000	19.725	826.3	0.244	0.012
208	19.75	0.000	1602.1	0.033	0.000	19.767	2119.2	0.410	0.021
209	19.783	0.000	2636.4	0.050	0.000	19.808	2943.9	0.807	0.041
210	19.833	0.000	3251.4	0.042	0.000	19.854	2970.2	0.635	0.032
211	19.88	0.000	2688.9	0.008	0.000	19.879	2632.7	0.108	0.005
212	19.883	0.000	2576.4	0.050	0.000	19.908	2126.4	0.501	0.025
213	19.933	0.000	1676.4	0.067	0.000	19.967	1496.4	0.425	0.021
214	20.00	0.000	1316.4	0.017	0.000	20.008	1271.4	0.085	0.004
215	20.017	0.000	1226.4	0.050	0.000	20.042	1151.4	0.231	0.012
216	20.067	0.000	1076.4	0.050	0.000	20.092	1016.4	0.204	0.010
217	20.117	0.000	956.4	0.050	0.000	20.142	866.4	0.175	0.009
218	20.167	0.000	776.4	0.033	0.000	20.183	712.1	0.096	0.005
219	20.200	0.000	647.8	0.050	0.000	20.225	607.0	0.123	0.006
220	20.25	0.000	566.1	0.033	0.000	20.267	538.9	0.073	0.004
221	20.283	0.000	511.7	0.050	0.000	20.308	478.3	0.097	0.005
222	20.333	0.000	444.8	0.033	0.000	20.350	430.6	0.058	0.003
223	20.367	0.000	416.4	0.083	0.000	20.408	371.4	0.126	0.006
224	20.450	0.000	326.4	0.050	0.000	20.475	307.1	0.063	0.003
225	20.50	0.000	287.8	0.033	0.000	20.517	275.0	0.038	0.002

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
226	20.533	0.000	262.1	0.083	0.000	20.575	232.9	0.080	0.004
227	20.617	0.000	203.7	0.083	0.000	20.658	190.0	0.065	0.003
228	20.700	0.000	176.4	0.083	0.000	20.742	149.1	0.052	0.002
229	20.783	0.000	121.9	0.083	0.000	20.825	111.6	0.039	0.002
230	20.867	0.000	101.4	0.167	0.000	20.950	78.9	0.055	0.003
231	21.033	0.000	56.4	0.083	0.000	21.075	45.8	0.016	0.001
232	21.117	0.000	35.2	0.133	0.000	21.183	34.1	0.019	0.001
233	21.25	0.000	32.9	0.167	0.000	21.333	31.5	0.022	0.001
234	21.417	0.000	30.0	0.083	0.000	21.458	40.8	0.015	0.001
235	21.50	0.000	51.6	0.033	0.000	21.517	55.9	0.008	0.000
236	21.533	0.000	60.2	0.083	0.000	21.575	1353.1	0.487	0.023
237	21.617	0.000	2646.0	0.050	0.000	21.642	2953.5	0.639	0.030
238	21.667	0.000	3261.0	0.050	0.000	21.692	2923.5	0.634	0.029
239	21.717	0.000	2586.0	0.033	0.000	21.733	2286.0	0.331	0.015
240	21.75	0.000	1986.0	0.017	0.000	21.758	1836.0	0.133	0.006
241	21.767	0.000	1686.0	0.083	0.000	21.808	1461.0	0.531	0.024
242	21.850	0.000	1236.0	0.050	0.000	21.875	1161.0	0.254	0.012
243	21.900	0.000	1086.0	0.050	0.000	21.925	1026.0	0.225	0.010
244	21.950	0.000	966.0	0.050	0.000	21.975	876.0	0.193	0.009
245	22.00	0.000	786.0			Σ		31.603	4.732

VII. Residence Time Distribution Calculations

RTD For Vertical Flow Bed Using Trapezoidal Rule

k_r = 25 1/day **σ^2_θ =** 26.99 **R.F=** 0.9892

k_r = 1.042 1/hour **Detention Time=** 7.8 hrs

Amount of Chemical Used: 200 g

Amount of Chemical Recovered: 153.16 g
76.58 %

No	Time (hrs)	Q (L/hrs)	$[Br^-]_e$ (mol/l)	Δt (hrs)	*Q bar* (L/hrs)	*$[Br^-]_e$ bar* (mol/l)	*t bar* (hrs)	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	<u>Ce</u> Co
1	0.00	420.00	0.000000	0.28	444.00	0.0000	0.14	0.000	0.000	0.000	0.000	0.000
2	0.28	468.00	0.000000	0.08	508.00	0.0000	0.33	0.000	0.000	0.000	0.000	0.000
3	0.37	548.00	0.000000	0.08	548.00	0.0000	0.41	0.000	0.000	0.000	0.000	0.000
4	0.45	548.00	0.000000	0.02	868.00	0.0000	0.46	0.000	0.000	0.000	0.000	0.000
5	0.47	1188.00	0.000000	0.08	1188.00	0.0000	0.51	0.000	0.000	0.000	0.000	0.000
6	0.55	1188.00	0.000000	0.45	1188.00	0.0000	0.78	0.000	0.000	0.000	0.000	0.000
7	1.00	1188.00	0.000000	0.50	1188.00	0.0000	1.25	0.000	0.000	0.000	0.000	0.000
8	1.50	1188.00	0.000000	0.05	1188.00	0.0000	1.53	0.000	0.000	0.000	0.000	0.000
9	1.55	1188.00	0.000000	0.02	948.00	0.0000	1.56	0.000	0.000	0.000	0.000	0.000
10	1.57	708.00	0.000000	0.25	708.00	0.0000	1.69	0.000	0.000	0.000	0.000	0.000
11	1.82	708.00	0.000000	0.02	660.00	0.0000	1.83	0.000	0.000	0.000	0.000	0.000
12	1.83	612.00	0.000000	0.17	612.00	0.0000	1.92	0.000	0.000	0.000	0.000	0.000
13	2.00	612.00	0.000000	0.05	612.00	0.0000	2.03	0.000	0.000	0.002	0.003	0.000
14	2.05	612.00	0.000010	0.02	580.00	0.0000	2.06	0.000	0.000	0.005	0.002	0.000
15	2.07	548.00	0.000013	0.03	548.00	0.0000	2.08	0.001	0.000	0.006	0.007	0.000
16	2.10	548.00	0.000020	0.10	548.00	0.0000	2.15	0.004	0.002	0.011	0.035	0.000
17	2.20	548.00	0.000040	0.08	553.00	0.0000	2.24	0.005	0.002	0.018	0.046	0.000
18	2.28	558.00	0.000057	0.02	566.00	0.0001	2.29	0.001	0.001	0.022	0.011	0.000
19	2.30	574.00	0.000060	0.07	606.00	0.0001	2.33	0.006	0.003	0.027	0.053	0.000
20	2.37	638.00	0.000073	0.03	638.00	0.0001	2.38	0.004	0.002	0.033	0.032	0.000
21	2.40	638.00	0.000080	0.05	638.00	0.0001	2.43	0.007	0.003	0.036	0.052	0.000
22	2.45	638.00	0.000090	0.02	958.00	0.0001	2.46	0.004	0.001	0.059	0.028	0.000
23	2.47	1278.00	0.000093	0.03	1278.00	0.0001	2.48	0.010	0.004	0.082	0.077	0.000
24	2.50	1278.00	0.000100	0.05	1278.00	0.0001	2.53	0.017	0.007	0.089	0.124	0.000
25	2.55	1278.00	0.000110	0.05	1278.00	0.0001	2.58	0.019	0.007	0.098	0.133	0.000
26	2.60	1278.00	0.000120	0.10	1278.00	0.0001	2.65	0.044	0.017	0.111	0.292	0.001
27	2.70	1278.00	0.000140	0.10	1278.00	0.0002	2.75	0.053	0.019	0.128	0.324	0.001
28	2.80	1278.00	0.000160	0.10	1278.00	0.0002	2.85	0.062	0.022	0.145	0.353	0.001
29	2.90	1278.00	0.000180	0.10	1278.00	0.0002	2.95	0.072	0.024	0.162	0.378	0.001
30	3.00	1278.00	0.000200	0.55	1278.00	0.0002	3.28	0.460	0.141	0.170	1.907	0.003
31	3.55	1278.00	0.000200	0.02	1038.00	0.0002	3.56	0.012	0.003	0.138	0.041	0.000

No	Time (hrs)	Q (L/hrs)	$[Br^-]_e$ (mol/l)	Δt (hrs)	*Q bar* (L/hrs)	*$[Br^-]_e$ bar* (mol/l)	*t bar* (hrs)	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	Ce/Co
32	3.57	798.00	0.000200	0.25	798.00	0.0002	3.69	0.147	0.040	0.106	0.446	0.001
33	3.82	798.00	0.000200	0.02	750.00	0.0002	3.83	0.010	0.002	0.100	0.026	0.000
34	3.83	702.00	0.000200	0.17	702.00	0.0002	3.92	0.092	0.023	0.094	0.233	0.000
35	4.00	702.00	0.000200	0.05	702.00	0.0002	4.03	0.028	0.007	0.094	0.066	0.000
36	4.05	702.00	0.000200	0.02	670.00	0.0002	4.06	0.009	0.002	0.089	0.021	0.000
37	4.07	638.00	0.000200	0.13	638.00	0.0002	4.13	0.070	0.017	0.085	0.151	0.000
38	4.20	638.00	0.000200	0.05	562.90	0.0002	4.23	0.024	0.006	0.075	0.048	0.000
39	4.25	487.80	0.000200	0.08	429.90	0.0002	4.29	0.031	0.007	0.057	0.058	0.000
40	4.33	372.00	0.000200	0.08	306.00	0.0002	4.38	0.022	0.005	0.041	0.040	0.000
41	4.42	240.00	0.000200	0.03	264.00	0.0002	4.43	0.008	0.002	0.035	0.013	0.000
42	4.45	288.00	0.000200	0.05	312.00	0.0002	4.48	0.014	0.003	0.042	0.023	0.000
43	4.50	336.00	0.000200	0.03	352.00	0.0002	4.52	0.011	0.002	0.049	0.018	0.000
44	4.53	368.00	0.000220	0.02	368.00	0.0002	4.54	0.006	0.001	0.055	0.010	0.000
45	4.55	368.00	0.000230	0.05	368.00	0.0002	4.58	0.021	0.005	0.060	0.031	0.000
46	4.60	368.00	0.000260	0.02	368.00	0.0003	4.61	0.007	0.002	0.065	0.011	0.000
47	4.62	368.00	0.000270	0.02	688.00	0.0003	4.63	0.015	0.003	0.126	0.021	0.000
48	4.63	1008.00	0.000280	0.02	1008.00	0.0003	4.64	0.022	0.005	0.191	0.032	0.000
49	4.65	1008.00	0.000290	0.05	1008.00	0.0003	4.68	0.072	0.015	0.205	0.099	0.000
50	4.70	1008.00	0.000320	0.02	1008.00	0.0003	4.71	0.026	0.005	0.218	0.034	0.000
51	4.72	1008.00	0.000330	0.03	1008.00	0.0003	4.73	0.054	0.011	0.228	0.071	0.000
52	4.75	1008.00	0.000350	0.05	1008.00	0.0004	4.78	0.088	0.018	0.245	0.111	0.000
53	4.80	1008.00	0.000380	0.05	1008.00	0.0004	4.83	0.096	0.020	0.265	0.116	0.000
54	4.85	1008.00	0.000410	0.05	1008.00	0.0004	4.88	0.104	0.021	0.286	0.121	0.000
55	4.90	1008.00	0.000440	0.05	1008.00	0.0005	4.93	0.113	0.023	0.306	0.125	0.000
56	4.95	1008.00	0.000470	0.05	1008.00	0.0005	4.98	0.122	0.024	0.326	0.129	0.000
57	5.00	1008.00	0.000500	0.25	1008.00	0.0005	5.13	0.646	0.126	0.336	0.595	0.000
58	5.25	1008.00	0.000500	0.05	1008.00	0.0005	5.28	0.130	0.025	0.329	0.104	0.000
59	5.30	1008.00	0.000480	0.05	1008.00	0.0005	5.33	0.126	0.024	0.316	0.096	0.000
60	5.35	1008.00	0.000460	0.05	1008.00	0.0005	5.38	0.122	0.023	0.302	0.088	0.000
61	5.40	1008.00	0.000440	0.05	1008.00	0.0004	5.43	0.118	0.022	0.289	0.081	0.000
62	5.45	1008.00	0.000420	0.05	1008.00	0.0004	5.48	0.113	0.021	0.275	0.074	0.000
63	5.50	1008.00	0.000400	0.22	1008.00	0.0004	5.61	0.490	0.087	0.269	0.276	0.000
64	5.72	1008.00	0.000400	0.02	768.00	0.0004	5.73	0.029	0.005	0.205	0.014	0.000
65	5.73	528.00	0.000400	0.25	528.00	0.0004	5.86	0.309	0.053	0.141	0.131	0.000
66	5.98	528.00	0.000400	0.02	480.00	0.0004	5.99	0.019	0.003	0.128	0.007	0.000
67	6.00	432.00	0.000400	0.22	432.00	0.0004	6.11	0.229	0.037	0.115	0.070	0.000
68	6.22	432.00	0.000400	0.02	400.00	0.0004	6.23	0.017	0.003	0.107	0.004	0.000
69	6.23	368.00	0.000400	0.02	368.00	0.0004	6.24	0.015	0.002	0.098	0.004	0.000
70	6.25	368.00	0.000400	0.12	368.00	0.0004	6.31	0.106	0.017	0.096	0.024	0.000
71	6.37	368.00	0.000384	0.13	349.85	0.0004	6.43	0.113	0.018	0.088	0.021	0.000
72	6.50	331.69	0.000367	0.08	320.35	0.0004	6.54	0.063	0.010	0.077	0.010	0.000
73	6.58	309.00	0.000356	0.17	291.75	0.0003	6.67	0.112	0.017	0.067	0.014	0.000
74	6.75	274.50	0.000333	0.17	257.25	0.0003	6.83	0.094	0.014	0.055	0.008	0.000
75	6.92	240.00	0.000311	0.08	232.50	0.0003	6.96	0.041	0.006	0.047	0.003	0.000

No	Time	Q	$[Br^-]_e$	Δt	*Q bar*	*$[Br^-]_e$ bar*	*t bar*	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD	σ^2_i	Ce
	(hrs)	(L/hrs)	(mol/l)	(hrs)	(L/hrs)	(mol/l)	(hrs)			(1/hrs)		Co
76	7.00	225.00	0.000300	0.25	202.50	0.0003	7.13	0.108	0.015	0.040	0.004	0.000
77	7.25	180.00	0.000300	0.25	157.50	0.0003	7.38	0.087	0.012	0.031	0.001	0.000
78	7.50	135.00	0.000300	0.08	127.50	0.0003	7.54	0.024	0.003	0.025	0.000	0.000
79	7.58	120.00	0.000292	0.17	112.88	0.0003	7.67	0.041	0.005	0.021	0.000	0.000
80	7.75	105.76	0.000275	0.17	98.64	0.0003	7.83	0.034	0.004	0.018	0.000	0.000
81	7.92	91.53	0.000258	0.08	91.53	0.0003	7.96	0.015	0.002	0.016	0.000	0.000
82	8.00	91.53	0.000250	0.25	91.53	0.0002	8.13	0.044	0.005	0.014	0.000	0.000
83	8.25	91.53	0.000225	0.25	91.53	0.0002	8.38	0.041	0.005	0.013	0.001	0.000
84	8.50	91.53	0.000200	1.00	91.53	0.0002	9.00	0.165	0.018	0.012	0.018	0.000
85	9.50	91.53	0.000200	0.42	91.53	0.0002	9.71	0.074	0.008	0.012	0.019	0.000
86	9.92	91.53	0.000200	0.58	91.53	0.0002	10.21	0.109	0.011	0.012	0.042	0.000
87	10.50	91.53	0.000200	1.00	91.53	0.0002	11.00	0.201	0.018	0.012	0.126	0.000
88	11.50	91.53	0.000200	0.50	91.53	0.0002	11.75	0.117	0.010	0.013	0.104	0.000
89	12.00	91.53	0.000233	0.50	91.53	0.0003	12.25	0.140	0.011	0.015	0.152	0.000
90	12.50	91.53	0.000267	0.50	91.53	0.0003	12.75	0.165	0.013	0.017	0.213	0.000
91	13.00	91.53	0.000300	1.00	91.53	0.0003	13.50	0.371	0.027	0.018	0.598	0.000
92	14.00	91.53	0.000300	0.13	91.53	0.0003	14.06	0.046	0.003	0.018	0.086	0.000
93	14.13	91.53	0.000275	0.13	91.53	0.0003	14.19	0.043	0.003	0.016	0.082	0.000
94	14.25	91.53	0.000250	0.13	91.53	0.0002	14.31	0.039	0.003	0.014	0.077	0.000
95	14.38	91.53	0.000225	0.13	91.53	0.0002	14.44	0.035	0.002	0.013	0.072	0.000
96	14.50	91.53	0.000200	0.50	91.53	0.0002	14.75	0.135	0.009	0.012	0.296	0.000
97	15.00	91.53	0.000200	0.50	91.53	0.0002	15.25	0.140	0.009	0.012	0.340	0.000
98	15.50	91.53	0.000200	0.50	91.53	0.0002	15.75	0.144	0.009	0.012	0.387	0.000
99	16.00	91.53	0.000200	0.92	91.53	0.0002	16.46	0.276	0.017	0.012	0.841	0.000
100	16.92	91.53	0.000200	0.08	98.58	0.0002	16.96	0.028	0.002	0.013	0.092	0.000
101	17.00	105.64	0.000200	0.13	116.23	0.0002	17.06	0.053	0.003	0.016	0.177	0.000
102	17.13	126.82	0.000225	0.07	133.17	0.0002	17.16	0.040	0.002	0.021	0.136	0.000
103	17.20	139.53	0.000240	0.05	163.53	0.0002	17.23	0.035	0.002	0.027	0.119	0.000
104	17.25	187.53	0.000250	0.03	203.53	0.0003	17.27	0.030	0.002	0.034	0.103	0.000
105	17.28	219.53	0.000257	0.08	219.53	0.0003	17.33	0.084	0.005	0.039	0.294	0.000
106	17.37	219.53	0.000273	0.01	379.53	0.0003	17.37	0.015	0.001	0.069	0.053	0.000
107	17.38	539.53	0.000275	0.01	699.53	0.0003	17.38	0.028	0.002	0.129	0.099	0.000
108	17.38	859.53	0.000277	0.08	859.53	0.0003	17.43	0.356	0.020	0.163	1.264	0.000
109	17.47	859.53	0.000293	0.03	859.53	0.0003	17.48	0.149	0.008	0.170	0.533	0.000
110	17.50	859.53	0.000300	0.13	859.53	0.0003	17.56	0.542	0.031	0.165	1.968	0.000
111	17.63	859.53	0.000275	0.13	859.53	0.0003	17.69	0.499	0.028	0.150	1.843	0.000
112	17.75	859.53	0.000250	0.13	859.53	0.0002	17.81	0.455	0.026	0.136	1.710	0.000
113	17.88	859.53	0.000225	0.13	859.53	0.0002	17.94	0.410	0.023	0.122	1.568	0.000
114	18.00	859.53	0.000200	0.25	859.53	0.0002	18.13	0.682	0.038	0.100	2.680	0.000

No	Time	Q	$[Br^-]_e$	Δt	*Q bar*	*$[Br^-]_e$ bar*	*t bar*	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD	σ^2_i	Ce/Co
	(hrs)	(L/hrs)	(mol/l)	(hrs)	(L/hrs)	(mol/l)	(hrs)			(1/hrs)		
115	18.25	859.53	0.000150	0.22	859.53	0.0001	18.36	0.439	0.024	0.074	1.781	0.000
116	18.47	859.53	0.000107	0.02	619.53	0.0001	18.48	0.020	0.001	0.043	0.083	0.000
117	18.48	379.53	0.000103	0.02	379.53	0.0001	18.49	0.012	0.001	0.026	0.049	0.000
118	18.50	379.53	0.000100	0.23	379.53	0.0001	18.62	0.165	0.009	0.025	0.692	0.000
119	18.73	379.53	0.000100	0.02	331.53	0.0001	18.74	0.010	0.001	0.022	0.044	0.000
120	18.75	283.53	0.000100	0.22	307.66	0.0001	18.86	0.126	0.007	0.021	0.545	0.000
121	18.97	331.80	0.000100	0.02	395.70	0.0001	18.98	0.013	0.001	0.026	0.055	0.000
122	18.98	459.60	0.000100	0.02	459.60	0.0001	18.99	0.015	0.001	0.031	0.064	0.000
123	19.00	459.60	0.000100				Σ	11.68	1.50	10.15	26.99	0.0108

RTD For Horizontal Flow Bed

k_r = 15 1/day

k_r = 0.625 1/hour

σ^2_θ = 27.67

Detention Time= 6.69 hrs

R.F= 0.9151

Amount of Chemical Used: 700 g

Amount of Chemical Recovered: 489.05 g

69.86 %

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]_e$bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	Ce/Co	t/T_{det}
1	0.00	0.00000	269.3	0.03	0.00000	0.02	255.69	0.0000	0.0000	0.000	0.00	0.0000	0.00
2	0.03	0.00001	242.1	0.07	0.00001	0.07	250.68	0.0000	0.0002	0.001	0.00	0.0000	0.01
3	0.10	0.00002	259.3	0.05	0.00003	0.13	265.78	0.0000	0.0003	0.001	0.00	0.0001	0.02
4	0.15	0.00003	272.3	0.05	0.00004	0.18	1047.99	0.0003	0.0018	0.008	0.02	0.0003	0.03
5	0.20	0.00004	1823.7	0.03	0.00004	0.22	2340.90	0.0007	0.0034	0.021	0.03	0.0005	0.03
6	0.23	0.00005	2858.1	0.05	0.00005	0.26	3165.56	0.0021	0.0082	0.035	0.07	0.0011	0.04
7	0.28	0.00006	3473.1	0.02	0.00006	0.29	3360.56	0.0010	0.0033	0.041	0.03	0.0004	0.04
8	0.30	0.00006	3248.1	0.03	0.00006	0.32	3023.06	0.0020	0.0064	0.040	0.05	0.0008	0.05
9	0.33	0.00007	2798.1	0.05	0.00007	0.36	2348.06	0.0030	0.0084	0.036	0.07	0.0010	0.05
10	0.38	0.00008	1898.1	0.02	0.00008	0.39	1853.06	0.0009	0.0024	0.031	0.02	0.0003	0.06
11	0.40	0.00008	1808.1	0.07	0.00009	0.43	1628.06	0.0041	0.0094	0.030	0.08	0.0010	0.06
12	0.47	0.00009	1448.1	0.05	0.00010	0.49	1373.06	0.0033	0.0068	0.029	0.05	0.0007	0.07
13	0.52	0.00010	1298.1	0.05	0.00011	0.54	1238.06	0.0036	0.0067	0.028	0.05	0.0006	0.08
14	0.57	0.00011	1178.1	0.03	0.00012	0.58	1118.06	0.0025	0.0043	0.028	0.03	0.0004	0.09
15	0.60	0.00012	1058.1	0.02	0.00012	0.61	1028.06	0.0013	0.0021	0.026	0.02	0.0002	0.09
16	0.62	0.00011	998.1	0.03	0.00013	0.63	933.77	0.0025	0.0039	0.025	0.03	0.0003	0.09
17	0.65	0.00012	869.5	0.08	0.00014	0.69	801.42	0.0064	0.0092	0.023	0.07	0.0007	0.10
18	0.73	0.00014	733.4	0.05	0.00015	0.76	699.91	0.0040	0.0053	0.022	0.04	0.0003	0.11
19	0.78	0.00016	666.5	0.02	0.00016	0.79	659.37	0.0014	0.0017	0.022	0.01	0.0001	0.12
20	0.80	0.00016	652.3	0.02	0.00016	0.81	645.16	0.0014	0.0017	0.022	0.01	0.0001	0.12
21	0.82	0.00016	638.1	0.08	0.00017	0.86	593.06	0.0073	0.0085	0.022	0.06	0.0005	0.13
22	0.90	0.00018	548.1	0.08	0.00019	0.94	515.91	0.0076	0.0081	0.021	0.06	0.0004	0.14
23	0.98	0.00020	483.8	0.02	0.00020	0.99	477.93	0.0016	0.0016	0.020	0.01	0.0001	0.15
24	1.00	0.00020	472.1	0.06	0.00021	1.03	450.17	0.0062	0.0060	0.020	0.04	0.0002	0.15
25	1.06	0.00023	428.3	0.00	0.00023	1.06	426.79	0.0004	0.0004	0.020	0.00	0.0000	0.16
26	1.07	0.00023	425.3	0.06	0.00024	1.10	415.78	0.0063	0.0058	0.021	0.04	0.0002	0.16
27	1.13	0.00025	406.2	0.02	0.00026	1.14	402.15	0.0029	0.0026	0.022	0.02	0.0001	0.17
28	1.15	0.00026	398.1	0.04	0.00027	1.17	385.78	0.0045	0.0039	0.022	0.02	0.0001	0.17
29	1.19	0.00028	373.5	0.05	0.00028	1.21	358.51	0.0057	0.0047	0.022	0.03	0.0001	0.18
30	1.23	0.00029	343.5	0.02	0.00030	1.24	341.47	0.0021	0.0017	0.021	0.01	0.0000	0.19
31	1.25	0.00030	339.4	0.07	0.00030	1.28	331.24	0.0085	0.0066	0.021	0.04	0.0002	0.19
32	1.32	0.00030	323.1	0.17	0.00030	1.40	300.56	0.0210	0.0150	0.019	0.09	0.0003	0.21

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]_e bar$* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t[Br^-]_e Qt$*	*$\Delta t[Br^-]_e Q$*	RTD (1/hrs)	σ^2_i	Ce/Co	t/T_{det}
33	1.48	0.00030	278.1	0.02	0.00030	1.49	275.94	0.0021	0.0014	0.017	0.01	0.0000	0.22
34	1.50	0.00030	273.8	0.05	0.00033	1.53	267.47	0.0067	0.0044	0.019	0.02	0.0001	0.23
35	1.55	0.00036	261.1	0.02	0.00037	1.56	259.00	0.0025	0.0016	0.020	0.01	0.0000	0.23
36	1.57	0.00038	256.9	0.03	0.00040	1.58	254.74	0.0054	0.0034	0.021	0.02	0.0001	0.24
37	1.60	0.00042	252.6	0.07	0.00046	1.63	248.34	0.0124	0.0076	0.024	0.04	0.0001	0.24
38	1.67	0.00050	244.1	0.13	0.00046	1.73	235.52	0.0251	0.0145	0.023	0.07	0.0002	0.26
39	1.80	0.00042	227.0	0.10	0.00039	1.85	220.58	0.0160	0.0086	0.018	0.04	0.0001	0.28
40	1.90	0.00036	214.2	0.10	0.00033	1.95	207.76	0.0134	0.0069	0.015	0.03	0.0001	0.29
41	2.00	0.00030	201.4	0.17	0.00030	2.08	190.68	0.0199	0.0095	0.012	0.04	0.0001	0.31
42	2.17	0.00030	180.0	0.08	0.00030	2.21	190.78	0.0105	0.0048	0.012	0.02	0.0000	0.33
43	2.25	0.00030	201.6	0.02	0.00032	2.26	204.80	0.0037	0.0016	0.014	0.01	0.0000	0.34
44	2.28	0.00034	208.0	0.01	0.00035	2.28	209.12	0.0014	0.0006	0.015	0.00	0.0000	0.34
45	2.28	0.00035	210.2	0.02	0.00037	2.29	468.77	0.0066	0.0029	0.036	0.01	0.0000	0.34
46	2.30	0.00038	727.4	0.07	0.00043	2.33	1761.68	0.1188	0.0509	0.161	0.20	0.0003	0.35
47	2.37	0.00049	2796.0	0.01	0.00049	2.37	2847.25	0.0278	0.0117	0.297	0.05	0.0001	0.35
48	2.38	0.00050	2898.5	0.04	0.00053	2.39	3129.13	0.1489	0.0622	0.350	0.24	0.0003	0.36
49	2.41	0.00056	3359.8	0.00	0.00056	2.41	3385.38	0.0192	0.0079	0.403	0.03	0.0000	0.36
50	2.42	0.00057	3411.0	0.03	0.00059	2.43	3186.00	0.1533	0.0630	0.400	0.24	0.0003	0.36
51	2.45	0.00062	2961.0	0.02	0.00063	2.46	2848.50	0.0739	0.0301	0.381	0.11	0.0001	0.37
52	2.47	0.00065	2736.0	0.03	0.00067	2.48	2436.00	0.1358	0.0547	0.347	0.20	0.0002	0.37
53	2.50	0.00070	2136.0	0.02	0.00070	2.51	1986.00	0.0584	0.0233	0.295	0.09	0.0001	0.38
54	2.52	0.00071	1836.0	0.05	0.00072	2.54	1712.25	0.1427	0.0562	0.259	0.20	0.0002	0.38
55	2.56	0.00073	1588.5	0.04	0.00073	2.58	1487.25	0.1055	0.0409	0.230	0.14	0.0001	0.39
56	2.60	0.00074	1386.0	0.02	0.00075	2.61	1348.50	0.0656	0.0251	0.212	0.09	0.0001	0.39
57	2.63	0.00075	1311.0	0.02	0.00076	2.64	1273.50	0.0634	0.0240	0.203	0.08	0.0001	0.39
58	2.65	0.00076	1236.0	0.05	0.00077	2.68	1176.00	0.1211	0.0453	0.191	0.15	0.0001	0.40
59	2.70	0.00078	1116.0	0.05	0.00079	2.73	1026.00	0.1104	0.0405	0.171	0.13	0.0001	0.41
60	2.75	0.00080	936.0	0.03	0.00081	2.77	871.71	0.0652	0.0236	0.149	0.08	0.0001	0.41
61	2.78	0.00082	807.4	0.04	0.00084	2.80	773.39	0.0756	0.0269	0.137	0.09	0.0001	0.42
62	2.83	0.00085	739.4	0.04	0.00086	2.85	705.33	0.0716	0.0252	0.128	0.08	0.0001	0.43
63	2.87	0.00086	671.3	0.05	0.00087	2.89	637.86	0.0801	0.0277	0.117	0.08	0.0001	0.43
64	2.92	0.00088	604.4	0.03	0.00088	2.93	590.21	0.0508	0.0173	0.110	0.05	0.0000	0.44
65	2.95	0.00089	576.0	0.05	0.00089	2.98	549.00	0.0729	0.0245	0.104	0.07	0.0000	0.45
66	3.00	0.00090	522.0	0.03	0.00090	3.02	504.00	0.0456	0.0151	0.096	0.04	0.0000	0.45
67	3.03	0.00090	486.0	0.08	0.00090	3.08	453.86	0.1047	0.0340	0.086	0.09	0.0001	0.46
68	3.12	0.00090	421.7	0.08	0.00090	3.16	392.49	0.0930	0.0294	0.075	0.08	0.0000	0.47
69	3.20	0.00090	363.3	0.05	0.00090	3.23	355.09	0.0515	0.0160	0.068	0.04	0.0000	0.48
70	3.25	0.00090	346.9	0.03	0.00091	3.27	341.45	0.0340	0.0104	0.066	0.03	0.0000	0.49
71	3.28	0.00093	336.0	0.04	0.00094	3.30	322.36	0.0419	0.0127	0.064	0.03	0.0000	0.49
72	3.33	0.00096	308.7	0.04	0.00098	3.35	295.09	0.0402	0.0120	0.061	0.03	0.0000	0.50
73	3.37	0.00099	281.5	0.03	0.00101	3.38	277.36	0.0315	0.0093	0.059	0.02	0.0000	0.51
74	3.40	0.00102	273.3	0.05	0.00104	3.43	267.14	0.0476	0.0139	0.059	0.03	0.0000	0.51
75	3.45	0.00106	261.0	0.05	0.00108	3.48	254.25	0.0477	0.0137	0.058	0.03	0.0000	0.52

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δt (hrs)	*$[Br^-]_e$bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	$\frac{Ce}{Co}$	t/T_{det}
76	3.50	0.00110	247.5	0.06	0.00113	3.53	239.06	0.0594	0.0168	0.057	0.04	0.0000	0.53
77	3.56	0.00115	230.6	0.05	0.00117	3.59	223.31	0.0509	0.0142	0.055	0.03	0.0000	0.54
78	3.62	0.00119	216.0	0.01	0.00120	3.62	214.94	0.0078	0.0021	0.054	0.00	0.0000	0.54
79	3.63	0.00120	213.9	0.06	0.00123	3.66	205.94	0.0576	0.0158	0.053	0.03	0.0000	0.55
80	3.69	0.00125	198.0	0.01	0.00126	3.69	196.41	0.0114	0.0031	0.052	0.01	0.0000	0.55
81	3.70	0.00126	194.8	0.05	0.00128	3.73	193.59	0.0462	0.0124	0.052	0.02	0.0000	0.56
82	3.75	0.00130	192.4	0.13	0.00133	3.81	189.26	0.1195	0.0313	0.053	0.05	0.0000	0.57
83	3.88	0.00135	186.2	0.13	0.00138	3.94	183.09	0.1239	0.0315	0.053	0.05	0.0000	0.59
84	4.00	0.00140	180.0	0.12	0.00135	4.06	195.10	0.1250	0.0308	0.056	0.04	0.0000	0.61
85	4.12	0.00131	210.2	0.01	0.00130	4.12	211.27	0.0095	0.0023	0.058	0.00	0.0000	0.62
86	4.13	0.00130	212.4	0.08	0.00127	4.16	1504.18	0.5964	0.1433	0.404	0.19	0.0000	0.62
87	4.20	0.00124	2796.0	0.05	0.00122	4.23	3103.50	0.7998	0.1893	0.800	0.24	0.0000	0.63
88	4.25	0.00120	3411.0	0.05	0.00120	4.28	3073.50	0.7884	0.1844	0.779	0.23	0.0000	0.64
89	4.30	0.00120	2736.0	0.05	0.00120	4.33	2286.00	0.5932	0.1372	0.580	0.16	0.0000	0.65
90	4.35	0.00120	1836.0	0.08	0.00120	4.39	1611.00	0.7075	0.1611	0.409	0.18	0.0000	0.66
91	4.43	0.00120	1386.0	0.05	0.00120	4.46	1311.00	0.3507	0.0787	0.332	0.08	0.0000	0.67
92	4.48	0.00120	1236.0	0.02	0.00120	4.49	1216.00	0.1092	0.0243	0.308	0.02	0.0000	0.67
93	4.50	0.00120	1196.0	0.03	0.00119	4.52	1156.00	0.2077	0.0460	0.292	0.05	0.0000	0.68
94	4.53	0.00119	1116.0	0.05	0.00118	4.56	1026.00	0.2752	0.0604	0.255	0.06	0.0000	0.68
95	4.58	0.00117	936.0	0.03	0.00116	4.60	871.71	0.1550	0.0337	0.214	0.03	0.0000	0.69
96	4.62	0.00115	807.4	0.01	0.00115	4.62	800.62	0.0355	0.0077	0.195	0.01	0.0000	0.69
97	4.63	0.00115	793.8	0.08	0.00114	4.66	732.55	0.2907	0.0624	0.176	0.05	0.0000	0.70
98	4.70	0.00112	671.3	0.05	0.00111	4.73	637.86	0.1673	0.0354	0.150	0.03	0.0000	0.71
99	4.75	0.00110	604.4	0.03	0.00109	4.77	590.21	0.1025	0.0215	0.136	0.02	0.0000	0.71
100	4.78	0.00109	576.0	0.08	0.00107	4.83	531.00	0.2285	0.0473	0.120	0.03	0.0000	0.72
101	4.87	0.00105	486.0	0.01	0.00105	4.87	482.79	0.0206	0.0042	0.107	0.00	0.0000	0.73
102	4.88	0.00105	479.6	0.08	0.00104	4.91	450.64	0.1718	0.0350	0.099	0.02	0.0000	0.74
103	4.95	0.00102	421.7	0.05	0.00101	4.98	404.18	0.1015	0.0204	0.086	0.01	0.0000	0.74
104	5.00	0.00100	386.6	0.03	0.00099	5.02	374.96	0.0623	0.0124	0.079	0.01	0.0000	0.75
105	5.03	0.00099	363.3	0.08	0.00097	5.08	349.64	0.1434	0.0283	0.072	0.02	0.0000	0.76
106	5.12	0.00095	336.0	0.01	0.00095	5.12	333.27	0.0135	0.0026	0.067	0.00	0.0000	0.77
107	5.13	0.00095	330.5	0.08	0.00094	5.16	306.00	0.1108	0.0215	0.060	0.01	0.0000	0.77
108	5.20	0.00092	281.5	0.05	0.00091	5.23	275.32	0.0655	0.0125	0.053	0.01	0.0000	0.78
109	5.25	0.00090	269.2	0.03	0.00091	5.27	265.09	0.0425	0.0081	0.051	0.00	0.0000	0.79
110	5.28	0.00093	261.0	0.03	0.00094	5.30	252.86	0.0367	0.0069	0.050	0.00	0.0000	0.79
111	5.31	0.00095	244.7	0.06	0.00098	5.34	227.29	0.0740	0.0139	0.047	0.01	0.0000	0.80
112	5.38	0.00100	209.9	0.06	0.00103	5.41	192.41	0.0666	0.0123	0.042	0.00	0.0000	0.81
113	5.44	0.00105	175.0	0.01	0.00106	5.44	195.49	0.0140	0.0026	0.044	0.00	0.0000	0.82
114	5.45	0.00106	216.0	0.05	0.00108	5.48	209.65	0.0620	0.0113	0.048	0.00	0.0000	0.82
115	5.50	0.00110	203.3	0.03	0.00111	5.52	199.06	0.0408	0.0074	0.047	0.00	0.0000	0.83
116	5.53	0.00113	194.8	0.03	0.00114	5.55	193.99	0.0357	0.0064	0.047	0.00	0.0000	0.83
117	5.56	0.00115	193.1	0.06	0.00118	5.59	191.35	0.0786	0.0141	0.048	0.00	0.0000	0.84
118	5.63	0.00120	189.6	0.06	0.00123	5.66	187.76	0.0813	0.0144	0.049	0.00	0.0000	0.85

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δt (hrs)	$[Br^-]_e bar$ (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	$\Delta t[Br^-]_e Qt$	$\Delta t[Br^-]_e Q$	RTD (1/hrs)	σ^2_i	$\frac{Ce}{Co}$	t/T_{det}
119	5.69	0.00125	186.0	0.06	0.00128	5.72	184.17	0.0839	0.0147	0.050	0.00	0.0000	0.86
120	5.75	0.00130	182.4	0.25	0.00130	5.88	175.18	0.3345	0.0569	0.048	0.01	0.0000	0.88
121	6.00	0.00130	168.0	0.01	0.00128	6.01	169.29	0.0130	0.0022	0.046	0.00	0.0000	0.90
122	6.01	0.00125	170.6	0.01	0.00123	6.02	171.88	0.0127	0.0021	0.044	0.00	0.0000	0.90
123	6.02	0.00120	173.2	0.01	0.00118	6.03	174.47	0.0124	0.0021	0.043	0.00	0.0000	0.90
124	6.03	0.00115	175.8	0.01	0.00113	6.04	177.06	0.0120	0.0020	0.042	0.00	0.0000	0.90
125	6.04	0.00110	178.4	0.01	0.00108	6.05	179.65	0.0117	0.0019	0.041	0.00	0.0000	0.91
126	6.05	0.00105	180.9	0.01	0.00103	6.06	182.23	0.0113	0.0019	0.039	0.00	0.0000	0.91
127	6.06	0.00100	183.5	0.01	0.00098	6.07	184.82	0.0109	0.0018	0.038	0.00	0.0000	0.91
128	6.07	0.00095	186.1	0.01	0.00093	6.08	187.84	0.0141	0.0023	0.037	0.00	0.0000	0.91
129	6.08	0.00090	189.6	0.03	0.00088	6.10	193.88	0.0347	0.0057	0.036	0.00	0.0000	0.91
130	6.12	0.00086	198.2	0.05	0.00083	6.14	973.94	0.2482	0.0404	0.171	0.00	0.0000	0.92
131	6.17	0.00080	1749.7	0.03	0.00080	6.18	2266.84	0.3738	0.0604	0.383	0.00	0.0000	0.93
132	6.20	0.00080	2784.0	0.05	0.00080	6.23	3091.50	0.7698	0.1237	0.523	0.01	0.0000	0.93
133	6.25	0.00080	3399.0	0.05	0.00080	6.28	3061.50	0.7684	0.1225	0.518	0.00	0.0000	0.94
134	6.30	0.00080	2724.0	0.03	0.00080	6.32	2424.00	0.4083	0.0646	0.410	0.00	0.0000	0.95
135	6.33	0.00080	2124.0	0.02	0.00080	6.34	1974.00	0.1669	0.0263	0.334	0.00	0.0000	0.95
136	6.35	0.00080	1824.0	0.07	0.00080	6.38	1644.00	0.5597	0.0877	0.278	0.00	0.0000	0.96
137	6.42	0.00080	1464.0	0.02	0.00080	6.43	1419.00	0.1216	0.0189	0.240	0.00	0.0000	0.96
138	6.43	0.00080	1374.0	0.05	0.00080	6.46	1299.00	0.3356	0.0520	0.220	0.00	0.0000	0.97
139	6.48	0.00080	1224.0	0.02	0.00080	6.49	1204.00	0.1042	0.0161	0.204	0.00	0.0000	0.97
140	6.50	0.00080	1184.0	0.03	0.00080	6.52	1144.00	0.1988	0.0305	0.193	0.00	0.0000	0.98
141	6.53	0.00080	1104.0	0.05	0.00080	6.56	1014.00	0.2660	0.0406	0.171	0.00	0.0000	0.98
142	6.58	0.00080	924.0	0.03	0.00080	6.60	859.71	0.1513	0.0229	0.145	0.00	0.0000	0.99
143	6.62	0.00080	795.4	0.08	0.00080	6.66	727.36	0.3229	0.0485	0.123	0.00	0.0000	1.00
144	6.70	0.00080	659.3	0.05	0.00080	6.73	625.86	0.1684	0.0250	0.106	0.00	0.0000	1.01
145	6.75	0.00080	592.4	0.03	0.00080	6.77	578.21	0.1043	0.0154	0.098	0.00	0.0000	1.01
146	6.78	0.00080	564.0	0.08	0.00080	6.83	519.00	0.2361	0.0346	0.088	0.00	0.0000	1.02
147	6.87	0.00080	474.0	0.08	0.00080	6.91	441.86	0.2035	0.0295	0.075	0.00	0.0000	1.03
148	6.95	0.00080	409.7	0.05	0.00080	6.98	392.18	0.1094	0.0157	0.066	0.00	0.0000	1.04
149	7.00	0.00080	374.6	0.03	0.00080	7.02	362.96	0.0679	0.0097	0.061	0.00	0.0000	1.05
150	7.03	0.00080	351.3	0.08	0.00080	7.08	337.64	0.1593	0.0225	0.057	0.00	0.0000	1.06
151	7.12	0.00080	324.0	0.08	0.00080	7.16	296.73	0.1416	0.0198	0.050	0.00	0.0000	1.07
152	7.20	0.00080	269.5	0.05	0.00080	7.23	263.32	0.0761	0.0105	0.045	0.00	0.0000	1.08
153	7.25	0.00080	257.2	0.03	0.00080	7.27	253.09	0.0488	0.0067	0.043	0.00	0.0000	1.09
154	7.28	0.00079	249.0	0.17	0.00077	7.37	226.50	0.2138	0.0290	0.037	0.00	0.0000	1.10
155	7.45	0.00075	204.0	0.05	0.00074	7.48	197.65	0.0547	0.0073	0.031	0.00	0.0000	1.12
156	7.50	0.00073	191.3	0.03	0.00073	7.52	187.06	0.0342	0.0045	0.029	0.00	0.0000	1.13
157	7.53	0.00072	182.8	0.22	0.00070	7.64	180.37	0.2077	0.0272	0.027	0.01	0.0000	1.14
158	7.75	0.00067	177.9	0.25	0.00063	7.88	175.10	0.2183	0.0277	0.023	0.01	0.0000	1.18
159	8.00	0.00060	172.3	0.25	0.00060	8.13	169.44	0.2065	0.0254	0.021	0.01	0.0000	1.22

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]_e$bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t[Br^-]_eQt$*	*$\Delta t[Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	Ce/Co	t/T_{det}
160	8.25	0.00060	166.6	0.13	0.00062	8.31	165.20	0.1062	0.0128	0.022	0.01	0.0000	1.24
161	8.38	0.00064	163.8	0.13	0.00066	8.44	162.38	0.1124	0.0133	0.023	0.01	0.0000	1.26
162	8.50	0.00068	161.0	0.38	0.00071	8.69	156.72	0.3638	0.0419	0.024	0.04	0.0000	1.30
163	8.88	0.00075	152.5	0.19	0.00079	8.97	150.36	0.1991	0.0222	0.025	0.02	0.0000	1.34
164	9.06	0.00083	148.2	0.19	0.00086	9.16	146.12	0.2164	0.0236	0.027	0.03	0.0000	1.37
165	9.25	0.00090	144.0	0.25	0.00086	9.38	136.28	0.2755	0.0294	0.025	0.05	0.0000	1.40
166	9.50	0.00083	128.6	0.25	0.00079	9.63	120.83	0.2290	0.0238	0.020	0.04	0.0000	1.44
167	9.75	0.00075	113.1	0.25	0.00071	9.88	105.38	0.1854	0.0188	0.016	0.04	0.0000	1.48
168	10.00	0.00068	97.7	0.25	0.00064	10.13	89.93	0.1451	0.0143	0.012	0.04	0.0000	1.52
169	10.25	0.00060	82.2	1.00	0.00060	10.75	51.30	0.3309	0.0308	0.007	0.11	0.0000	1.61
170	11.25	0.00060	20.4	0.25	0.00056	11.38	20.40	0.0326	0.0029	0.002	0.01	0.0000	1.70
171	11.50	0.00053	20.4	0.25	0.00049	11.63	20.40	0.0289	0.0025	0.002	0.01	0.0000	1.74
172	11.75	0.00045	20.4	0.25	0.00041	11.88	20.40	0.0250	0.0021	0.002	0.01	0.0000	1.78
173	12.00	0.00038	20.4	0.25	0.00034	12.13	20.40	0.0209	0.0017	0.001	0.01	0.0000	1.82
174	12.25	0.00030	20.4	1.00	0.00030	12.75	20.40	0.0780	0.0061	0.001	0.05	0.0000	1.91
175	13.25	0.00030	20.4	0.50	0.00028	13.50	20.40	0.0379	0.0028	0.001	0.03	0.0000	2.02
176	13.75	0.00025	20.4	0.25	0.00024	13.88	20.40	0.0168	0.0012	0.001	0.01	0.0000	2.08
177	14.00	0.00023	20.4	0.25	0.00021	14.13	20.40	0.0153	0.0011	0.001	0.01	0.0000	2.11
178	14.25	0.00020	20.4	0.50	0.00020	14.50	20.40	0.0296	0.0020	0.001	0.03	0.0000	2.17
179	14.75	0.00020	20.4	0.12	0.00020	14.81	35.50	0.0123	0.0008	0.002	0.01	0.0000	2.22
180	14.87	0.00020	50.6	0.08	0.00020	14.91	1343.50	0.3338	0.0224	0.057	0.32	0.0000	2.23
181	14.95	0.00020	2636.4	0.05	0.00020	14.98	2943.90	0.4408	0.0294	0.124	0.43	0.0000	2.24
182	15.00	0.00020	3251.4	0.05	0.00020	15.03	2913.90	0.4378	0.0291	0.123	0.43	0.0000	2.25
183	15.05	0.00020	2576.4	0.05	0.00020	15.08	2126.40	0.3206	0.0213	0.090	0.32	0.0000	2.26
184	15.10	0.00020	1676.4	0.08	0.00020	15.14	1451.40	0.3663	0.0242	0.061	0.37	0.0000	2.27
185	15.18	0.00020	1226.4	0.05	0.00020	15.21	1151.40	0.1751	0.0115	0.049	0.18	0.0000	2.28
186	15.23	0.00020	1076.4	0.02	0.00020	15.24	1056.40	0.0537	0.0035	0.045	0.05	0.0000	2.28
187	15.25	0.00020	1036.4	0.03	0.00020	15.27	996.40	0.1014	0.0066	0.042	0.10	0.0000	2.29
188	15.28	0.00020	956.4	0.05	0.00020	15.31	866.40	0.1326	0.0087	0.037	0.14	0.0000	2.29
189	15.33	0.00020	776.4	0.03	0.00020	15.35	712.11	0.0729	0.0047	0.030	0.08	0.0000	2.30
190	15.37	0.00020	647.8	0.08	0.00020	15.41	579.76	0.1489	0.0097	0.025	0.16	0.0000	2.31
191	15.45	0.00020	511.7	0.05	0.00020	15.48	478.26	0.0740	0.0048	0.020	0.08	0.0000	2.32
192	15.50	0.00020	444.8	0.03	0.00020	15.52	430.61	0.0445	0.0029	0.018	0.05	0.0000	2.32
193	15.53	0.00020	416.4	0.08	0.00020	15.58	371.40	0.0964	0.0062	0.016	0.10	0.0000	2.33
194	15.62	0.00020	326.4	0.08	0.00020	15.66	294.26	0.0768	0.0049	0.012	0.08	0.0000	2.34
195	15.70	0.00020	262.1	0.08	0.00020	15.74	232.89	0.0611	0.0039	0.010	0.07	0.0000	2.36
196	15.78	0.00020	203.7	0.08	0.00020	15.83	190.04	0.0501	0.0032	0.008	0.06	0.0000	2.37
197	15.87	0.00020	176.4	0.08	0.00020	15.91	149.13	0.0395	0.0025	0.006	0.04	0.0000	2.38
198	15.95	0.00020	121.9	0.08	0.00020	15.99	111.63	0.0298	0.0019	0.005	0.03	0.0000	2.39
199	16.03	0.00020	101.4	0.17	0.00020	16.12	78.90	0.0424	0.0026	0.003	0.05	0.0000	2.41
200	16.20	0.00020	56.4	0.05	0.00020	16.23	50.05	0.0081	0.0005	0.002	0.01	0.0000	2.43
201	16.25	0.00020	43.7	0.03	0.00020	16.27	39.46	0.0043	0.0003	0.002	0.01	0.0000	2.44

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δt (hrs)	$[Br^-]_e bar$ (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	$\Delta t[Br^-]_e Qt$	$\Delta t[Br^-]_e Q$	RTD (1/hrs)	σ^2_i	$\frac{Ce}{Co}$	t/T_{det}
202	16.28	0.00020	35.2	0.97	0.00020	16.77	27.81	0.0902	0.0054	0.001	0.12	0.0000	2.51
203	17.25	0.00020	20.4	0.50	0.00023	17.50	20.40	0.0402	0.0023	0.001	0.06	0.0000	2.62
204	17.75	0.00025	20.4	0.50	0.00028	18.00	20.40	0.0505	0.0028	0.001	0.08	0.0000	2.69
205	18.25	0.00030	20.4	1.33	0.00030	18.92	20.40	0.1544	0.0082	0.001	0.26	0.0000	2.83
206	19.58	0.00030	20.4	0.12	0.00030	19.64	35.50	0.0244	0.0012	0.002	0.04	0.0000	2.94
207	19.70	0.00030	50.6	0.05	0.00030	19.73	826.34	0.2445	0.0124	0.052	0.45	0.0000	2.95
208	19.75	0.00030	1602.1	0.03	0.00029	19.77	2119.24	0.4096	0.0207	0.131	0.75	0.0000	2.96
209	19.78	0.00029	2636.4	0.05	0.00028	19.81	2943.90	0.8067	0.0407	0.172	1.48	0.0000	2.97
210	19.83	0.00027	3251.4	0.04	0.00026	19.85	2970.15	0.6347	0.0320	0.162	1.17	0.0000	2.97
211	19.88	0.00025	2688.9	0.01	0.00025	19.88	2632.65	0.1083	0.0054	0.138	0.20	0.0000	2.98
212	19.88	0.00025	2576.4	0.05	0.00024	19.91	2126.40	0.5009	0.0252	0.106	0.93	0.0000	2.98
213	19.93	0.00023	1676.4	0.07	0.00021	19.97	1496.40	0.4249	0.0213	0.067	0.79	0.0000	2.99
214	20.00	0.00020	1316.4	0.02	0.00020	20.01	1271.40	0.0848	0.0042	0.054	0.16	0.0000	3.00
215	20.02	0.00020	1226.4	0.05	0.00020	20.04	1151.40	0.2308	0.0115	0.049	0.43	0.0000	3.00
216	20.07	0.00020	1076.4	0.05	0.00020	20.09	1016.40	0.2042	0.0102	0.043	0.39	0.0000	3.01
217	20.12	0.00020	956.4	0.05	0.00020	20.14	866.40	0.1745	0.0087	0.037	0.33	0.0000	3.02
218	20.17	0.00020	776.4	0.03	0.00020	20.18	712.11	0.0958	0.0047	0.030	0.18	0.0000	3.02
219	20.20	0.00020	647.8	0.05	0.00020	20.23	606.99	0.1228	0.0061	0.026	0.24	0.0000	3.03
220	20.25	0.00020	566.1	0.03	0.00020	20.27	538.92	0.0728	0.0036	0.023	0.14	0.0000	3.03
221	20.28	0.00020	511.7	0.05	0.00020	20.31	478.26	0.0971	0.0048	0.020	0.19	0.0000	3.04
222	20.33	0.00020	444.8	0.03	0.00020	20.35	430.61	0.0584	0.0029	0.018	0.11	0.0000	3.05
223	20.37	0.00020	416.4	0.08	0.00020	20.41	371.40	0.1263	0.0062	0.016	0.25	0.0000	3.06
224	20.45	0.00020	326.4	0.05	0.00020	20.48	307.11	0.0629	0.0031	0.013	0.12	0.0000	3.07
225	20.50	0.00020	287.8	0.03	0.00020	20.52	274.97	0.0376	0.0018	0.012	0.07	0.0000	3.07
226	20.53	0.00020	262.1	0.08	0.00020	20.58	232.89	0.0799	0.0039	0.010	0.16	0.0000	3.08
227	20.62	0.00020	203.7	0.08	0.00020	20.66	190.04	0.0654	0.0032	0.008	0.13	0.0000	3.09
228	20.70	0.00020	176.4	0.08	0.00020	20.74	149.13	0.0516	0.0025	0.006	0.10	0.0000	3.11
229	20.78	0.00020	121.9	0.08	0.00020	20.83	111.63	0.0387	0.0019	0.005	0.08	0.0000	3.12
230	20.87	0.00020	101.4	0.17	0.00020	20.95	78.90	0.0551	0.0026	0.003	0.11	0.0000	3.14
231	21.03	0.00020	56.4	0.08	0.00020	21.08	45.81	0.0161	0.0008	0.002	0.03	0.0000	3.16
232	21.12	0.00020	35.2	0.13	0.00020	21.18	34.06	0.0192	0.0009	0.001	0.04	0.0000	3.17
233	21.25	0.00020	32.9	0.17	0.00020	21.33	31.45	0.0224	0.0010	0.001	0.05	0.0000	3.19
234	21.42	0.00020	30.0	0.08	0.00020	21.46	40.78	0.0146	0.0007	0.002	0.03	0.0000	3.21
235	21.50	0.00020	51.6	0.03	0.00020	21.52	55.88	0.0080	0.0004	0.002	0.02	0.0000	3.22
236	21.53	0.00020	60.2	0.08	0.00020	21.58	1353.10	0.4866	0.0226	0.057	1.06	0.0000	3.23
237	21.62	0.00020	2646.0	0.05	0.00020	21.64	2953.50	0.6392	0.0295	0.125	1.40	0.0000	3.24
238	21.67	0.00020	3261.0	0.05	0.00020	21.69	2923.50	0.6342	0.0292	0.124	1.39	0.0000	3.25
239	21.72	0.00020	2586.0	0.03	0.00020	21.73	2286.00	0.3312	0.0152	0.097	0.73	0.0000	3.25
240	21.75	0.00020	1986.0	0.02	0.00020	21.76	1836.00	0.1332	0.0061	0.078	0.29	0.0000	3.26
241	21.77	0.00020	1686.0	0.08	0.00020	21.81	1461.00	0.5310	0.0244	0.062	1.18	0.0000	3.27
242	21.85	0.00020	1236.0	0.05	0.00020	21.88	1161.00	0.2540	0.0116	0.049	0.57	0.0000	3.28
243	21.90	0.00020	1086.0	0.05	0.00020	21.93	1026.00	0.2250	0.0103	0.043	0.50	0.0000	3.28
244	21.95	0.00020	966.0	0.05	0.00020	21.98	876.00	0.1925	0.0088	0.037	0.43	0.0000	3.29
245	22.00	0.00020	786.0				Σ	31.6032	4.7317	21.212	27.08	0.0151	

VIII. Simulation of Day Flow and Night Flow for Horizontal Flow Bed

Day Flow For Vertical Flow Bed

Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t Δt (m^3*hrs)	t Δt (hrs^2)	Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t Δt (m^3*hrs)	t Δt (hrs^2)
0.00	0.09	1.25	0.00	0.00	6.63	0.60	0.22	0.87	1.44
1.25	0.09	0.28	0.03	0.35	6.85	0.60	0.02	0.07	0.11
1.53	0.14	0.08	0.02	0.13	6.87	0.54	0.13	0.49	0.92
1.62	0.22	0.08	0.03	0.13	7.00	0.54	0.08	0.31	0.58
1.70	0.22	0.02	0.01	0.03	7.08	0.62	0.08	0.37	0.59
1.72	0.86	0.08	0.12	0.14	7.17	0.62	0.02	0.07	0.12
1.80	0.86	1.00	1.55	1.80	7.18	1.24	0.08	0.74	0.60
2.80	0.86	0.02	0.04	0.05	7.27	1.24	1.00	9.01	7.27
2.82	0.38	0.25	0.27	0.70	8.27	1.24	0.07	0.68	0.55
3.07	0.38	0.02	0.02	0.05	8.33	0.76	0.28	1.79	2.36
3.08	0.28	0.22	0.19	0.67	8.62	0.47	0.08	0.34	0.72
3.30	0.33	0.02	0.02	0.05	8.70	0.55	0.08	0.40	0.73
3.32	0.46	0.12	0.18	0.39	8.78	0.55	0.02	0.08	0.15
3.43	0.46	0.02	0.03	0.06	8.80	1.19	0.08	0.87	0.73
3.45	1.10	0.08	0.32	0.29	8.88	1.19	1.00	10.55	8.88
3.53	1.10	1.00	3.89	3.53	9.88	1.19	0.02	0.20	0.16
4.53	1.10	0.02	0.08	0.08	9.90	0.71	0.25	1.75	2.48
4.55	0.62	0.25	0.71	1.14	10.15	0.71	0.02	0.12	0.17
4.80	0.62	0.02	0.05	0.08	10.17	0.61	0.22	1.35	2.20
4.82	0.52	0.22	0.55	1.04	10.38	0.61	0.02	0.11	0.17
5.03	0.52	0.02	0.04	0.08	10.40	0.55	0.13	0.76	1.39
5.05	0.54	0.13	0.36	0.67	10.53	0.55	0.08	0.48	0.88
5.18	0.54	0.07	0.19	0.35	10.62	0.56	0.08	0.49	0.88
5.25	0.54	0.02	0.05	0.09	10.70	0.64	0.08	0.57	0.89
5.27	1.18	0.08	0.52	0.44	10.78	0.64	0.02	0.11	0.18
5.35	1.18	1.00	6.31	5.35	10.80	1.28	0.08	1.15	0.90
6.35	1.18	0.02	0.12	0.11	10.88	1.28	1.00	13.91	10.88
6.37	0.70	0.25	1.11	1.59	11.88	1.28	0.02	0.25	0.20
6.62	0.70	0.02	0.08	0.11	11.90	0.80	0.10	0.95	1.19
					12.00	0.80	Σ	16.87	19.50

Day Flow For Vertical Flow Bed

Q_{ave} 0.969031 **m3/hrs**

Volume = 18.2 **m^3**

Detention time = Volume/Q_{ave}

= 18.78166 hrs

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right)$$

k_r = 0.9 1/day

k_r = 0.038 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.494449$$

R.F = 0.505551

k_r (1/day)	0.3	0.35	0.4	0.45	0.5	0.6	0.9
R.F (%)	20.9	24.0	26.9	29.7	32.4	37.5	50.6

Night Flow For Vertical Flow Bed

Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t Δt (m^3*hrs)	t Δt (hrs^2)
0.00	0.80	0.17	0.00	0.00
0.17	0.70	0.22	0.03	0.04
0.38	0.70	0.02	0.00	0.01
0.40	0.64	0.13	0.03	0.05
0.53	0.64	0.05	0.02	0.03
0.58	0.49	0.08	0.02	0.05
0.67	0.37	0.08	0.02	0.06
0.75	0.24	0.03	0.01	0.03
0.78	0.29	0.08	0.02	0.07
0.87	0.37	0.08	0.03	0.07
0.95	0.37	0.02	0.01	0.02
0.97	1.01	0.08	0.08	0.08
1.05	1.01	1.00	1.06	1.05
2.05	1.01	0.02	0.03	0.03
2.07	0.53	0.25	0.27	0.52
2.32	0.53	0.02	0.02	0.04
2.33	0.43	0.22	0.22	0.51
2.55	0.43	0.02	0.02	0.04
2.57	0.37	0.13	0.13	0.34
2.70	0.37	0.22	0.22	0.59
2.92	0.31	0.33	0.30	0.97
3.25	0.24	0.33	0.26	1.08
3.58	0.18	0.33	0.22	1.19
3.92	0.12	0.08	0.04	0.33
4.00	0.09	0.25	0.09	1.00
4.25	0.09	2.00	0.78	8.50
6.25	0.09	5.75	3.29	35.94
12.00	0.09	Σ	7.20	52.61

Night Flow For Vertical Flow Bed

Q_{ave} 0.136863 **m3/hrs**

Volume = 18.2 $\mathbf{m^3}$

Detention time=Volume/Q_{ave}
= 132.9797 hrs

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right)$$

k_r = 0.9 1/day
k_r = 0.038 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.006828$$

R.F = 0.993172

k_r (1/day)	0.3	0.35	0.4	0.45	0.5	0.6	0.9
R.F (%)	81.0	85.6	89.1	91.7	93.7	96.4	99.3

Day Flow For Horizontal Flow Bed

Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t □t (m^3*hrs)	t Δt (hrs^2)	Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t □t (m^3*hrs)	t Δt (hrs^2)
0.00	0.02	0.33	0.00	0.00	3.20	0.21	0.08	0.06	0.27
0.33	0.02	0.12	0.00	0.04	3.28	0.19	0.08	0.05	0.27
0.45	0.05	0.08	0.00	0.04	3.37	0.13	0.08	0.04	0.28
0.53	2.64	0.05	0.07	0.03	3.45	0.11	0.13	0.05	0.46
0.58	3.25	0.05	0.09	0.03	3.58	0.14	0.03	0.02	0.12
0.63	2.58	0.05	0.08	0.03	3.62	0.07	0.08	0.02	0.30
0.68	1.68	0.08	0.10	0.06	3.70	0.17	0.08	0.05	0.31
0.77	1.23	0.05	0.05	0.04	3.78	2.76	0.05	0.52	0.19
0.82	1.08	0.05	0.04	0.04	3.83	3.37	0.05	0.65	0.19
0.87	0.96	0.05	0.04	0.04	3.88	2.70	0.05	0.52	0.19
0.92	0.78	0.03	0.02	0.03	3.93	1.80	0.08	0.59	0.33
0.95	0.65	0.08	0.05	0.08	4.02	1.35	0.05	0.27	0.20
1.03	0.51	0.05	0.03	0.05	4.07	1.20	0.05	0.24	0.20
1.08	0.44	0.03	0.02	0.04	4.12	1.08	0.05	0.22	0.21
1.12	0.42	0.08	0.04	0.09	4.17	0.90	0.03	0.12	0.14
1.20	0.33	0.08	0.03	0.10	4.20	0.77	0.08	0.27	0.35
1.28	0.26	0.08	0.03	0.11	4.28	0.63	0.05	0.14	0.21
1.37	0.20	0.08	0.02	0.11	4.33	0.57	0.03	0.08	0.14
1.45	0.18	0.08	0.02	0.12	4.37	0.54	0.08	0.20	0.36
1.53	0.12	0.08	0.02	0.13	4.45	0.45	0.08	0.17	0.37
1.62	0.10	0.17	0.03	0.27	4.53	0.38	0.08	0.14	0.38
1.78	0.06	0.08	0.01	0.15	4.62	0.32	0.08	0.12	0.38
1.87	0.04	0.30	0.02	0.56	4.70	0.30	0.05	0.07	0.23
2.17	0.03	0.12	0.01	0.25	4.75	0.27	0.03	0.04	0.16
2.28	0.06	0.08	0.01	0.19	4.78	0.24	0.12	0.14	0.56
2.37	2.65	0.05	0.31	0.12	4.90	0.27	0.08	0.11	0.41
2.42	3.26	0.05	0.39	0.12	4.98	2.86	0.05	0.71	0.25
2.47	2.59	0.05	0.32	0.12	5.03	3.47	0.05	0.87	0.25
2.52	1.69	0.08	0.35	0.21	5.08	2.80	0.05	0.71	0.25
2.60	1.24	0.05	0.16	0.13	5.13	1.90	0.08	0.81	0.43
2.65	1.09	0.05	0.14	0.13	5.22	1.45	0.05	0.38	0.26
2.70	0.97	0.05	0.13	0.14	5.27	1.30	0.05	0.34	0.26
2.75	0.79	0.03	0.07	0.09	5.32	1.18	0.05	0.31	0.27
2.78	0.66	0.08	0.15	0.23	5.37	1.00	0.03	0.18	0.18
2.87	0.52	0.05	0.07	0.14	5.40	0.87	0.08	0.39	0.45
2.92	0.45	0.03	0.04	0.10	5.48	0.73	0.05	0.20	0.27
2.95	0.43	0.08	0.10	0.25	5.53	0.67	0.03	0.12	0.18
3.03	0.34	0.08	0.08	0.25	5.57	0.64	0.08	0.30	0.46
3.12	0.27	0.08	0.07	0.26	5.65	0.55	0.08	0.26	0.47

Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t □t (m^3*hrs)	t Δt (hrs^2)	Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t □t (m^3*hrs)	t Δt (hrs^2)
5.73	0.48	0.08	0.23	0.48	9.37	0.81	0.08	0.63	0.78
5.82	0.43	0.08	0.21	0.48	9.45	0.67	0.05	0.32	0.47
5.90	0.40	0.08	0.20	0.49	9.50	0.60	0.03	0.19	0.32
5.98	0.34	0.08	0.17	0.50	9.53	0.58	0.08	0.46	0.79
6.07	0.32	0.17	0.33	1.01	9.62	0.49	0.08	0.39	0.80
6.23	0.28	0.08	0.14	0.52	9.70	0.42	0.08	0.34	0.81
6.32	0.26	0.60	0.97	3.79	9.78	0.36	0.08	0.30	0.82
6.92	0.18	0.12	0.15	0.81	9.87	0.34	0.08	0.28	0.82
7.03	0.21	0.08	0.12	0.59	9.95	0.28	0.08	0.23	0.83
7.12	2.80	0.05	0.99	0.36	10.03	0.26	0.17	0.44	1.67
7.17	3.41	0.05	1.22	0.36	10.20	0.22	0.08	0.18	0.85
7.22	2.74	0.05	0.99	0.36	10.28	0.19	0.47	0.93	4.80
7.27	1.84	0.08	1.11	0.61	10.75	0.17	0.12	0.21	1.25
7.35	1.39	0.05	0.51	0.37	10.87	0.20	0.08	0.18	0.91
7.40	1.24	0.05	0.46	0.37	10.95	2.78	0.05	1.52	0.55
7.45	1.12	0.05	0.42	0.37	11.00	3.40	0.05	1.87	0.55
7.50	0.94	0.03	0.23	0.25	11.05	2.72	0.05	1.51	0.55
7.53	0.81	0.08	0.51	0.63	11.10	1.82	0.08	1.69	0.93
7.62	0.67	0.05	0.26	0.38	11.18	1.37	0.05	0.77	0.56
7.67	0.60	0.03	0.15	0.26	11.23	1.22	0.05	0.69	0.56
7.70	0.58	0.08	0.37	0.64	11.28	1.10	0.05	0.62	0.56
7.78	0.49	0.08	0.32	0.65	11.33	0.92	0.03	0.35	0.38
7.87	0.42	0.08	0.28	0.66	11.37	0.80	0.08	0.75	0.95
7.95	0.36	0.08	0.24	0.66	11.45	0.66	0.05	0.38	0.57
8.03	0.34	0.08	0.22	0.67	11.50	0.59	0.03	0.23	0.38
8.12	0.28	0.08	0.19	0.68	11.53	0.56	0.08	0.54	0.96
8.20	0.26	0.17	0.36	1.37	11.62	0.47	0.08	0.46	0.97
8.37	0.22	0.08	0.15	0.70	11.70	0.41	0.08	0.40	0.98
8.45	0.19	0.30	0.49	2.54	11.78	0.35	0.08	0.34	0.98
8.75	0.18	0.12	0.18	1.02	11.87	0.32	0.08	0.32	0.99
8.87	0.21	0.08	0.16	0.74	11.95	0.27	0.05	0.16	0.60
8.95	2.80	0.05	1.25	0.45	12.00	0.26	Σ	3.25	4.92
9.00	3.41	0.05	1.53	0.45					
9.05	2.74	0.05	1.24	0.45					
9.10	1.84	0.08	1.39	0.76					
9.18	1.39	0.05	0.64	0.46					
9.23	1.24	0.05	0.57	0.46					
9.28	1.12	0.05	0.52	0.46					
9.33	0.94	0.03	0.29	0.31					

Day Flow For Horizontal Flow Bed

Q_{ave}= 0.719 **m3/hrs**

Volume = 17 **m^3**

Detention time=Volume/Q_{ave}

= 23.6 hrs

$$\frac{\overline{C_e}}{C_o} = \exp(-k_r T_{det})$$

k_r = 0.8 1/day

k_r = 0.033 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.45472$$

R.F = 0.54528

k_r (1/day)	0.4	0.44	0.5	0.6	0.7	0.8	1
R.F (%)	35.2	35.2	38.9	44.6	49.8	54.5	62.6

Night Flow For Horizontal Flow Bed

Time (hrs)	Q (m^3/hrs)	Δt (hrs)	Q t Δt (m^3*hrs)	t Δt (hrs^2)
0.00	0.25	0.03	0.00	0.00
0.03	0.25	0.17	0.00	0.01
0.20	0.20	0.08	0.00	0.02
0.28	0.18	1.72	0.09	0.49
2.00	0.14	2.00	0.58	4.00
4.00	0.02	3.50	0.29	14.00
7.50	0.02	0.12	0.02	0.88
7.62	0.05	0.08	0.03	0.63
7.70	2.64	0.05	1.02	0.38
7.75	3.25	0.05	1.26	0.39
7.80	2.58	0.05	1.00	0.39
7.85	1.68	0.08	1.10	0.65
7.93	1.23	0.05	0.49	0.40
7.98	1.08	0.05	0.43	0.40
8.03	0.96	0.05	0.38	0.40
8.08	0.78	0.03	0.21	0.27
8.12	0.65	0.08	0.44	0.68
8.20	0.51	0.05	0.21	0.41
8.25	0.44	0.03	0.12	0.27
8.28	0.42	0.08	0.29	0.69
8.37	0.33	0.08	0.23	0.70
8.45	0.26	0.08	0.18	0.70
8.53	0.20	0.08	0.14	0.71
8.62	0.18	0.08	0.13	0.72
8.70	0.12	0.08	0.09	0.72
8.78	0.10	0.17	0.15	1.46
8.95	0.06	0.08	0.04	0.75
9.03	0.04	0.97	0.31	8.73
10.00	0.02	2.00	0.41	20.00
12.00	0.02	Σ	9.63	59.85

Night Flow For Horizontal Flow Bed

Q_{ave} = 0.16 **m3/hrs**

Volume = 17 m^3

Detention time = Volume/Q_{ave}

= 105.7 hrs

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right)$$

k_r = 1 1/day

k_r = 0.042 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.012231$$

R.F = 0.987769

k_r (1/day)	0.4	0.44	0.5	0.6	0.7	0.8	1
R.F (%)	82.8	85.6	88.9	92.9	95.4	97.0	98.8

IX. Feeding Tank Data

Feeding Tank For Vertical Flow Bed

Dimensions of Feeding Tank

Length: 1.00 m

Width: 1.70 m

Average Water Level Before Flushing: 1.10 m

Average Water Level After Flushing: 0.40 m

Average Discharge Volume: 1.19 m^3

Feeding Tank For Horizontal Flow Bed

Dimensions of Feeding Tank

Length: 2.00 m

Width: 0.63 m

Average Water Level Before Flushing: 1.45 m

Average Water Level After Flushing: 0.60 m

Average Discharge Volume: 1.06 m^3

X. Estimated Theoretical Detention Time

CW for Sushma Koirala Hospital Constructed Wetlands System (Sub-Surface)

Design Flow rate:	10	m^3/day
Three chambered settlement tank:	10	m^3

Both beds planted with *Phargmites Karka* (local reeds)

Horizontal System

Given:	Length =	9	m	
	Width =	8	m	
	Area =	72	m^2	
	n=	39%		
	d =	0.6	m	(filled with broken gravel)
Assume:	Q=	10	m^3/day	
Estimate t:	t=	1.6848	days	
	q =	1.9	m/day	(In the direction along 8 m)
	v=	4.7	m/day	(In the direction along 8 m)

Vertical System

Given:	Length =	9	m	
	Width =	7.5	m	
	Area =	67.5	m^2	
Assume:	Kf =	0.001	m/s	
	d =	0.9	m	(filled with clean sand)
Assume:	Q=	10	m^3/day	
	n=	0.3		(clean sand ranges from 0.1 to 0.3)
Estimate t:	t=	1.8225	days	
	q=	0.15	m/day	
	v=	0.49	m/day	

XI. Minimum Amount of NaBr Required

Mass for Tracer

Specifications from vendor:

Concentration range: 1.0 to 5 x 10^{-6} M Br^-

79900 to 0.4 ppm

Calculations:

$CaBr_2$ (MW) = 200 g/mol   NaBr (MW)= 103 g/mol

Use equation: **M = C*V**

M= Mass of Tracer
C= Concentration of detection
V= Vol of system

Assume: Using NaBr to set C

Choose C range= 1.00E-04 M (mol/L) Br-

C = 7.99E-03 g/L Br-
7.99 mg/L (ppm) Br-

Horizontal System:

V = Area of wetland*d * n
= 16.848 m^3
= 16848 L

M= 134.6 g Br-

M= 173.5 g NaBr

Vertical System:

V = Area of wetland*d * n
= 18.225 m^3
= 18225 L

M= 145.62 g Br-

M = 187.72 g NaBr

Total M needed per test= 361.3 g

APPENDIX B

Dhulikhel Hospital’s Constructed Wetland System

I. Field Data For Dhulikhel Hospital

Dhulikhel Hospital

Effluent For Vertical Flow Bed

Chemical Used:	NaBr	
Amount of Chemical Used:	1150	g
Tracer introduced at:	17:50	
	5:50 PM	
Date:	1/19/2003	

No	Time Date	Time (hrs:min)	Time Interval (hr:min)	Time Interval (hrs)	[Br^-] Detected (mol/l)	Note
1	1/19/03 5:50 PM	17:50	0:00	0.00	0.0000	
2	1/19/03 6:30 PM	18:30	0:40	0.67	0.0000	
3	1/19/03 7:00 PM	19:00	1:10	1.17	0.0001	
4	1/19/03 7:15 PM	19:15	1:25	1.42	0.0001	
5	1/19/03 7:30 PM	19:30	1:40	1.67	0.0002	
6	1/19/03 7:45 PM	19:45	1:55	1.92	0.0002	
7	1/19/03 8:00 PM	20:00	2:10	2.17	0.0002	
8	1/19/03 8:15 PM	20:15	2:25	2.42	0.0003	
9	1/19/03 8:30 PM	20:30	2:40	2.67	0.0003	
10	1/19/03 9:00 PM	21:00	3:10	3.17	0.0003	
11	1/19/03 9:30 PM	21:30	3:40	3.67	0.0003	
12	1/19/03 10:00 PM	22:00	4:10	4.17	0.0003	
13	1/19/03 10:15 PM	22:15	4:25	4.42	0.0003	
14	1/19/03 10:45 PM	22:45	4:55	4.92	0.0005	
15	1/19/03 11:00 PM	23:00	5:10	5.17	0.0003	
16	1/19/03 11:30 PM	23:30	5:40	5.67	0.0003	
17	1/20/03 12:00 AM	0:00	6:10	6.17	0.0003	
18	1/20/03 12:30 AM	0:30	6:40	6.67	0.0003	
19	1/20/03 1:00 AM	1:00	7:10	7.17	0.0002	
20	1/20/03 3:00 AM	3:00	9:10	9.17	0.0002	
21	1/20/03 5:30 AM	5:30	11:40	11.67	0.0002	
22	1/20/03 8:00 AM	8:00	14:10	14.17	0.0002	
23	1/20/03 8:35 AM	8:35	14:45	14.75	0.0002	
24	1/20/03 8:55 AM	8:55	15:05	15.08	0.0002	
25	1/20/03 9:15 AM	9:15	15:25	15.42	0.0003	
26	1/20/03 9:30 AM	9:30	15:40	15.67	0.0003	
27	1/20/03 9:45 AM	9:45	15:55	15.92	0.0003	
28	1/20/03 10:15 AM	10:15	16:25	16.42	0.0002	

No	Time	Time	Time Interval	Time Interval	[Br⁻] Detected	Note
	Date	(hrs:min)	(hr:min)	(hrs)	(mol/l)	
29	1/20/03 10:30 AM	10:30	16:40	16.67	0.0002	
30	1/20/03 10:45 AM	10:45	16:55	16.92	0.0003	
31	1/20/03 11:00 AM	11:00	17:10	17.17	0.0002	
32	1/20/03 11:15 AM	11:15	17:25	17.42	0.0002	
33	1/20/03 11:30 AM	11:30	17:40	17.67	0.0002	
34	1/20/03 12:00 PM	12:00	18:10	18.17	0.0001	
35	1/20/03 1:00 PM	13:00	19:10	19.17	0.0002	
36	1/20/03 1:30 PM	13:30	19:40	19.67	0.0002	
37	1/20/03 2:00 PM	14:00	20:10	20.17	0.0001	
38	1/20/03 3:00 PM	15:00	21:10	21.17	0.0001	
39	1/20/03 3:30 PM	15:30	21:40	21.67	0.0001	
40	1/20/03 4:00 PM	16:00	22:10	22.17	0.0001	
41	1/20/03 5:00 PM	17:00	23:10	23.17	0.0001	More than 24 hrs
42	1/20/03 6:00 PM	18:00	0:10	24.17	0.0001	
43	1/20/03 6:45 PM	18:45	0:55	24.92	0.0000	
44	1/20/03 7:00 PM	19:00	1:10	25.17	0.0000	
45	1/20/03 8:00 PM	20:00	2:10	26.17	0.0000	
46	1/20/03 8:50 PM	20:50	3:00	27.00	0.0000	
47	1/21/03 6:00 AM	6:00	12:10	36.17	0.0000	
48	1/21/03 6:30 AM	6:30	12:40	36.67	0.0000	
49	1/21/03 7:00 AM	7:00	13:10	37.17	0.0000	
50	1/21/03 8:00 AM	8:00	14:10	38.17	0.0000	

Effluent For Horizontal Flow Bed

Chemical Used: NaBr

Amount of Chemical Used: 1200 g

Tracer introduced at: 6:50
6:50 AM

Date: 1/21/2003

No	Time Date	Time (hrs:min)	Time Interval (hr:min)	Time Interval (hrs)	[Br ⁻] Detected (mol/l)	Note
1	1/21/03 6:50 AM	6:50	0:00	0.00	0.0000	
2	1/21/03 7:00 AM	7:00	0:10	0.17	0.0000	
3	1/21/03 7:30 AM	7:30	0:40	0.67	0.0000	
4	1/21/03 8:00 AM	8:00	1:10	1.17	0.0004	
5	1/21/03 8:30 AM	8:30	1:40	1.67	0.0007	
6	1/21/03 9:00 AM	9:00	2:10	2.17	0.0008	
7	1/21/03 9:30 AM	9:30	2:40	2.67	0.0009	
8	1/21/03 10:00 AM	10:00	3:10	3.17	0.0008	
9	1/21/03 10:30 AM	10:30	3:40	3.67	0.0005	
10	1/21/03 11:00 AM	11:00	4:10	4.17	0.0004	
11	1/21/03 11:30 AM	11:30	4:40	4.67	0.0006	
12	1/21/03 11:45 AM	11:45	4:55	4.92	0.0005	
13	1/21/03 12:00 PM	12:00	5:10	5.17	0.0004	
14	1/21/03 12:15 PM	12:15	5:25	5.42	0.0005	
15	1/21/03 12:30 PM	12:30	5:40	5.67	0.0004	
16	1/21/03 12:45 PM	12:45	5:55	5.92	0.0004	
17	1/21/03 1:00 PM	13:00	6:10	6.17	0.0003	
18	1/21/03 1:30 PM	13:30	6:40	6.67	0.0003	
19	1/21/03 2:00 PM	14:00	7:10	7.17	0.0003	
20	1/21/03 2:15 PM	14:15	7:25	7.42	0.0003	
21	1/21/03 2:30 PM	14:30	7:40	7.67	0.0004	
22	1/21/03 3:00 PM	15:00	8:10	8.17	0.0003	
23	1/21/03 3:30 PM	15:30	8:40	8.67	0.0003	
24	1/21/03 4:00 PM	16:00	9:10	9.17	0.0002	
25	1/21/03 4:30 PM	16:30	9:40	9.67	0.0002	
26	1/21/03 5:00 PM	17:00	10:10	10.17	0.0002	
27	1/21/03 5:20 PM	17:20	10:30	10.50	0.0002	
28	1/21/03 5:45 PM	17:45	10:55	10.92	0.0002	
29	1/21/03 6:00 PM	18:00	11:10	11.17	0.0002	
30	1/21/03 7:00 PM	19:00	12:10	12.17	0.0002	
31	1/21/03 8:15 PM	20:15	13:25	13.42	0.0001	
32	1/21/03 8:40 PM	20:40	13:50	13.83	0.0001	

No	Time Date	Time (hrs:min)	Time Interval (hr:min)	Time Interval (hrs)	[Br⁻] Detected (mol/l)	Note
33	1/21/03 9:30 PM	21:30	14:40	14.67	0.0001	
34	1/21/03 10:30 PM	22:30	15:40	15.67	0.0001	
35	1/21/03 11:40 PM	23:40	16:50	16.83	0.0001	
36	1/22/03 12:15 AM	0:15	17:25	17.42	0.0000	More than 24 hrs
37	1/22/03 1:00 AM	1:00	18:10	18.17	0.0001	
38	1/22/03 1:30 AM	1:30	18:40	18.67	0.0000	
39	1/22/03 2:00 AM	2:00	19:10	19.17	0.0000	
40	1/22/03 3:00 AM	3:00	20:10	20.17	0.0000	
41	1/22/03 7:00 AM	7:00	0:10	24.17	0.0000	
42	1/22/03 8:30 AM	8:30	1:40	25.67	0.0000	
43	1/22/03 9:00 AM	9:00	2:10	26.17	0.0000	
44	1/22/03 10:00 AM	10:00	3:10	27.17	0.0000	

II. Number of Flushes Recorded

Number of Flushes into the VFB

No of Flushes	Time Date	Time (hrs)	Note
1	1/19/03 3:15 PM	15:15	Test on VFB
2	1/19/03 4:04 PM	16:04	
3	1/19/03 5:08 PM	17:08	
4	1/19/03 5:50 PM	17:50	
5	1/19/03 7:14 PM	19:14	
6	1/19/03 8:10 PM	20:10	
7	1/19/03 9:05 PM	21:05	
8	1/19/03 10:05 PM	22:05	
9	1/19/03 11:10 PM	23:10	
10	1/20/03 1:05 AM	1:05	
11	1/20/03 6:00 AM	6:00	
12	1/20/03 7:00 AM	7:00	
13	1/20/03 7:20 AM	7:20	
14	1/20/03 7:45 AM	7:45	
15	1/20/03 8:27 AM	8:27	
16	1/20/03 9:20 AM	9:20	
17	1/20/03 9:50 AM	9:50	
18	1/20/03 10:30 AM	10:30	
19	1/20/03 11:03 AM	11:03	
20	1/20/03 11:45 AM	11:45	
21	1/20/03 12:25 PM	12:25	
22	1/20/03 12:57 PM	12:57	
23	1/20/03 1:35 PM	13:35	
24	1/20/03 2:25 PM	14:25	
25	1/20/03 3:15 PM	15:15	
26	1/20/03 4:10 PM	16:10	
1	1/21/03 7:55 AM	7:55	Test on HFB
2	1/21/03 8:55 AM	8:55	
3	1/21/03 9:50 AM	9:50	
4	1/21/03 10:42 AM	10:42	
5	1/21/03 11:30 AM	11:30	
6	1/21/03 12:20 PM	12:20	
7	1/21/03 1:10 PM	13:10	
8	1/21/03 2:14 PM	14:14	
9	1/21/03 3:17 PM	15:17	
10	1/21/03 4:14 PM	16:14	
11	1/21/03 5:00 PM	17:00	
12	1/21/03 5:50 PM	17:50	
13	1/21/03 6:45 PM	18:45	Dinner
14	1/21/03 9:03 PM	21:03	
15	1/21/03 10:05 PM	22:05	
16	1/21/03 11:15 PM	23:15	
17	1/22/03 12:34 AM	0:34	
18	1/22/03 2:16 AM	2:16	

Number of Flushes into the HFB

No of Flushes	Time Date	Time (hrs)	Note
1	1/19/03 4:20 PM	16:20	
2	1/19/03 4:50 PM	16:50	
3	1/19/03 5:15 PM	17:15	
4	1/19/03 5:45 PM	17:45	
5	1/19/03 8:12 PM	20:12	
6	1/19/03 8:50 PM	20:50	
7	1/19/03 9:30 PM	21:30	
8	1/19/03 10:10 PM	22:10	
9	1/19/03 11:45 PM	23:45	
10	1/20/03 2:00 AM	2:00	
11	1/20/03 5:00 AM	5:00	
12	1/20/03 7:05 AM	7:05	
13	1/20/03 7:35 AM	7:35	
14	1/20/03 8:00 AM	8:00	
15	1/20/03 8:40 AM	8:40	
16	1/20/03 9:20 AM	9:20	
17	1/20/03 9:40 AM	9:40	
18	1/20/03 10:10 AM	10:10	
19	1/20/03 10:30 AM	10:30	
20	1/20/03 10:50 AM	10:50	
21	1/20/03 11:20 AM	11:20	
22	1/20/03 11:48 AM	11:48	
23	1/20/03 12:15 PM	12:15	
24	1/20/03 12:30 PM	12:30	
25	1/20/03 12:52 PM	12:52	
26	1/20/03 1:14 PM	13:14	
27	1/20/03 1:55 PM	13:55	
28	1/20/03 3:10 PM	15:10	
29	1/20/03 3:45 PM	15:45	
30	1/20/03 4:15 PM	16:15	
31	1/20/03 4:45 PM	16:45	
32	1/20/03 5:23 PM	17:23	
33	1/20/03 5:50 PM	17:50	
1	1/21/03 6:50 AM	6:50	
2	1/21/03 7:20 AM	7:20	
3	1/21/03 7:40 AM	7:40	
4	1/21/03 8:10 AM	8:10	
5	1/21/03 8:50 AM	8:50	
6	1/21/03 9:20 AM	9:20	
7	1/21/03 9:50 AM	9:50	
8	1/21/03 10:25 AM	10:25	
9	1/21/03 10:45 AM	10:45	
10	1/21/03 11:20 AM	11:20	
11	1/21/03 11:55 AM	11:55	
12	1/21/03 12:25 PM	12:25	
13	1/21/03 1:05 PM	13:05	
14	1/21/03 1:41 PM	13:41	

No of Flushes	Time Date	Time (hrs)	Note
15	1/21/03 2:29 PM	14:29	
16	1/21/03 3:00 PM	15:00	
17	1/21/03 3:32 PM	15:32	
18	1/21/03 4:10 PM	16:10	
19	1/21/03 4:33 PM	16:33	
20	1/21/03 5:10 PM	17:10	
21	1/21/03 5:35 PM	17:35	
22	1/21/03 6:06 PM	18:06	
23	1/21/03 7:00 PM	19:00	
24	1/21/03 7:40 PM	19:40	
25	1/21/03 8:25 PM	20:25	
26	1/21/03 8:56 PM	20:56	
27	1/21/03 9:37 PM	21:37	
28	1/21/03 10:18 PM	22:18	
29	1/21/03 11:20 PM	23:20	
30	1/22/03 1:46 AM	1:46	

III. Feeding Tank Data

Feeding Tank For Vertical Flow Bed

Dimensions of Feeding Tank

Length: 2.50 m

Width: 1.00 m

Average Water Level Before Flushing: 0.83 m

Average Water Level After Flushing: 0.48 m

Average Discharge Volume: 0.88 m^3

Feeding Tank For Horizontal Flow Bed

Dimensions of Feeding Tank

Length: 2.75 m

Width: 1.00 m

Average Water Level Before Flushing: 1.62 m

Average Water Level After Flushing: 1.30 m

Average Discharge Volume: 0.88 m^3

IV. Estimation of Effluent Flowrate

Estimation of Effluent Flowrate into the Vertical Flow Bed for NaBr Tracer Test

No of Flushes	Time Date	Time (hrs)	Time (hrs)	Flowrate (m^3/hr)
1	1/19/03 5:50 PM	17:50	0.00	0.63
2	1/19/03 7:14 PM	19:14	1.40	0.63
3	1/19/03 8:10 PM	20:10	2.33	0.94
4	1/19/03 9:05 PM	21:05	3.25	0.95
5	1/19/03 10:05 PM	22:05	4.25	0.88
6	1/19/03 11:10 PM	23:10	5.33	0.81
7	1/20/03 1:05 AM	1:05	7.25	0.46
8	1/20/03 6:00 AM	6:00	12.17	0.18
9	1/20/03 7:00 AM	7:00	13.17	0.88
10	1/20/03 7:20 AM	7:20	13.50	2.63
11	1/20/03 7:45 AM	7:45	13.92	2.10
12	1/20/03 8:27 AM	8:27	14.62	1.25
13	1/20/03 9:20 AM	9:20	15.50	0.99
14	1/20/03 9:50 AM	9:50	16.00	1.75
15	1/20/03 10:30 AM	10:30	16.67	1.31
16	1/20/03 11:03 AM	11:03	17.22	1.59
17	1/20/03 11:45 AM	11:45	17.92	1.25
18	1/20/03 12:25 PM	12:25	18.58	1.31
19	1/20/03 12:57 PM	12:57	19.12	1.64
20	1/20/03 1:35 PM	13:35	19.75	1.38
21	1/20/03 2:25 PM	14:25	20.58	1.05
22	1/20/03 3:15 PM	15:15	21.42	1.05
23	1/20/03 4:10 PM	16:10	22.33	0.95
24	1/20/03 5:14 PM	17:08	23.30	0.91
25	1/20/03 5:57 PM	17:50	24.00	1.25
26	1/20/03 7:20 PM	19:14	25.40	0.62
27	1/20/03 8:16 PM	20:10	26.43	0.85
28	1/20/03 9:11 PM	21:05	27.35	0.95
29	1/20/03 10:11 PM	22:05	28.35	0.88
30	1/20/03 11:16 PM	23:10	29.43	0.81
31	1/21/03 1:11 AM	1:05	31.35	0.46
32	1/212003 6:06 AM	6:00	36.27	0.18
33	1/21/03 7:06 AM	7:00	37.27	0.88
34	1/21/03 7:26 AM	7:20	37.60	2.63
35	1/21/03 7:55 AM	7:55	38.08	1.81

Estimation of Effluent Flowrate into the Vertical Flow Bed in a day

12am - 12pm	
hrs	**m3/hrs**
0.00	0.66
1.08	0.46
6.00	0.18
7.00	0.88
7.33	2.63
7.75	2.10
8.00	1.80
8.45	1.25
9.33	0.99
9.83	1.75
10.50	1.31
11.05	1.59
11.75	1.25
12.42	1.31
12.95	1.64
13.58	1.38
14.42	1.05
15.25	1.05
16.17	0.95
17.13	0.91
17.83	1.25
19.23	0.62
20.00	0.79
20.27	0.85
21.18	0.95
22.18	0.88
23.27	0.81
24.00	0.66

Estimation of Effluent Flowrate into the Horizontal Flow Bed for NaBr Tracer Test

No of Flushes	Time Date	Time (hrs)	Time (hrs)	Flowrate (m^3/hr)
1	1/21/03 6:50 AM	6:50	0.00	1.76
2	1/21/03 7:20 AM	7:20	0.50	1.76
3	1/21/03 7:40 AM	7:40	0.83	2.64
4	1/21/03 8:10 AM	8:10	1.33	1.76
5	1/21/03 8:50 AM	8:50	2.00	1.32
6	1/21/03 9:20 AM	9:20	2.50	1.76
7	1/21/03 9:50 AM	9:50	3.00	1.76
8	1/21/03 10:25 AM	10:25	3.58	1.51
9	1/21/03 10:45 AM	10:45	3.92	2.64
10	1/21/03 11:00 AM	11:00	4.17	3.52
11	1/21/03 11:20 AM	11:20	4.50	2.64
12	1/21/03 11:55 AM	11:55	5.08	1.51
13	1/21/03 12:25 PM	12:25	5.58	1.76
14	1/21/03 12:45 PM	12:45	5.92	2.64
15	1/21/03 1:05 PM	13:05	6.25	2.64
16	1/21/03 1:41 PM	13:41	6.85	1.47
17	1/21/03 2:29 PM	14:29	7.65	1.10
18	1/21/03 3:00 PM	15:00	8.17	1.70
19	1/21/03 3:32 PM	15:32	8.70	1.65
20	1/21/03 4:10 PM	16:10	9.33	1.39
21	1/21/03 4:33 PM	16:33	9.72	2.30
22	1/21/03 5:10 PM	17:10	10.33	1.43
23	1/21/03 5:35 PM	17:35	10.75	2.11
24	1/21/03 6:06 PM	18:06	11.27	1.70
25	1/21/03 7:00 PM	19:00	12.17	0.98
26	1/21/03 7:40 PM	19:40	12.83	1.32
27	1/21/03 8:25 PM	20:25	13.58	1.17
28	1/21/03 8:56 PM	20:56	14.10	1.70
29	1/21/03 9:37 PM	21:37	14.78	1.29
30	1/21/03 10:18 PM	22:18	15.47	1.29
31	1/21/03 11:20 PM	23:20	16.50	0.85
32	1/22/03 1:46 AM	1:46	18.93	0.36
33	1/20/03 4:45 AM	4:45	21.92	0.29
34	1/20/03 6:50 AM	6:50	24.00	0.42
35	1/20/03 7:20 AM	7:20	24.50	1.76
36	1/20/03 7:45 AM	7:45	24.92	2.11
37	1/20/03 8:25 AM	8:25	25.58	1.32
38	1/20/03 9:05 AM	9:05	26.25	1.32
39	1/20/03 9:25 AM	9:25	26.58	2.64
40	1/20/03 10:00 AM	10:00	27.17	1.51

Estimation of Effluent Flowrate into the Horizontal Flow Bed in a day

12am - 12pm	
hrs	**m3/hrs**
0.00	0.85
2.43	0.36
5.42	0.29
7.50	0.42
8.00	1.76
8.42	2.11
9.08	1.32
9.75	1.32
10.08	2.64
10.67	1.51
11.42	2.64
11.67	3.52
12.00	2.64
12.58	1.51
13.08	1.76
13.42	2.64
13.75	2.64
14.35	1.47
15.15	1.10
15.67	1.70
16.20	1.65
16.83	1.39
17.22	2.30
17.83	1.43
18.25	2.11
18.77	1.70
19.67	0.98
20.33	1.32
21.08	1.17
21.60	1.70
22.28	1.29
22.97	1.29
24.00	0.85

V. Detention Time Calculations for Flow Beds (Constant Q)

Detention Time For Vertical Flow Bed Using Trapezoidal Rule

Assume : Flowrate is constant

Detention Time= 11.0 hrs

No	Time (hrs:min)	Time Int. (hr:min)	Time Int. (hrs)	[Br$^-$] Det. (mol/l)	Δt (hrs)	*[Br-]* bar (mol/l)	*t bar* (hrs)	*Δt * [Br$^-$]*t*	*Δt * [Br$^-$]*
1	17:50	0:00	0.00	0.0000	0.67	0	0.3333	0	0
2	18:30	0:40	0.67	0.0000	0.50	0.00005	0.9167	2.29167E-05	2.5E-05
3	19:00	1:10	1.17	0.0001	0.25	0.0001	1.2917	3.22917E-05	0.000025
4	19:15	1:25	1.42	0.0001	0.25	0.00015	1.5417	5.78125E-05	3.75E-05
5	19:30	1:40	1.67	0.0002	0.25	0.0002	1.7917	8.95833E-05	0.00005
6	19:45	1:55	1.92	0.0002	0.25	0.0002	2.0417	0.000102083	0.00005
7	20:00	2:10	2.17	0.0002	0.25	0.00025	2.2917	0.000143229	6.25E-05
8	20:15	2:25	2.42	0.0003	0.25	0.0003	2.5417	0.000190625	0.000075
9	20:30	2:40	2.67	0.0003	0.50	0.0003	2.9167	0.0004375	0.00015
10	21:00	3:10	3.17	0.0003	0.50	0.0003	3.4167	0.0005125	0.00015
11	21:30	3:40	3.67	0.0003	0.50	0.0003	3.9167	0.0005875	0.00015
12	22:00	4:10	4.17	0.0003	0.25	0.0003	4.2917	0.000321875	7.5E-05
13	22:15	4:25	4.42	0.0003	0.50	0.0004	4.6667	0.000933333	0.0002
14	22:45	4:55	4.92	0.0005	0.25	0.0004	5.0417	0.000504167	0.0001
15	23:00	5:10	5.17	0.0003	0.50	0.0003	5.4167	0.0008125	0.00015
16	23:30	5:40	5.67	0.0003	0.50	0.0003	5.9167	0.0008875	0.00015
17	0:00	6:10	6.17	0.0003	0.50	0.0003	6.4167	0.0009625	0.00015
18	0:30	6:40	6.67	0.0003	0.50	0.00025	6.9167	0.000864583	0.000125
19	1:00	7:10	7.17	0.0002	2.00	0.0002	8.1667	0.003266667	0.0004
20	3:00	9:10	9.17	0.0002	2.50	0.0002	10.417	0.005208333	0.0005
21	5:30	11:40	11.67	0.0002	2.50	0.0002	12.917	0.006458333	0.0005
22	8:00	14:10	14.17	0.0002	0.58	0.0002	14.458	0.001686806	0.000117
23	8:35	14:45	14.75	0.0002	0.33	0.0002	14.917	0.000994444	6.67E-05
24	8:55	15:05	15.08	0.0002	0.33	0.00025	15.25	0.001270833	8.33E-05
25	9:15	15:25	15.42	0.0003	0.25	0.0003	15.542	0.001165625	0.000075
26	9:30	15:40	15.67	0.0003	0.25	0.0003	15.792	0.001184375	0.000075
27	9:45	15:55	15.92	0.0003	0.50	0.00025	16.167	0.002020833	0.000125
28	10:15	16:25	16.42	0.0002	0.25	0.0002	16.542	0.000827083	0.00005
29	10:30	16:40	16.67	0.0002	0.25	0.00025	16.792	0.001049479	6.25E-05
30	10:45	16:55	16.92	0.0003	0.25	0.00025	17.042	0.001065104	6.25E-05
31	11:00	17:10	17.17	0.0002	0.25	0.0002	17.292	0.000864583	0.00005
32	11:15	17:25	17.42	0.0002	0.25	0.0002	17.542	0.000877083	0.00005
33	11:30	17:40	17.67	0.0002	0.50	0.00015	17.917	0.00134375	0.000075
34	12:00	18:10	18.17	0.0001	1.00	0.00015	18.667	0.0028	0.00015

No	Time	Time Int.	Time Int.	[Br$^-$] Det.	Δt	*[Br-]* bar	*t bar*	*Δt * [Br$^-$]*t*	*Δt * [Br$^-$]*
	(hrs:min)	(hr:min)	(hrs)	(mol/l)	(hrs)	(mol/l)	(hrs)		
35	13:00	19:10	19.17	0.0002	0.50	0.0002	19.417	0.001941667	0.0001
36	13:30	19:40	19.67	0.0002	0.50	0.00015	19.917	0.00149375	0.000075
37	14:00	20:10	20.17	0.0001	1.00	0.0001	20.667	0.002066667	0.0001
38	15:00	21:10	21.17	0.0001	0.50	0.0001	21.417	0.001070833	0.00005
39	15:30	21:40	21.67	0.0001	0.50	0.0001	21.917	0.001095833	0.00005
40	16:00	22:10	22.17	0.0001	1.00	0.0001	22.667	0.002266667	0.0001
41	17:00	23:10	23.17	0.0001	1.00	0.0001	23.667	0.002366667	0.0001
42	18:00	0:10	24.17	0.0001	0.75	0.00005	24.542	0.000920312	3.75E-05
43	18:45	0:55	24.92	0.0000	0.25	0	25.042	0	0
44	19:00	1:10	25.17	0.0000	1.00	0	25.667	0	0
45	20:00	2:10	26.17	0.0000	0.83	0	26.583	0	0
46	20:50	3:00	27.00	0.0000	9.17	0	31.583	0	0
47	6:00	12:10	36.17	0.0000	0.50	0	36.417	0	0
48	6:30	12:40	36.67	0.0000	0.50	0	36.917	0	0
49	7:00	13:10	37.17	0.0000	1.00	0	37.667	0	0
50	8:00	14:10	38.17	0.0000			Σ	0.052768229	0.004779

Detention Time For Horizontal Flow Bed

Assume : Flowrate is constant

Detention Time= 6.29 hrs

No	Time (hrs:min)	Time Int. (hr:min)	Time Int. (hrs)	$[Br^-]$ Det. (mol/l)	Δt (hrs)	*[Br-]* bar (mol/l)	*t bar* (hrs)	$\Delta t * [Br^-] * t$	$\Delta t * [Br^-]$
1	6:50	0:00	0.00	0.0000	0.17	0	0.083333	0	0
2	7:00	0:10	0.17	0.0000	0.50	0	0.416667	0	0
3	7:30	0:40	0.67	0.0000	0.50	0.0002	0.916667	9.17E-05	1E-04
4	8:00	1:10	1.17	0.0004	0.50	0.00055	1.416667	0.00039	0.000275
5	8:30	1:40	1.67	0.0007	0.50	0.00075	1.916667	0.000719	0.000375
6	9:00	2:10	2.17	0.0008	0.50	0.00085	2.416667	0.001027	0.000425
7	9:30	2:40	2.67	0.0009	0.50	0.00085	2.916667	0.00124	0.000425
8	10:00	3:10	3.17	0.0008	0.50	0.00065	3.416667	0.00111	0.000325
9	10:30	3:40	3.67	0.0005	0.50	0.00045	3.916667	0.000881	0.000225
10	11:00	4:10	4.17	0.0004	0.50	0.0005	4.416667	0.001104	0.00025
11	11:30	4:40	4.67	0.0006	0.25	0.00055	4.791667	0.000659	0.000138
12	11:45	4:55	4.92	0.0005	0.25	0.00045	5.041667	0.000567	0.000112
13	12:00	5:10	5.17	0.0004	0.25	0.00045	5.291667	0.000595	0.000113
14	12:15	5:25	5.42	0.0005	0.25	0.00045	5.541667	0.000623	0.000113
15	12:30	5:40	5.67	0.0004	0.25	0.0004	5.791667	0.000579	0.0001
16	12:45	5:55	5.92	0.0004	0.25	0.00035	6.041667	0.000529	8.75E-05
17	13:00	6:10	6.17	0.0003	0.50	0.0003	6.416667	0.000963	0.00015
18	13:30	6:40	6.67	0.0003	0.50	0.0003	6.916667	0.001038	0.00015
19	14:00	7:10	7.17	0.0003	0.25	0.0003	7.291667	0.000547	0.000075
20	14:15	7:25	7.42	0.0003	0.25	0.00035	7.541667	0.00066	8.75E-05
21	14:30	7:40	7.67	0.0004	0.50	0.00035	7.916667	0.001385	0.000175
22	15:00	8:10	8.17	0.0003	0.50	0.0003	8.416667	0.001263	0.00015
23	15:30	8:40	8.67	0.0003	0.50	0.00025	8.916667	0.001115	0.000125
24	16:00	9:10	9.17	0.0002	0.50	0.0002	9.416667	0.000942	0.0001
25	16:30	9:40	9.67	0.0002	0.50	0.0002	9.916667	0.000992	1E-04
26	17:00	10:10	10.17	0.0002	0.33	0.0002	10.33333	0.000689	6.67E-05
27	17:20	10:30	10.50	0.0002	0.42	0.0002	10.70833	0.000892	8.33E-05
28	17:45	10:55	10.92	0.0002	0.25	0.0002	11.04167	0.000552	0.00005
29	18:00	11:10	11.17	0.0002	1.00	0.0002	11.66667	0.002333	0.0002
30	19:00	12:10	12.17	0.0002	1.25	0.00015	12.79167	0.002398	0.000188
31	20:15	13:25	13.42	0.0001	0.42	0.0001	13.625	0.000568	4.17E-05
32	20:40	13:50	13.83	0.0001	0.83	0.0001	14.25	0.001187	8.33E-05
33	21:30	14:40	14.67	0.0001	1.00	0.0001	15.16667	0.001517	0.0001

No	Time	Time Int.	Time Int.	[Br⁻] Det.	Δt	*[Br-]* bar	*t bar*	*Δt * [Br⁻]*t*	*Δt * [Br⁻]*
	(hrs:min)	(hr:min)	(hrs)	(mol/l)	(hrs)	(mol/l)	(hrs)		
34	22:30	15:40	15.67	0.0001	1.17	0.0001	16.25	0.001896	0.000117
35	23:40	16:50	16.83	0.0001	0.58	0.00005	17.125	0.000499	2.92E-05
36	0:15	17:25	17.42	0.0000	0.75	0.00005	17.79167	0.000667	3.75E-05
37	1:00	18:10	18.17	0.0001	0.50	0.00005	18.41667	0.00046	0.000025
38	1:30	18:40	18.67	0.0000	0.50	0	18.91667	0	0
39	2:00	19:10	19.17	0.0000	1.00	0	19.66667	0	0
40	3:00	20:10	20.17	0.0000	4.00	0	22.16667	0	0
41	7:00	0:10	24.17	0.0000	1.50	0	24.91667	0	0
42	8:30	1:40	25.67	0.0000	0.50	0	25.91667	0	0
43	9:00	2:10	26.17	0.0000	1.00	0	26.66667	0	0
44	10:00	3:10	27.17	0.0000			Σ	0.032678	0.005196

VI. Detention Time Calculations for Flow Beds with Q Factor

Detention Time For Vertical Flow Bed Using Trapezoidal Rule

Detention Time= 12.2 hrs

No	Time Int. (hrs)	[Br⁻] Det. (mol/l)	Q (L/hrs)	Δ t (hrs)	*[Br⁻] bar (mol/l)*	*t bar (hrs)*	*Q bar (L/hrs)*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
1	0.00	0.0000	625.0	0.6667	0	0.3333	625	0	0
2	0.67	0.0000	625.0	0.5000	0.00005	0.9167	625	0.014322917	0.015625
3	1.17	0.0001	625.0	0.2500	0.0001	1.2917	781.25	0.025227865	0.01953125
4	1.42	0.0001	937.5	0.2500	0.00015	1.5417	937.5	0.054199219	0.03515625
5	1.67	0.0002	937.5	0.2500	0.0002	1.7917	937.5	0.083984375	0.046875
6	1.92	0.0002	937.5	0.2500	0.0002	2.0417	937.5	0.095703125	0.046875
7	2.17	0.0002	937.5	0.2500	0.00025	2.2917	937.5	0.134277344	0.05859375
8	2.42	0.0003	937.5	0.2500	0.0003	2.5417	937.5	0.178710938	0.0703125
9	2.67	0.0003	937.5	0.5000	0.0003	2.9167	937.5	0.41015625	0.140625
10	3.17	0.0003	937.5	0.5000	0.0003	3.4167	946.02	0.484836648	0.141903409
11	3.67	0.0003	954.5	0.5000	0.0003	3.9167	954.55	0.560795455	0.143181818
12	4.17	0.0003	954.5	0.2500	0.0003	4.2917	914.77	0.294442472	0.068607955
13	4.42	0.0003	875.0	0.5000	0.0004	4.6667	875	0.816666667	0.175
14	4.92	0.0005	875.0	0.2500	0.0004	5.0417	875	0.441145833	0.0875
15	5.17	0.0003	875.0	0.5000	0.0003	5.4167	841.35	0.68359375	0.126201923
16	5.67	0.0003	807.7	0.5000	0.0003	5.9167	807.69	0.716826923	0.121153846
17	6.17	0.0003	807.7	0.5000	0.0003	6.4167	807.69	0.777403846	0.121153846
18	6.67	0.0003	807.7	0.5000	0.00025	6.9167	807.69	0.698317308	0.100961538
19	7.17	0.0002	807.7	2.0000	0.0002	8.1667	632.11	2.064882943	0.252842809
20	9.17	0.0002	456.5	2.5000	0.0002	10.417	456.52	2.377717391	0.22826087
21	11.67	0.0002	456.5	2.5000	0.0002	12.917	1278.3	8.255434783	0.639130435
22	14.17	0.0002	2100.0	0.5833	0.0002	14.458	1675	2.825399306	0.195416667
23	14.75	0.0002	1250.0	0.3333	0.0002	14.917	1250	1.243055556	0.083333333
24	15.08	0.0002	1250.0	0.3333	0.00025	15.25	1250	1.588541667	0.104166667
25	15.42	0.0003	1250.0	0.2500	0.0003	15.542	1120.3	1.305829894	0.084021226
26	15.67	0.0003	990.6	0.2500	0.0003	15.792	990.57	1.173201651	0.074292453
27	15.92	0.0003	990.6	0.5000	0.00025	16.167	1370.3	2.769113601	0.171285377
28	16.42	0.0002	1750.0	0.2500	0.0002	16.542	1531.3	1.266471354	0.0765625
29	16.67	0.0002	1312.5	0.2500	0.00025	16.792	1312.5	1.377441406	0.08203125
30	16.92	0.0003	1312.5	0.2500	0.00025	17.042	1312.5	1.397949219	0.08203125
31	17.17	0.0002	1312.5	0.2500	0.0002	17.292	1451.7	1.255119555	0.072585227
32	17.42	0.0002	1590.9	0.2500	0.0002	17.542	1420.5	1.245857008	0.071022727
33	17.67	0.0002	1250.0	0.5000	0.00015	17.917	1250	1.6796875	0.09375
34	18.17	0.0001	1250.0	1.0000	0.00015	18.667	1445.3	4.046875	0.216796875
35	19.17	0.0002	1640.6	0.5000	0.0002	19.417	1640.6	3.185546875	0.1640625
36	19.67	0.0002	1640.6	0.5000	0.00015	19.917	1511.1	2.257208573	0.113332648

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
37	20.17	0.0001	1381.6	1.0000	0.0001	20.667	1215.8	2.512631579	0.121578947
38	21.17	0.0001	1050.0	0.5000	0.0001	21.417	1050	1.124375	0.0525
39	21.67	0.0001	1050.0	0.5000	0.0001	21.917	1050	1.150625	0.0525
40	22.17	0.0001	1050.0	1.0000	0.0001	22.667	1002.3	2.271818182	0.100227273
41	23.17	0.0001	954.5	1.0000	0.0001	23.667	1102.3	2.608712121	0.110227273
42	24.17	0.0001	1250.0	0.7500	0.00005	24.542	1250	1.150390625	0.046875
43	24.92	0.0000	1250.0	0.2500	0	25.042	1250	0	0
44	25.17	0.0000	1250.0	1.0000	0	25.667	937.5	0	0
45	26.17	0.0000	625.0	0.8333	0	26.583	735.89	0	0
46	27.00	0.0000	846.8	9.1667	0	31.583	651.65	0	0
47	36.17	0.0000	456.5	0.5000	0	36.417	317.24	0	0
48	36.67	0.0000	178.0	0.5000	0	36.917	177.97	0	0
49	37.17	0.0000	178.0	1.0000	0	37.667	994.16	0	0
50	38.17	0.0000	1810.3				Σ	58.60449672	4.808091393

Detention Time For Horizontal Flow Bed Using Trapezoidal Rule

Detention Time= 5.60 hrs

No	Time Int. (hrs)	$[Br^-]$ Det. (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]$ bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t * [Br^-] * Q * t$*	*$\Delta t * [Br^-] * Q$*
1	0.00	0.0000	1760.00	0.1667	0	0.083	1760	0	0
2	0.17	0.0000	1760.00	0.5000	0	0.417	2200	0	0
3	0.67	0.0000	2640.00	0.5000	0.0002	0.917	2640	0.242	0.264
4	1.17	0.0004	2640.00	0.5000	0.00055	1.417	2200	0.857083333	0.605
5	1.67	0.0007	1760.00	0.5000	0.00075	1.917	1540	1.106875	0.5775
6	2.17	0.0008	1320.00	0.5000	0.00085	2.417	1540	1.581708334	0.6545
7	2.67	0.0009	1760.00	0.5000	0.00085	2.917	1760	2.181666667	0.748
8	3.17	0.0008	1760.00	0.5000	0.00065	3.417	1634.3	1.814738095	0.531142857
9	3.67	0.0005	1508.57	0.5000	0.00045	3.917	2514.3	2.215714286	0.565714286
10	4.17	0.0004	3520.00	0.5000	0.0005	4.417	2514.3	2.776190476	0.628571429
11	4.67	0.0006	1508.57	0.2500	0.00055	4.792	1508.6	0.993928571	0.207428571
12	4.92	0.0005	1508.57	0.2500	0.00045	5.042	1634.3	0.926946429	0.183857143
13	5.17	0.0004	1760.00	0.2500	0.00045	5.292	1760	1.04775	0.198
14	5.42	0.0005	1760.00	0.2500	0.00045	5.542	2200	1.3715625	0.2475
15	5.67	0.0004	2640.00	0.2500	0.0004	5.792	2640	1.529	0.264
16	5.92	0.0004	2640.00	0.2500	0.00035	6.042	2640	1.395625	0.231
17	6.17	0.0003	2640.00	0.5000	0.0003	6.417	2053.3	1.976333333	0.308
18	6.67	0.0003	1466.67	0.5000	0.0003	6.917	1283.3	1.331458333	0.1925
19	7.17	0.0003	1100.00	0.2500	0.0003	7.292	1100	0.6015625	0.0825
20	7.42	0.0003	1100.00	0.2500	0.00035	7.542	1401.6	0.924918515	0.122641129
21	7.67	0.0004	1703.23	0.5000	0.00035	7.917	1703.2	2.359677419	0.298064516
22	8.17	0.0003	1703.23	0.5000	0.0003	8.417	1676.6	2.11672379	0.251491935
23	8.67	0.0003	1650.00	0.5000	0.00025	8.917	1519.7	1.693873355	0.189967105
24	9.17	0.0002	1389.47	0.5000	0.0002	9.417	1842.6	1.735080092	0.184256293
25	9.67	0.0002	2295.65	0.5000	0.0002	9.917	1861.3	1.845828437	0.18613396
26	10.17	0.0002	1427.03	0.3333	0.0002	10.33	1769.5	1.218998198	0.117967568
27	10.50	0.0002	2112.00	0.4167	0.0002	10.71	1907.6	1.70227957	0.158967742
28	10.92	0.0002	1703.23	0.2500	0.0002	11.04	1703.2	0.940322581	0.08516129
29	11.17	0.0002	1703.23	1.0000	0.0002	11.67	1340.5	3.127837515	0.268100358
30	12.17	0.0002	977.78	1.2500	0.00015	12.79	1075.6	2.579652778	0.201666667
31	13.42	0.0001	1173.33	0.4167	0.0001	13.63	1438.3	0.816523297	0.059928315
32	13.83	0.0001	1703.23	0.8333	0.0001	14.25	1495.5	1.775924469	0.124626279
33	14.67	0.0001	1287.80	1.0000	0.0001	15.17	1069.7	1.622391817	0.106970889

No	Time Int.	[Br⁻] Det.	Q	Δ t	*[Br⁻] bar*	*t bar*	*Q bar*	*Δt * [Br⁻]*Q*t*	*Δt * [Br⁻]*Q*
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)		
34	15.67	0.0001	851.61	1.1667	0.0001	16.25	606.63	1.150066284	0.07077331
35	16.83	0.0001	361.64	0.5833	0.00005	17.13	361.64	0.180633562	0.010547945
36	17.42	0.0000	361.64	0.7500	0.00005	17.79	361.64	0.241284247	0.013561644
37	18.17	0.0001	361.64	0.5000	0.00005	18.42	361.64	0.166506849	0.009041096
38	18.67	0.0000	361.64	0.5000	0	18.92	328.31	0	0
39	19.17	0.0000	294.97	1.0000	0	19.67	294.97	0	0
40	20.17	0.0000	294.97	4.0000	0	22.17	1027.5	0	0
41	24.17	0.0000	1760.00	1.5000	0	24.92	1540	0	0
42	25.67	0.0000	1320.00	0.5000	0	25.92	1320	0	0
43	26.17	0.0000	1320.00	1.0000	0	26.67	1414.3	0	0
44	27.17	0.0000	1508.57				Σ	50.14866563	8.949082327

VII. Residence Time Distribution Calculations

RTD For Vertical Flow Bed Using Trapezoidal Rule

k_r = 5 1/day

k_r = 0.208 1/hour

σ^2_θ = 39.28

Detention Time= 12.64 hrs

R.F= 0.8401

Amount of Chemical Used: 1150 g

Amount of Chemical Recovered: 527.5 g

45.9 %

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]_e$ bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t\ [Br^-]_e Qt$*	*$\Delta t\ [Br^-]_e Q$*	RTD (1/hrs)	σ^2_i	$\frac{Ce}{Co}$	t/T_{det}
1	0.00	0.0000	625.0	0.67	0.00	0.33	625.00	0.00	0.00	0.00	0.00	0.00	0.027
2	0.67	0.0000	625.0	0.50	0.00	0.92	625.00	0.01	0.02	0.01	0.41	0.00	0.075
3	1.17	0.0001	625.0	0.25	0.00	1.29	781.25	0.03	0.02	0.02	0.48	0.00	0.106
4	1.42	0.0001	937.5	0.25	0.00	1.54	937.50	0.05	0.04	0.03	0.83	0.00	0.126
5	1.67	0.0002	937.5	0.25	0.00	1.79	937.50	0.08	0.05	0.04	1.05	0.00	0.147
6	1.92	0.0002	937.5	0.25	0.00	2.04	937.50	0.10	0.05	0.04	1.00	0.00	0.168
7	2.17	0.0002	937.5	0.25	0.00	2.29	937.50	0.13	0.06	0.05	1.19	0.00	0.188
8	2.42	0.0003	937.5	0.25	0.00	2.54	937.50	0.18	0.07	0.06	1.36	0.00	0.209
9	2.67	0.0003	937.5	0.50	0.00	2.92	937.50	0.41	0.14	0.06	2.51	0.00	0.239
10	3.17	0.0003	937.5	0.50	0.00	3.42	946.02	0.48	0.14	0.06	2.27	0.00	0.280
11	3.67	0.0003	954.5	0.50	0.00	3.92	954.55	0.56	0.14	0.06	2.04	0.00	0.321
12	4.17	0.0003	954.5	0.25	0.00	4.29	914.77	0.29	0.07	0.06	0.89	0.00	0.352
13	4.42	0.0003	875.0	0.50	0.00	4.67	875.00	0.82	0.18	0.07	2.06	0.00	0.383
14	4.92	0.0005	875.0	0.25	0.00	5.04	875.00	0.44	0.09	0.07	0.93	0.00	0.414
15	5.17	0.0003	875.0	0.50	0.00	5.42	841.35	0.68	0.13	0.05	1.20	0.00	0.444
16	5.67	0.0003	807.7	0.50	0.00	5.92	807.69	0.72	0.12	0.05	0.99	0.00	0.485
17	6.17	0.0003	807.7	0.50	0.00	6.42	807.69	0.78	0.12	0.05	0.84	0.00	0.526
18	6.67	0.0003	807.7	0.50	0.00	6.92	807.69	0.70	0.10	0.04	0.58	0.00	0.567
19	7.17	0.0002	807.7	2.00	0.00	8.17	632.11	2.06	0.25	0.03	0.85	0.00	0.670
20	9.17	0.0002	456.5	2.50	0.00	10.42	456.52	2.38	0.23	0.02	0.15	0.00	0.855
21	11.67	0.0002	456.5	2.50	0.00	12.92	1278.26	8.26	0.64	0.05	0.07	0.00	1.060
22	14.17	0.0002	2100.0	0.58	0.00	14.46	1675.00	2.83	0.20	0.07	0.21	0.00	1.186
23	14.75	0.0002	1250.0	0.33	0.00	14.92	1250.00	1.24	0.08	0.05	0.13	0.00	1.224
24	15.08	0.0002	1250.0	0.33	0.00	15.25	1250.00	1.59	0.10	0.06	0.20	0.00	1.251
25	15.42	0.0003	1250.0	0.25	0.00	15.54	1120.28	1.31	0.08	0.07	0.20	0.00	1.275
26	15.67	0.0003	990.6	0.25	0.00	15.79	990.57	1.17	0.07	0.06	0.20	0.00	1.296
27	15.92	0.0003	990.6	0.50	0.00	16.17	1370.28	2.77	0.17	0.07	0.56	0.00	1.326
28	16.42	0.0002	1750.0	0.25	0.00	16.54	1531.25	1.27	0.08	0.06	0.30	0.00	1.357

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]_e$ bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t\,[Br^-]_eQt$*	*$\Delta t\,[Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	<u>Ce</u> Co	t/T_{det}
29	16.67	0.0002	1312.5	0.25	0.00	16.79	1312.50	1.38	0.08	0.07	0.36	0.00	1.378
30	16.92	0.0003	1312.5	0.25	0.00	17.04	1312.50	1.40	0.08	0.07	0.40	0.00	1.398
31	17.17	0.0002	1312.5	0.25	0.00	17.29	1451.70	1.26	0.07	0.06	0.39	0.00	1.419
32	17.42	0.0002	1590.9	0.25	0.00	17.54	1420.45	1.25	0.07	0.06	0.42	0.00	1.439
33	17.67	0.0002	1250.0	0.50	0.00	17.92	1250.00	1.68	0.09	0.04	0.64	0.00	1.470
34	18.17	0.0001	1250.0	1.00	0.00	18.67	1445.31	4.05	0.22	0.05	1.89	0.00	1.531
35	19.17	0.0002	1640.6	0.50	0.00	19.42	1640.63	3.19	0.16	0.07	1.78	0.00	1.593
36	19.67	0.0002	1640.6	0.50	0.00	19.92	1511.10	2.26	0.11	0.05	1.41	0.00	1.634
37	20.17	0.0001	1381.6	1.00	0.00	20.67	1215.79	2.51	0.12	0.03	1.82	0.00	1.696
38	21.17	0.0001	1050.0	0.50	0.00	21.42	1050.00	1.12	0.05	0.02	0.93	0.00	1.757
39	21.67	0.0001	1050.0	0.50	0.00	21.92	1050.00	1.15	0.05	0.02	1.03	0.00	1.798
40	22.17	0.0001	1050.0	1.00	0.00	22.67	1002.27	2.27	0.10	0.02	2.29	0.00	1.860
41	23.17	0.0001	954.5	1.00	0.00	23.67	1102.27	2.61	0.11	0.02	3.02	0.00	1.942
42	24.17	0.0001	1250.0	0.75	0.00	24.54	1250.00	1.15	0.05	0.01	1.49	0.00	2.013
43	24.92	0.0000	1250.0	0.25	0.00	25.04	1250.00	0.00	0.00	0.00	0.00	0.00	2.054
44	25.17	0.0000	1250.0	1.00	0.00	25.67	937.50	0.00	0.00	0.00	0.00	0.00	2.106
45	26.17	0.0000	625.0	0.83	0.00	26.58	735.89	0.00	0.00	0.00	0.00	0.00	2.181
46	27.00	0.0000	846.8	9.17	0.00	31.58	651.65	0.00	0.00	0.00	0.00	0.00	2.591
47	36.17	0.0000	456.5	0.50	0.00	36.42	317.24	0.00	0.00	0.00	0.00	0.00	2.988
48	36.67	0.0000	178.0	0.50	0.00	36.92	177.97	0.00	0.00	0.00	0.00	0.00	3.029
49	37.17	0.0000	178.0	1.00	0.00	37.67	994.16	0.00	0.00	0.00	0.00	0.00	3.090
50	38.17	0.0000	1810.3				Σ	58.60	4.81	1.95	41.41	0.01	

RTD For Horizontal Flow Bed

k_r = 40 1/day

k_r = 1.667 1/hour

σ^2_θ = 13.42

Detention Time= 5.6 hrs

R.F= 0.9823

Amount of Chemical Used: 1200 g

Amount of Chemical Recovered: 921.8 g

76.8 %

No	Time (hrs)	$[Br^-]_e$ (mol/l)	Q (L/hrs)	Δ t (hrs)	*$[Br^-]_e$ bar* (mol/l)	*t bar* (hrs)	*Q bar* (L/hrs)	*$\Delta t\ [Br^-]_eQt$*	*$\Delta t\ [Br^-]_eQ$*	RTD (1/hrs)	σ^2_i	Ce/Co	t/T_{det}
1	0.00	0.0000	1760.00	0.17	0.00000	0.08	1760.00	0.00	0.00	0.00	0.00	0.00	0.015
2	0.17	0.0000	1760.00	0.50	0.00000	0.42	2200.00	0.00	0.00	0.00	0.00	0.00	0.074
3	0.67	0.0000	2640.00	0.50	0.00020	0.92	2640.00	0.24	0.26	0.06	0.65	0.01	0.164
4	1.17	0.0004	2640.00	0.50	0.00055	1.42	2200.00	0.86	0.61	0.14	1.19	0.01	0.253
5	1.67	0.0007	1760.00	0.50	0.00075	1.92	1540.00	1.11	0.58	0.13	0.88	0.00	0.342
6	2.17	0.0008	1320.00	0.50	0.00085	2.42	1540.00	1.58	0.65	0.15	0.74	0.00	0.431
7	2.67	0.0009	1760.00	0.50	0.00085	2.92	1760.00	2.18	0.75	0.17	0.60	0.00	0.520
8	3.17	0.0008	1760.00	0.50	0.00065	3.42	1634.29	1.81	0.53	0.12	0.28	0.00	0.610
9	3.67	0.0005	1508.57	0.50	0.00045	3.92	2514.29	2.22	0.57	0.13	0.18	0.00	0.699
10	4.17	0.0004	3520.00	0.50	0.00050	4.42	2514.29	2.78	0.63	0.14	0.10	0.00	0.788
11	4.67	0.0006	1508.57	0.25	0.00055	4.79	1508.57	0.99	0.21	0.09	0.02	0.00	0.855
12	4.92	0.0005	1508.57	0.25	0.00045	5.04	1634.29	0.93	0.18	0.08	0.01	0.00	0.900
13	5.17	0.0004	1760.00	0.25	0.00045	5.29	1760.00	1.05	0.20	0.09	0.00	0.00	0.944
14	5.42	0.0005	1760.00	0.25	0.00045	5.54	2200.00	1.37	0.25	0.11	0.00	0.00	0.989
15	5.67	0.0004	2640.00	0.25	0.00040	5.79	2640.00	1.53	0.26	0.12	0.00	0.00	1.034
16	5.92	0.0004	2640.00	0.25	0.00035	6.04	2640.00	1.40	0.23	0.10	0.00	0.00	1.078
17	6.17	0.0003	2640.00	0.50	0.00030	6.42	2053.33	1.98	0.31	0.07	0.02	0.00	1.145
18	6.67	0.0003	1466.67	0.50	0.00030	6.92	1283.33	1.33	0.19	0.04	0.04	0.00	1.234
19	7.17	0.0003	1100.00	0.25	0.00030	7.29	1100.00	0.60	0.08	0.04	0.03	0.00	1.301
20	7.42	0.0003	1100.00	0.25	0.00035	7.54	1401.61	0.92	0.12	0.05	0.05	0.00	1.346
21	7.67	0.0004	1703.23	0.50	0.00035	7.92	1703.23	2.36	0.30	0.07	0.18	0.00	1.413
22	8.17	0.0003	1703.23	0.50	0.00030	8.42	1676.61	2.12	0.25	0.06	0.22	0.00	1.502
23	8.67	0.0003	1650.00	0.50	0.00025	8.92	1519.74	1.69	0.19	0.04	0.23	0.00	1.591
24	9.17	0.0002	1389.47	0.50	0.00020	9.42	1842.56	1.74	0.18	0.04	0.30	0.00	1.680
25	9.67	0.0002	2295.65	0.50	0.00020	9.92	1861.34	1.85	0.19	0.04	0.39	0.00	1.770
26	10.17	0.0002	1427.03	0.33	0.00020	10.33	1769.51	1.22	0.12	0.04	0.29	0.00	1.844
27	10.50	0.0002	2112.00	0.42	0.00020	10.71	1907.61	1.70	0.16	0.04	0.46	0.00	1.911
28	10.92	0.0002	1703.23	0.25	0.00020	11.04	1703.23	0.94	0.09	0.04	0.28	0.00	1.970
29	11.17	0.0002	1703.23	1.00	0.00020	11.67	1340.50	3.13	0.27	0.03	1.10	0.00	2.082
30	12.17	0.0002	977.78	1.25	0.00015	12.79	1075.56	2.58	0.20	0.02	1.16	0.00	2.283

No	Time	$[Br^-]_e$	Q	Δ t	*$[Br^-]_e$ bar*	*t bar*	*Q bar*	*Δt $[Br^-]_e$Qt*	*Δt $[Br^-]_e$Q*	RTD	σ^2_i	Ce	t/T_{det}
	(hrs)	(mol/l)	(L/hrs)	(hrs)	(mol/l)	(hrs)	(L/hrs)			(1/hrs)		Co	
31	13.42	0.0001	1173.33	0.42	0.00010	13.63	1438.28	0.82	0.06	0.02	0.43	0.00	2.431
32	13.83	0.0001	1703.23	0.83	0.00010	14.25	1495.52	1.78	0.12	0.02	1.04	0.00	2.543
33	14.67	0.0001	1287.80	1.00	0.00010	15.17	1069.71	1.62	0.11	0.01	1.09	0.00	2.707
34	15.67	0.0001	851.61	1.17	0.00010	16.25	606.63	1.15	0.07	0.01	0.90	0.00	2.900
35	16.83	0.0001	361.64	0.58	0.00005	17.13	361.64	0.18	0.01	0.00	0.16	0.00	3.056
36	17.42	0.0000	361.64	0.75	0.00005	17.79	361.64	0.24	0.01	0.00	0.23	0.00	3.175
37	18.17	0.0001	361.64	0.50	0.00005	18.42	361.64	0.17	0.01	0.00	0.17	0.00	3.286
38	18.67	0.0000	361.64	0.50	0.00000	18.92	328.31	0.00	0.00	0.00	0.00	0.00	3.376
39	19.17	0.0000	294.97	1.00	0.00000	19.67	294.97	0.00	0.00	0.00	0.00	0.00	3.510
40	20.17	0.0000	294.97	4.00	0.00000	22.17	1027.49	0.00	0.00	0.00	0.00	0.00	3.956
41	24.17	0.0000	1760.00	1.50	0.00000	24.92	1540.00	0.00	0.00	0.00	0.00	0.00	4.446
42	25.67	0.0000	1320.00	0.50	0.00000	25.92	1320.00	0.00	0.00	0.00	0.00	0.00	4.625
43	26.17	0.0000	1320.00	1.00	0.00000	26.67	1414.29	0.00	0.00	0.00	0.00	0.00	4.759
44	27.17	0.0000	1508.57				Σ	50.15	8.95	2.30	13.4	0.02	

VIII. Simulation of Day Flow and Night Flow for Horizontal Flow Bed

Day Flow For Vertical Flow Bed

8am - 8pm				
t (hrs)	Q (m^3/hrs)	Δt	Q t Δt	t Δt
0.000	1.796	0.45	0.00	0.00
0.450	1.250	0.88	0.50	0.40
1.333	0.991	0.50	0.66	0.67
1.833	1.750	0.67	2.14	1.22
2.500	1.313	0.55	1.80	1.38
3.050	1.591	0.70	3.40	2.14
3.750	1.250	0.67	3.13	2.50
4.417	1.313	0.53	3.09	2.36
4.950	1.641	0.63	5.14	3.13
5.583	1.382	0.83	6.43	4.65
6.417	1.050	0.83	5.61	5.35
7.250	1.050	0.92	6.98	6.65
8.167	0.955	0.97	7.54	7.89
9.133	0.905	0.70	5.79	6.39
9.833	1.250	1.40	17.21	13.77
11.233	0.625	0.77	5.38	8.61
12.000	0.790	Σ	74.79	67.10

Q_{ave} = 1.11 m^3/hrs

Volume = 33 m^3

Detention time = Volume/Q_{ave}
= 29.61 hrs

$$\frac{\overline{C_e}}{C_o} = \exp(-k_r T_{det})$$

k_r = 2.5 1/day
k_r = 0.104 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.045778$$

R.F = 0.954222

k_r (1/day)	0.8	1	1.3	1.5	1.7	2	2.5
R.F (%)	62.7	70.9	79.9	84.3	87.7	91.5	95.4

Night Flow For Vertical Flow Bed

8pm - 8am				
t (hrs)	Q (m^3/hrs)	Δt	Q t Δt	t Δt
0.00	0.79	0.27	0.00	0.00
0.27	0.85	0.92	0.21	0.24
1.18	0.95	1.00	1.13	1.18
2.18	0.88	1.08	2.07	2.37
3.27	0.81	0.73	1.93	2.40
4.00	0.66	1.08	2.84	4.33
5.08	0.46	4.92	11.41	24.99
10.00	0.18	1.00	1.78	10.00
11.00	0.88	0.33	3.21	3.67
11.33	2.63	0.42	12.40	4.72
11.75	2.10	0.25	6.17	2.94
12.00	1.80	Σ	43.14	56.84

Q_{ave} 0.76 **m3/hrs**

Volume = 33 **m^3**

Detention time= Volume/Q_{ave}

= 43.48 hrs

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right)$$

k_r = 2.5 1/day

k_r = 0.104 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.010791$$

R.F = 0.989209

k_r (1/day)	0.8	1	1.3	1.5	1.7	2	2.5
R.F (%)	76.5	83.7	90.5	93.4	95.4	97.3	99.0

Day Flow For Horizontal Flow Bed

8am - 8pm				
t (hrs)	Q (m^3/hrs)	Δt	Q t Δt	t Δt
0.00	1.76	0.42	0.00	0.00
0.42	2.11	0.67	0.59	0.28
1.08	1.32	0.67	0.95	0.72
1.75	1.32	0.33	0.77	0.58
2.08	2.64	0.58	3.21	1.22
2.67	1.51	0.75	3.02	2.00
3.42	2.64	0.25	2.26	0.85
3.67	3.52	0.33	4.30	1.22
4.00	2.64	0.58	6.16	2.33
4.58	1.51	0.50	3.46	2.29
5.08	1.76	0.33	2.98	1.69
5.42	2.64	0.33	4.77	1.81
5.75	2.64	0.60	9.11	3.45
6.35	1.47	0.80	7.45	5.08
7.15	1.10	0.52	4.06	3.69
7.67	1.70	0.53	6.96	4.09
8.20	1.65	0.63	8.57	5.19
8.83	1.39	0.38	4.70	3.39
9.22	2.30	0.62	13.05	5.68
9.83	1.43	0.42	5.85	4.10
10.25	2.11	0.52	11.18	5.30
10.77	1.70	0.90	16.50	9.69
11.67	0.98	0.33	3.80	3.89
12.00	1.15	Σ	123.71	68.55

Day Flow For Horizontal Flow Bed

Q_{ave} = 1.80 m^3/hrs

Volume = 33 m^3

Detention time= Volume/Q_{ave}
= 18.29 hrs

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right)$$

k_r = 2 1/day
k_r = 0.083 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.217873$$

R.F = 0.782127

k_r (1/day)	0.44	0.5	0.65	0.75	0.9	1.2	2
R.F (%)	28.5	31.7	39.1	43.5	49.6	60.0	78.2

Night Flow For Horizontal Flow Bed

8pm - 8am				
t (hrs)	Q (m^3/hrs)	Δt	Q t Δt	t Δt
0.00	1.15	0.33	0.00	0.00
0.33	1.32	0.75	0.33	0.25
1.08	1.17	0.52	0.66	0.56
1.60	1.70	0.68	1.86	1.09
2.28	1.29	0.68	2.01	1.56
2.97	1.29	1.03	3.95	3.07
4.00	0.85	2.43	8.29	9.73
6.43	0.36	2.98	6.94	19.19
9.42	0.29	2.08	5.79	19.62
11.50	0.42	0.50	2.43	5.75
12.00	1.76	Σ	32.25	60.82

Q_{ave} 0.530 **m^3/hrs**

Volume = 10 **m^3**

Detention time=Volume/Q_{ave}

= 18.86 hrs

Volume = 33 **m^3**

Detention time=Volume/Q_{ave}

= 62.23 hrs

$$\frac{\overline{C_e}}{C_o} = \exp\left(-k_r T_{det}\right)$$

k_r = 1.2 1/day

k_r = 0.050 1/hour

$$\frac{\overline{C_e}}{C_o} = 0.044524$$

R.F = 0.955476

k_r (1/day)	0.44	0.5	0.65	0.75	0.9	1.2	2
R.F (%)	68.0	72.7	81.5	85.7	90.3	95.5	99.4

IX. Estimated Theoretical Detention Time

CW for Dhulikhel Hospital Constructed Wetlands System (Sub-Surface)

Design Flow rate:	20	m^3/day
Three chambered settlement tank:	18	m^3

Both beds planted with *Phargmites Karka* (local reeds)

Horizontal System

Given:	Length =	20	m			
	Width =	7	m			
	Area =	140	m^2			
	n=	39%		Kf =	0.03	m/s
	d =	0.6	m			
Assume:	Q=	35	m^3/day			
Estimate t:	t=	0.94	days	t =	22.46	hrs
	q =	2.9	m/day	(In the direction along 7 m)		
	v=	7.5	m/day	(In the direction along 7 m)		

Vertical System

Given:	Length=	11	m	
	Width=	11	m	
	Area =	121	m^2	
	Kf =	0.001	m/s	
	d =	0.9	m	(filled with clean sand)
Assume:	Q=	35	m^3/day	
	n=	0.3		(clean sand ranges from 0.1 to 0.3)
Estimate t:	t=	0.93	days	
	q=	0.29	m/day	
	v=	0.96	m/day	

X. Minimum Amount of NaBr Required

Mass for Tracer

Specifications from vendor:

Concentration range: 1.0 to 5 x 10^{-6}M Br^-

79900 to 0.4 ppm

Calculations:

NaBr (MW)= 103 g/mol

Use equation: **M = C*V**

M= Mass of Tracer
C= Concentration of detection
V= Vol of system

Assume: Using NaBr to set C

Choose C range= 1.00E-04 M (mol/L) Br-

C = 7.99E-03 g/L Br-
7.99 mg/L (ppm) Br-

Horizontal System:

V = Area of wetland*d * n
= 32.76 m^3
= 32760 L

M= 261.75 g Br-

M= 327.19 g

Vertical System:

V = Area of wetland*d * n
= 32.67 m^3
= 32670 L

M= 261.03 g Br-

M = 326.29 g

Total M needed per test= 653.48 g