Performance evaluation of slow sand filters: a probabilistic approach.

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Civil Engineering

June 1997

Abstract

The proposed thesis incorporates a statistical approach to evaluate the performance of slow sand filtration, with an emphasis on removal efficiency of indicator microorganisms. The data for the analysis of removal efficiency have been taken from 15 months study on a slow sand filters. Three pilot scale slow sand filters of 2m diameters were operated under different conditions of controlled parameters namely; filtration rate, sand bed depth and media grain size. The population of and fecal coliforms in the tertiary effluents have been used to calculate the risk involved in violation of effluent stndards promulgated by local regulating agencies. For this purpose different statistical distributions namely; Normal, Longnormal and Weibull distributions were employed. The Longnormal distribution was found to be the most appropriation distribution to fit the microbiological data. The removal efficiency data of microbiological indicators; total coliform, fecal coliform, standard plate counts and coliphages have been fitted on 3 different distributions. In case of removal efficiency the Type III maximum extreme value asymptotic distribution was proved to be the best in comparison to Normal and Lognormal distributions. The K-S test was used for goodness-of-fit of the distributions on 14 conditions of all four microorganisms. The characteristic parameters of the distribution; shape factor and scale factor, were used to calculate the mean and standard deviation of the data. This mean of the distribution have been used to develop the regression models. The regression equations of the removal efficiency were the function of filtration rate, sand bed depth and media grain size only. These equations are capable of predicting removal efficiency of different indicators under given conditions of controlled parameters.

Performance Evaluation of Slow Sand Filters: A Probabilistic Approach

by

Rehan Sadiq

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

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In

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This thesis, written by **Rehan Sadiq** under the direction of his thesis adviser, and approved by his Thesis Committee has been presented to and accepted by the Dean of College of Graduate Studies in partial fulfilment of the requirements of the degree of

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بسم الله الرحمن الرحيم

To My Brother, Haroon

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Praise and thanks be to ***Almighty Allah****, the most Gracious, the most Merciful*, and Peace and Blessings of ***Almighty Allah*** be upon ***His Prophet*** *(SAW)*.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

y	Removal Efficiency (%)
y_{max} or y_m	Max. Value of Removal Efficiency (%)
$y_{med.} = y_{0.5}$	Median Value of Removal Efficiency (%)
$y_{mean} = \mu_y$	Mean Value of Removal Efficiency (%)
m	Shape Factor for Type III or Weibull Distribution
θ	Scale Factor for Type III or Weibull Distribution
P	Probability of Desired Level
x	No. of Effluent FC or TC /100ml
x_O	Median Value of Effluent FC or TC /100ml
s	Lognormal Scatter Factor
R	Risk of Violation of Standards
N	Total No. of Data points
F	F-Statistics
F	Cumulative Distribution Function
σ	Standard Deviation
Γ	Gamma Function
d	Depth of Sand Bed (cm)
c	Sand Grain Size (mm)
q	Flow Rate (L/min), Filtration Rate (m/hr)
ϕ^{-1}	Transformation Factor (NORMSINV)

THESIS ABSTRACT

NAME OF STUDENT	Rehan Sadiq
TITLE OF STUDY	Performance Evaluation of Slow Sand Filters : A Probabilistic Approach
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The proposed thesis incorporates a statistical approach to evaluate the performance of slow sand filtration, with an emphasis on removal efficiency of indicator microorganisms. The data for the analysis of removal efficiency have been taken from 15 months study on slow sand filters. Three pilot scale slow sand filters of 2m diameters were operated under different conditions of controlled parameters namely; filtration rate, sand bed depth and media grain size. The population of total and fecal coliforms in the tertiary effluents have been used to calculate the risk involved in violation of effluent standards promulgated by local regulating agencies. For this purpose different statistical distributions namely; Normal, Lognormal and Weibull distributions were employed. The Lognormal distribution was found to be the most appropriate distribution to fit the microbiological data. The removal efficiency data of microbiological indicators; total coliform, fecal coliform, standard plate counts and coliphages have been fitted on 3 different distributions. In case of removal efficiency the Type III maximum extreme value asymptotic distribution was proved to be the best in comparison to Normal and Lognormal distributions. The K-S test was used for goodness-of-fit of the distributions on 14 conditions of all four microorganisms. The characteristic parameters of the distribution; shape factor and scale factor, were used to calculate the mean and standard deviation of the data. This mean of the distribution have been used to develop the regression models. The regression equations of the removal efficiency were the function of filtration rate, sand bed depth and media grain size only. These equations are capable of predicting removal efficiency of different indicators under given conditions of controlled parameters.

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خلاصة الرسالة

اسم الطالب: ريحان صادق

عنوان الدراسة: تقويم أداء المرشحات الرملية البطيئة (دراسة احتمالية)

التخصص: هندسة مدنية (مصادر مياه وهندسة بيئية)

تاريخ الدرجة: يونيو ١٩٩٧م

في هذه الأطروحة تمت دراسة وتقويم أداء المرشحات الرملية البطيئة بطريقة إحصائية مع التركيز على فعالية إزالة الميكروبات وذلك من خلال تحليل المعلومات المتوفرة الناتجة عن بحث ميداني سابق، استغرق مدة (١٥) شهراً، استخدمت فيه ثلاث وحدات تجريبية من المرشحات الرملية البطيئة قطر كل وحدة (٢) متر، وقد تمت التجربة تحت الظروف المتغيرة التالية: سرعة الترشيح، وعمق طبقة الترشيح، وحجم الحبيبات الرملية.

وبناء على نتائج التجربة المذكورة فقد تم استخدام المعلومات المتوفرة عن الكوليفورم الإجمالي والمكور العقدي الغائطي لحساب الخطر الناتج عن مخالفة هذه الميكروبات للمقاييس الموضوعة من قبل الهيئات المحلية. وبعد تحليل المعلومات المتوفرة عن الميكروبات لإيجاد التوزيع الإحصائي الأمثل [توزيع قياسي (أوغاسي) توزيع لوغارثمي وتوزيع ويبل] وجد أن التوزيع اللوغارثمي هو الأنسب من بين التوزيعات المدروسة لتمثيل المعلومات الميكروبية ومن خلال تحليل البيانات المتعلقة بمؤشرات وجود الميكروبات وجد أن التوزيع من طراز III الأقصى هو الأفضل لتمثيل كفاءة الإزالة المبنى على هذه المؤشرات مقارنة بالتوزيعات الأخرى (التوزيع القياسي واللوغارثمي) وأثبت ذلك من خلال اختبار K-S الإحصائي.

وباستخدام المُعَاملات المُميزة للتوزيع الأفضل (عامل المظهر وعامل القياس) تم حساب المعدل والانحراف المعياري للمعلومات ومن ثم تم تطوير نموذج رياضي لحساب كفاءة إزالة الميكروبات مبني على سرعة الترشيح إضافة إلى عمق طبقة الترشيح وحجم الحبيبات الرملية.

إن المعادلات المطورة في هذه الدراسة قادرة على مساعدة الباحث على التنبؤ بكفاءة إزالة الميكروبات من خلال مؤشراتها تحت أي ظروف مختلفة.

درجة الماجستير

جامعة الملك فهد للبترول والمعادن

الظهران – المملكة العربية السعودية

يونيو ١٩٩٧م

1. INTRODUCTION

Scarcity of water in arid region like Saudi Arabia, emphasizes the need of reuse of wastewater for agriculture and recharge of ground water. To meet the standards promulgated by national agencies, secondary wastewater effluents are required further treatment before their beneficial uses. Major concern in wastewater reuse are related to health aspects. Although properly operated biological wastewater treatment plants employing chlorination as a final treatment can reduce pathogens by many log scales but it is still not possible to eliminate pathogens completely from the wastewater.

In recognition to the importance of conserving water sources, the Kingdom has planned in its third five year development plan to recycle 730 million m^3 by the year 2000 [Khan, 1996]. To remove the microorganism pathogens from the secondary wastewater effluents slow sand filtration technique is being used in many developed countries. Recent research has documented the suitability of secondary effluents to tertiary treatment by slow sand filters. The slow sand filters are operated at low filtration rates and the general range for the filter operation is 2-5 $m^3/m^2/d$ although exceptions of higher and lower rates are documented.

Previous studies of slow sand filters at laboratory and pilot scale reveal this technique as effective and reliable way of removing microbiological pollutants from secondary effluents. The available equations and models for filtration in water treatment are used for the removal efficiency of the filters in wastewater filtration also. Much data and information are not available in the literature for the slow sand filters as wastewater treatment unit.

Operation of filters and their efficiency always depends on the proper control of filter's variables. In this research the adopted approach is towards optimizing the controlling factors and variables which could maximize the removal efficiency. In the following study removal efficiency of different pollutants under different operating conditions of filtration rate, filter media size and filter sand bed depth, is observed.

One of the main objectives of this study is to assess the possible risk involved in using the tertiary effluent of slow sand filter for beneficial uses. For this purpose statistical distributions like Normal, Lognormal and Weibull distributions are fitted to the tertiary effluent data of total coliform and fecal coliform concentrations. The most suitable distribution will be employed to model the results.

Filtration is a complex mechanism and it depends on many variables, out of which some are very important and do play a significant role in removing pollutants. In this study the above described variables are taken to develop a statistical model based on the weekly sampling data. The filters have been

operated at varying control conditions of sand bed depth, filtration rate and sand grain size. These different conditions helped in developing regression equations for total coliform, fecal coliform, standard plate counts and coliphage. These design variables are considered as controlling factors for better performance and the operation of the filter. The performance of the filter is measured by the pollutant's removal through the filter. The main goal of this thesis is to study the removal efficiency of indicator microorganisms under different control variable conditions. To develop this model the removal efficiency data will be fitted on the on Normal, Lognormal and Type III maximum extreme value asymptotic distribution. The most suitable distribution will be selected by using Kolomogorov-Smirnov goodness-of-fit test. The characteristic parameters of the selected distributions will be used to calculate the mean response of the removal efficiency of microorganism indicators. These mean values are used to develop the regression model of removal efficiency as the function of sand bed depth, filtration rate and sand grain size. To verify these models, the results are compared with the data available in the literature.

2. OBJECTIVES

The main objective of this study is to evaluate removal efficiency of the slow sand filter as tertiary treatment unit for secondary effluents based on statistical analysis.

The specific objectives of this research can be summarized as given below:

1. To assess the possible risk involved in using treated effluent from slow sand filters for beneficial purposes by modeling effluent concentrations of *total coliforms* and *fecal coliforms* using appropriate statistical distribution.

2. To fit the removal efficiency data for four indicator microorganisms, i.e., *total coliform, fecal coliform, standard plate counts* and *coliphages* using suitable statistical distributions for different conditions of sand bed depth, filtration rate and sand grain size.

3. To develop a regression model for *total coliform, fecal coliform, standard plate counts* and *coliphage* from the mean values of fitted distribution under different conditions of filter sand bed depth, filtration rate, and filter media grain size.

4. To study the effects of control variables on the removal efficiency of the filters for the four indicator microorganisms using the developed regression models.

5. To compare the results of developed models with the results available in the literature.

3. LITERATURE REVIEW

The literature survey comprehensively covers the following major topics including slow sand filters and their performance, reuse standards and risk analysis, statistical distributions and their selection, and regression analysis.

3.1 Slow Sand Filters

Slow sand filtration units are conventionally used for drinking water treatment. Its early application dates back as start of last century [Russel, 1983]. The excellent performance of slow sand filters in removal of microorganism contaminants from public supplies is documented in the literature. Poynter and Slade [1977] observed *polio virus 1* and *coliform* removals over 99.9% and Bellamy *et al.* [1985a] report *giardia cyst* and *coliform* removals of 99.98% and 99.01% respectively.

Published research work regarding application of slow sand filtration for treatment of wastewater effluents is very limited [Borrego *et al.*,1986; Cabelli *et al.*, 1982]. Earlier work [Cleasby,1984a; Collins,1991] on this subject revealed BOD and suspended solids removal of 60-65% and *coliform bacteria* removal of 95% from the settled effluents of an operational trickling filter plant. Almost same

results were observed when secondary effluent from an activated sludge plant was used.

Slow sand filtration is a unique treatment process which requires little attention for operation. Slow sand filters operate at lower hydraulic loading rates as it is obvious from its name. The filtration rates in the rapid sand filters are 20-150 times higher than those of slow sand filters [Russel, 1983]. Hence to cope with the higher volume of waters, the land area requirements of slow sand filters are much larger than the rapid sand filters. Slow sand filters leads to drastically different filtration behavior than at higher filtration rates. During regular operation of slow sand filters biological growth occurs within filtration bed. A layer of solid deposits and biological material forms on the surface of the bed. This layer is referred to as "***Schumutzedecke***", a German word meaning "dirt layer". Both *schumutzedecke* and the biological growth within the bed play an important role in the performance of slow sand filters. They may requires several weeks to develop, a period referred to as "Ripening Period" of the filter. Many types of predatory organisms (such as protozoa) are usually present in the upper parts of the filter.

As the filtration progresses, head losses due to clogging builds up in the bed. When the head loss reaches the maximum allowable limit, the filters need cleaning. The cleaning process of slow sand filter is different from that of rapid sand filters. The cleaning process for the rapid sand filters is back-washing of the filter bed in the reverse direction, whereas, in the slow sand filters the cleaning

involves the scrapping of 2-4 cm of biological layer after each run. Hence, a gradual decrease in the depth of sand takes place. The frequency of cleaning depends mainly on the influent characteristics and the rate of filtration. The filter run can extend to several months. In single media filters, the back-washing of rapid sand filters result in the natural gradation of sand with smaller grain in the upper part of filter bed. As a result the upper part of the filter clogs more easily and head losses reach to allowable limit before an effective use of the whole sand bed is exploited. In slow sand filters, however, there is no such adverse stratification because there is no such back-washing. The operational requirements of slow sand filters covers; removal of the biological layer and re-sanding of bed.

The slow sand filters are generally criticized for their larger area requirements and unsuitability for highly turbid waters. Inspite of these handicaps, the slow sand filters are popular water treatment units. In Saudi Arabia larger land area requirements is not an important issue and turbidity of secondary effluents is quite low. Added to the above mentioned conditions the slow sand filters have following advantages:

1. Stable and effective suspended solids and microorganism removal
2. Low cost of construction
3. Simplicity in the design
4. Minimal operational problems and skilled labor requirements

In view of the above discussion and within the frame work of the need and keen interest dedicated to conservation of water in Kingdom, slow sand filters are most suitable technology for wastewater treatment.

3.1.1 Microorganisms

Many studies have been directed towards the survival of enteric viruses in sewage during and after wastewater treatment processes. Disease causing enteric viruses are present in the domestic wastewater. Enteric viruses are of very small size so they have the potential of passing through small pores of soil causing groundwater contamination. Detection of levels of *bacteriophage* in water and wastewater is sensitive, convenient, economical and reliable. *Coliphages* have been used as an indicator of enteric viruses by many investigators.

Coliforms are considered as the indicator organisms of bacterial and viral pollution by many scientists. The indicator organisms, most often used, is a group of organisms which are normally present in the digestive system of warm blooded animals. It is observed that the *coliforms* are plentiful, hence not difficult to detect. They are found to live longer than most known pathogens. That is why *coliforms* are the most universal indicator organisms of wastewater pollution. Recent American epidemiological investigation [Dufours,1982; Edward *et al.,*

1988] proved that there is a correlation of health risk and fecal bacterial indicator organisms such as *Escherichia coli* and *enterococci*.

The *standard plate counts* provide a single standardized mean of determining the density of aerobic and facultative anaerobic heterotrophic bacteria in water. The EPA's primary drinking water standard specify that public water supplies provide a potable water with not greater than 500 organisms per ml as determined by *standard plate count*.

It is experimentally proved that there are some microorganisms which can serve as the indicators of various pathogens. Over many years *E.coli* and *fecal streptococci* were used as the indicators for viral pollution. However, there have been some cases when epidemics were broken out even when these bacteria were not present. In 1974, some studies suggested that *coliphages* might serve as indicators of fecal pollution. Borrego *et al.* [1986] developed a numerical relationship between *E.coli* and its parasitic phages . The results of the study indicated that *coliphages* are good indicators of the presence of pathogenic microorganisms. Ratto *et al.* [1988] conducted a study in Peru in which 20 samples were analyzed for *coliphage* content from five different sources. It was found that in 50% of the samples the *coliphages* were the only indicator organisms.

3.1.2 Microorganism Removal Through Filtration

Work conducted by Robeck *et al.* [1962] confirmed the ability of slow sand filters to reduce the *poliovirus-1* by 83-98% and lower flow rates were found to provide greater efficiencies of poliovirus removal. Detailed work was done by Poynter and Slade [1977] using 0.99 m^2 (area of cross-section) sand column at a flow rate of 0.2-0.5 m/hr. The results revealed that 98.25-99.99% removal of *poliovirus-1*, more than 88% removal of *E-coli* and 81-98.3% removal of *plate counts* were obtained. Cleasby *et al.* [1984] investigated three parameters of filtrate quality namely turbidity, particle counts, and *total coliform counts*. Results indicated that removal efficiency improved with the addition of coagulant prior to filtration. Bellamy *et al.* [1985b] investigated the effects of filter biological aging, *schmutzedecke* development and hydraulic loading rate. The percentage removal of total coliform bacteria evaluated the effectiveness of filter's response to test conditions. Percent removal of coliforms were maximum (97.6-99.96%) when the filter was mature. The efficiency decreased considerably when the biological layer was removed. It was observed that the bacterial removal was not very sensitive with the sand bed depth i.e. the depth reduction from 1 to 0.5m did not cause any significant decrease in the bacterial removal. It was also observed that the sand grain size reduction increased the removal efficiency of *coliforms*.

A pilot study conducted by Farooq *et al.* [1993] over a period of one year using secondary effluent of wastewater treatment plant with infiltration rate of 0.16 m/hr revealed plate counts reduction of 90 to 91.5 %.

3.1.3 Removal Of Turbidity & Organic Matter

Turbidity is the most important parameter for studying the performance of a filter. It is proved that turbidity carries nutrients that result in biological activity. Suhail [1987] reported 77-92% turbidity removal in rapid sand filters. Al-Sawaf [1986] investigated the treatability of secondary effluents using direct filtration with some chemical mixing. He reported that the average removal of turbidity was 75-90% in case of chemical addition, whereas the removal was 28-39% when chemicals were not added.

Farooq *et al.* [1993] have reported the removal of turbidity from slow sand filters ranged from 87 to 95% for secondary effluents. They also recommended that larger depths of sand bed will result in high removal efficiency. Al-Adham [1989] reported the turbidity removal of 88% for effective sand size of 0.23 mm and sand depth of 84 cm. Cleasby *et al.*[1984] reported that average turbidity removal for 0.94 mm sand depth in the early two days of run produced water with the turbidity of well below 1 NTU and the turbidity of the effluent in the last days of the run reduced to 0.1 NTU. But in the study he concluded the turbidity removal alone was not enough to judge the performance of filters.

In wastewater the impurities are found in form of dissolved matter, and sand filtration is quite efficient in the removal of organics from the water. Andredakis [1982] conducted a study for the removal of organic matter with upflow gravel filter, sand filter and soil column. He observed that in upflow gravel filter BOD5 removal was 24 to 69%. The suspended solid removal varied from 23 to 49% with an average value of 39%. Andredakis concluded that the removal efficiency did not depend on the hydraulic loading (flow per unit area of filter) and sewage strength.

Ellis [1980] reported that suspended solid (SS) removal of 60-70% and BOD5 removal of 50-60% can be achieved when the experiment was run on the grass plot. In an other study conducted by Ellis [1984] in which he treated secondary effluent with slow sand filter at the rate of 3.5 m/d and 7 m/d. Here he recommended that slow sand filter was able to remove 88% SS, 70% BOD5, 50% COD and 97% of *total coliforms*. He also observed that the removal rate of BOD5, COD and suspended solids dropped when the filtration rate was doubled but the removal rate of coliforms improved from 97 to 99%.

Al-Adham [1989] used slow sand filtration as a tertiary treatment of the municipal sewage and found out that at the hydraulic loading of 0.16 m/h, a removal of 89% of BOD5, 69% of SS, 88% of turbidity and 99% of *total coliform bacteria* ware achieved. Farooq *et al.* [1993] conducted a pilot study using slow sand filtration with effective sand sizes of 0.31 mm and 0.56 mm and found that by using fine sand better percentage removal of organic matter was achieved.

The percentage removal of BOD was 79-92% and for COD the percentage removal varied from 50 to 67%.

3.1.4 Filter Performance and Control Variables

Bellamy *et al.* [1985a] conducted a pilot plant studies to determine the efficiency of slow sand filters in removing *giardia cyst*. They reported that *giardia cyst* removal exceeded 98% for all operating conditions tested. *coliform* removal exceeded 99% averaged over all operating conditions. Removal of *standard plate count bacteria* ranged from 88 to 91%. Bellamy *et al.* [1985b] performed another research to determine the influences of selected process variables on the treatment efficiency of slow sand filtration. Their findings are summarized below:

- ***Temperature:*** The slow sand filters removal efficiency decreased with declining the ambient temperature in terms of *coliforms* and *standard plate count bacteria*.
- ***Sand Bed Depth:*** There is no significant effect in effluent water quality permeating through the sand bed up to a depth of 48 cm.
- ***Sand Size:*** No significant decrease in removal efficiency was observed with the increase in the effective grain size.

• ***Hydraulic Loading Rate:*** In general, there was an apparent decrease in the removal efficiency of *total coliforms*, *standard plate counts* and turbidity with an increase in hydraulic loading.

• ***Filter Medium:*** The filter bed may employ any inert, granular material as a filtration medium. and used in slow sand filtration should be relatively fine with an effective size of 0.15- 0.30 mm and a uniformity coefficient below 3. Filter media of larger size increases the potential for particle breakthroughs and allows deposits to be driven deeper into the filter, thereby increasing the amount of medium to be scrapped.

In this research the effect of sand bed depth, filtration rate and sand grain size are studied.

3.1.5 Mechanisms of Removal

The purification achieved in slow sand filter may be considered to be principally the result of straining through the developed filter skin and the top layer of sand. However, Huisman [1974, 1978] suggested mechanical straining, sedimentation, adsorption, and chemical and biological activity as the important processes of slow sand filtration [Ellis, 1985].

3.1.5.1 Sedimentation and Straining

Sedimentation and straining take place usually during the first few days of operation. The average time the water remains above the sand bed ranges from 3 to 12 hours depending on the filtration rate. Heavier particles of suspended matter will start to settle, while lighter particles will be drawn through the pores of the sand grains and are removed by straining on the top layer. During the filtration process the inert deposits and biological growth form a layer on the sand bed. This layer as mentioned earlier is referred to as the *schmutzedecke* layer. Biological growth also occurs within the sand bed and gravel support. Both *schmutzedecke* layer and biological growth have significant effect on the purification mechanism.

3.1.5.2 Chemical and Bacteriological

On the surface of the sand the thin *schmutzedecke* layer consists of thread like algae and other forms of life including *diatoms, rotifers, protozoa, fungi, bacteria,* and *actinomycetes*. When the water passes through this layer, all suspended matter and bacteria are removed. These impurities stick to the *schmutzedecke* layer and are subsequently broken down by biochemical action. The bacteria caught up in the *schmutzedecke* layer have not enough food and slowly start dying and may be eaten by protozoa. Accordingly, some of the living organisms feeding upon bacteria are also affected. As a result, some additional organic

matter is also available from dead organisms as a feed for bacteria at lower depth of sand. This feed is depleted at lower depths. In other words, the original degradable organic matter present is gradually broken down and discharged with effluent as inorganic compounds such as nitrates, sulfates and phosphates [Farooq *et al.*, 1993].

3.2 Reuse Standards

The objective of tertiary level treatment is to reduce the health risks associated with the wastewater and its potential for reuse the water for irrigation or recharge of ground water. The study conducted by Shuval *et al.* [1986] concluded that wastewater treatment processes which effectively removed all or most of the pathogens in wastewater provide a major or total reduction in the negative health effects caused by raw sewage reuse. Furthermore the study found the recommended criteria for effective wastewater treatment for irrigation reuse in developing countries to be, in order of priority: (1) maximum removal of helminths; (2) effective reduction of bacterial and viral pathogens; and (3) freedom from odor and appearance nuisances (i.e. effective reduction of BOD, but not necessarily nutrients). Although health risks are clearly associated with the use of raw wastewater in agriculture, the epidemiological evidence compiled in the study suggested that the bacterial standards commonly used today are strict for most situations (and for most developing countries they are unaffordable

and unachievable) while, at the same time, they disregard the risk of parasitic infections prevalent in tropical areas [Bartone, 1990].

The study suggested a guideline for restricted wastewater irrigation based on an effluent with less than one *nematode egg* (Ascaris, Trichuris or Hookworm) per liter and a geometric mean *fecal coliform* concentration of 1000 per 100ml (median value for Lognormal distribution). For restricted irrigation such as forest trees, industrial crops, fodder crops, fruit trees and pastures, less than one nematode egg per liter is recommended as guideline. These recommended guidelines were closely studied by WHO, UNDP and FAO, in addition to UNDP and the world bank, and were initially endorsed by a group of experts at a meeting convened in Engelberg, Switzerland [IRCWD, 1985]. They were again examined by successive expert group meetings in Adelboden and Geneva in 1987, and were formally published by WHO (1989) as recognized international guidelines [Bartone, 1990]. The guidelines for *helminth egg* are intended to be a design standard, not a standard requiring routine testing of the effluent [Crook ,1991].

A number of technical and policy options for reducing and controlling the health risks associated with wastewater reuse in agriculture were also evaluated by the UNDP/World Bank study [Shuval *et al.*, 1987a,b, Katzenelson, 1976]. The following measures were found to be most effective for reducing possible risks: (1) wastewater treatment and storage practices aimed at effectively reducing the concentration of the priority pathogens to low levels (e.g. the WHO guidelines);

(2) restrictions on the type of crops irrigated so as to prevent consumers from being exposed directly to vegetable or salad crops eaten raw; (3) modifications of irrigation techniques and procedures so as to prevent or minimize direct contact between wastewater and crops; and (4) human exposure control for farm workers, crop handlers, consumers and those living near reuse sites. An integrated set of such measures should be adopted for any reuse project to provide maximum security (WHO,1989).

3.2.1 U.S. and Other International Standards

There are no federal standards governing wastewater reuse in the USA , although the US Environmental Protection Agency published wastewater reuse guidelines in 1980 [EPA, 1980]. The guidelines are currently being updated and expanded. Regulations that do exist have been developed at the state level.

The state of California has a long history of wastewater reuse and developed the first reuse regulations in 1918 , which have been modified and expanded through the years. The state's current Wastewater Reclamation Criteria (State of California, 1978) were adopted in 1978 and have served as the basis for reuse standards in other states and countries. The reclamation criteria include water quality standards, treatment process requirements, operational requirements, and treatment reliability requirements [Crook,1991].

At the time the regulations were developed, the California Department of Health Services concluded that epidemiological studies of the exposed population at water reuse sites would be of limited value, and that it was not possible to ascribe numerical risk estimates to reclaimed water with any degree of confidence. Thus, the reclamation criteria were based on the capability of well designed and operated wastewater treatment plants to consistently attain specific effluent quality limits, experience at existing wastewater disposal and reuse operations, evaluation of pertinent research studies and health related data, and the desire not to allow unreasonable risks due to the use of reclaimed water [Crook, 1991]. This full treatment process is often referred to as the "Title 22 Process" erroneously, because Title 22 of the California Code of Regulation contains many other unrelated regulations [Asano *et al.*, 1992].

According to standards, the required degree of treatment and micro biological quality increase as the likelihood of human exposure to the reclaimed water increases. If intimate direct contact with the reclaimed water is expected, such as swimming, or indirect contact is likely, such as consuming produce spray irrigated with reclaimed water, the regulations specify treatment and water quality requirements intended to produce an effluent that is essentially free of pathogens, including viruses. Since low levels of viruses can initiate infection a fundamental decision was made to reduce *enteroviruses* below detection limits. Controlling *enterovirus* would produce reclaimed water free from any human pathogen and thus be safe for their intended use [Crook, 1985].

Selection of the treatment chain specified in the Wastewater Reclamation Criteria to produce an essentially pathogen free effluent, i.e. oxidation, chemical coagulation, clarification, filtration, and disinfection to a coliform level not exceeding 2.2 MPN/100ml, was predicated on studies conducted several years ago to determine the virus removal capacity of advanced wastewater treatment processes [Crook, 1991]. More recent studies [County Sanitation Districts of Los Angeles County, 1977; Engineering Science, 1987] indicated that equivalent virus removal can be achieved by direct filtration of high quality secondary effluent, using low coagulant and/or polymer dosages. This abbreviated treatment chain, in conjunction with specific design and operational controls has been judged to be equivalent to the full treatment chain specified in the regulations [Crook, 1991].

Wastewater Regulations adopted by the state of Arizona contain enteric virus limits; for example, wastewater is not to exceed 1 plague forming unit (PFU) per 40 L for applications such as spray irrigation of food crops [Metcalf & Eddy, 1991].

The state of Florida requires no detectable fecal coliform per 100ml. This level of disinfection is achieved by requiring tertiary filtration and by maintaining a 1.0 mg/l total chlorine residual after a contact time of 30 minutes at average daily flow [Metcalf & Eddy, 1991].

In Jordan the reuse of wastewater is a common practice. The only legislation in use until September 1989 was Martial Law No.2 which issued in

1982. It defined and recommended wastewater reuse for different types of crops but irrigation of cereals and vegetables was not allowed [Al Salem , 1989]. In September 1989, a new version of the Martial Law was issued because of the following reasons:

(a) New version related the types of crops to be irrigated, with the quality of effluent to be used in irrigation.

(b) It allowed irrigation of cereals and vegetables eaten cooked under certain conditions.

(c) It allowed the use of exposed water (exposed to contamination) in irrigation except on vegetables eaten raw and greenery in sports fields and public parks [Gur and Al-Salem ,1992].

However, some disadvantages of the 1989 Martial Law are as follows:

(a) Specification of the number of samples to be tested in a month is not a useful criterion as two grab samples do not represent the quality of water during a whole month. Instead, it is preferable to specify a sampling program which will disclose the real quality of water tested.

(b) The Martial law did not allow irrigation of crops eaten uncooked by any type of effluent, regardless of its microbiological quality whereas it allows the irrigation of sports fields and public parks with an effluent that will have more or less, the same potential risk as crops eaten uncooked.

(c) The Martial law did not even allow localized irrigation of industrial crops and trees by raw wastewater. This means that wastewater treatment is a must [Gur and Al-Salem ,1992].

3.2.2 Water Reuse Legislation in Kingdom of Saudi Arabia

The less availability of fresh water in middle region emphasize the need of reuse of wastewater. Not only in Saudi Arabia rather other countries around it, like Jordan, recycling their wastewater and are also maintaining there own reuse standards.

Where as in Saudi Arabia the Ministry of Agriculture and Water has promulgated draft standards for Maximum Contaminant levels in wastewater being reused for restricted and unrestricted irrigation. The standards allow an average *fecal coliform* count (in the last 7 samples) of 2.2MPN/100ml for unrestricted irrigation and an average *fecal coliform* count (in the last 7 samples) of 23 MPN/100ml for restricted irrigation. The maximum *fecal coliform* count allowed in any one sample is 100 MPN/100ml for unrestricted irrigation and 200 MPN/100ml for restricted irrigation. For both restricted and unrestricted irrigation the MLC *intestinal nematode* count is 1.0 per litter.

Wastewater direct from secondary treatment plants is permitted to be used for irrigation under controlled conditions. The area using such wastewater should have signs indicating the use of the polluted water and access to the area

must be controlled. The acceptable crops to be grown with the wastewater are legumes, forages and field crops or vegetables that are mechanically processed. The forage crops are not to be grazed for 24 hour period following irrigation and no vegetables are to be eaten raw. For crops to be eaten raw and for fish culturing the secondary treated effluent has to be subjected to additional treatment involving all or most of the following methods; sand filtration, disinfection, carbon adsorption, denitrification and phosphate removal.

Clearly the standards adopted by the, Ministry of Agriculture and Water (MAW) are modeled on the California Wastewater Reclamation Criteria. Looking at the precautions advocated it is also clear that the Ministry of Agriculture and Water have also incorporated a number of technical and policy options (similar to the ones evaluated by the UNDP/World Bank study) for reducing and controlling the health risks associated with wastewater reuse in agriculture.

The National Wastewater Regulations put forward by the Meteorological and Environmental Protection Administration (Saudi Arabia) [MEPA, unpublished] have set a maximum contaminant level of 200 MPN/100ml for *fecal coliform* for unrestricted irrigation.

ARAMCO too has done considerable work in the field of characterizing the various uses of water and developing water quality criteria for various uses [ARAMCO, 1980].

3.3 Risk Assessment

The literary definition of "Risk" is the probability of danger or hazard. Risk of producing harmful consequences is always associated with the environmental decision. Risk involves both the frequency of undesirable event and the severity of consequences. Engineering risk analysis is used to estimate the frequency and physical consequences of undesirable events which can produce harm [Ricci *et al.*, 1981].

In engineering risk analyses, various techniques are used to calculate the frequencies and consequences of events .These techniques include

1. Statistical analysis of past events having similar consequences.
2. Extrapolation techniques which extrapolate the past occurrences of less severe events.
3. Event tree techniques which can connect basic events to form accidental consequences.
4. Fault tree techniques which decompose the event on to basic causes.

Risk assessment by statistical analysis has been especially useful for setting standards for contaminants in water which will achieve acceptable safety levels of risk for the population, similarly in this research risk of violating standards is the primary goal of this study.

Haas *et al.* [1983] evaluated three probability models for their ability to describe infection by low level exposure to enteric pathogens in drinking waters.

The results of human exposure studies of variety of bacteria, viruses and protozoa were evaluated in dose-response fashion with the development of best fit curve defining the data set. According to Haas *et al.* [1983] the beta distribution probability model was the most appropriate for the investigated data sets, however an exponential model was used for *giardia* [Rose *et al* ,1988 and 1991].

There is a level of risk involved due to presence of *total coliforms* and *fecal coliforms* in the treated tertiary effluent based on the MEPA and MAW standards. Generally probabilistic concepts are used to estimate the risk. The quantity defining the risk is treated as a random variable and its probability distribution defines the probability of the event that this random variable is below certain value. If this value is a predefined "Target" then violation of this target is unacceptable risk, whereas having a value less than the target (which usually based on the standards) is an acceptable risk. [Lewis, 1978].

3.4 Filtration Removal Efficiency Models

Several mathematical filtration models have been proposed during the last 30 years. Most of these models were originally developed to describe aerosol removal by fibrous filter and later applied to aquasols.

In filtration process mechanism, traditionally, macroscopic and microscopic theories are widely accepted. In the macroscopic approach the first

order kinetics in the removal of particulate is assumed, whereas, the microscopic approach takes into account the single collector efficiency. Filtration equations describing the deep bed filtration of aquasols were originally proposed by Yao *et al.* (1971). Single collector efficiency of Yao model are based on spherical collectors, and are

$$\eta_d = 4\left(\frac{U_o d_c}{D}\right)^{-2/3} \tag{3.1}$$

$$\eta_I = \frac{1}{2}\left(\frac{d_P}{d_C}\right)^2 \tag{3.2}$$

$$\eta_G = \left(\frac{U_P}{U_o}\right) \tag{3.3}$$

where

U_O= Filter superficial velocity

U_P= Filter settling velocity

D= The particle diffusivity

d_p= diameter particulate to be removed

d_c= diameter of collector

The single collector efficiency is the sum of η_D (diffusion), η_I (interception) and η_G (gravity). Similarly there are many other models available in the literature which give the relation for single collector efficiency, like Hind's model [1983], Rubow and Liu model [1986], Tien and Paytakes [1976] and Fuch's model

[1964]. These models requires detailed data of filter media characteristic, type of flow and liquid characteristic and types of particles to be removed for computing the filter removal efficiency. During this research the data were generated from the pilot plant in the field and all necessary data required to use above equations were not collected. So there is a need of developing a simple model of removal efficiency as function of very few controllable variables like sand bed depth, sand grain size and filtration rate.

4. METHODOLOGY

Before discussing the risk assessment and the removal efficiency behavior of filter on statistical basis it is necessary to discuss some of the basic statistical distributions.

4.1 Statistical Distributions

The probabilistic analysis is based on precisely defined concepts. It is well accepted that a population of supposedly identical systems operating under similar conditions gives dissimilar random results then their results can only be defined under probabilistic framework. The probability theory defines this random behavior by statistical distributions. The best way to select a distribution model would be to describe the physical phenomena producing the results and these phenomena as a logical basis for deriving of the distribution model. In practice, one is usually forced to select the distribution model without having enough data to actually verify its appropriateness. The selection must be based on either previous experience or knowledge of the particular physical situation producing particular results, so if it were possible, it would indeed be very desirable to be

able to identify associations between certain physical situations and particular model.

Many probability distributions for continuous variables are available in statistics and each distribution has its particular characteristics. These distributions can be used only in specific conditions. Most common distributions used are; Exponential, Normal, Lognormal, Weibull and Extreme value distributions. Plotting the probability distribution function versus the random variable on appropriate probability paper normally yields valuable information. The available "Statistical Packages" such as Statgraphics, SAS, Statistica etc., are commonly used for probability distribution fittings but spread sheet package like MS-Excel can also fit the data to some particular distribution by linear regression analysis. This facilitates the quick assessment of the nature of data and model can be used more readily in the analytical techniques. In order to obtain the parameteric models for removal efficiency of microorganisms and other contaminants there is a need to determine which distribution will adequately represent the data and what are its characteristic parameters.

4.1.1 Normal Distribution

Normal distribution is the most widely applied in statistics and generally referred to as the Gaussian distribution. A unique feature of the Normal distribution is its characteristic parameters, which are, the "mean" and the "standard deviation".

Normal distribution is generally used when the results have the effect of many variables and none of them is predominant. Sum or difference of statistically independent normally distributed quantities are also normally distributed. The cumulative distribution function (CDF), mean and the standard deviation of normal distribution are given in Table 4.1.

4.1.2 Lognormal Distribution

The division or multiplication of different quantities may not be normal in general. The Lognormal distribution which is actually the transformation of normal distribution, is used when there is large uncertainty within the data *e.g.* in case of influent and effluent population of microorganisms from the filter which can create an order of magnitude difference. The characteristic parameters of the Lognormal distribution are "median"(mean of the Log data) and the "standard deviation of Log of quantity". Sum or difference of statistically independent Lognormal quantity will also be Lognormally distributed, whereas, it is not necessary that if two quantities are Lognormally distributed then there division will also be Lognormal distribution rather it could be some other distribution. Variance and corresponding standard deviation of the distribution are very large in case of Lognormal distribution [Lewis, 1978; Ramakumar, 1993; Kapur, 1977]. The CDF, mean and standard deviation of the Lognormal distribution are given in Table 4.1.

Table 4.1: Summary of Candidate Distributions

Distribution	CDF*	Mean, μ	Variance, σ^2
Normal (μ,σ)	$\phi((x-\mu)/\sigma)$	μ	σ^2
Lognormal (y_o,s)	$\phi[(1/s)Ln(y/y_o)]$	$y_o \exp(s^2/2)$	$y_o^2 \exp(s^2)[\exp(s^2)-1]$
Weibull (θ,m)	$1-\exp[-(y/\theta)^m]$	$\theta\Gamma(1+1/m)$	$\theta^2\{\Gamma(1+2/m)-[\Gamma(1+1/m)]^2\}$
Type III(y_m,θ,m)	$\exp[-(y_m-y/\theta)^m]$	$y_m-\theta\Gamma(1+1/m)$	$\theta^2\{\Gamma(1+2/m)-[\Gamma(1+1/m)]^2\}$

- 'x' & 'y' are any random variables

Where

y_m = Maximum value of variable y

θ = Scale factor of the distribution

m = Shape factor of the distribution

s = Lognormal scatter factor

y_o = median value

4.1.3 Extreme Value Distribution

Normal and Lognormal distributions can not explain the extreme behavior of the data. Some times results are not simply the addition of different factors (Normal) and also the results of product do not explain the behavior as well rather (Lognormal). The extreme lower or extreme higher values are important *e.g.* in case of flood, the design is always based on the highest flood and in water quality management the addition of wastewater in to the natural streams is always based on the lowest flows in the streams. In these circumstances that behavior can be very well explained by Extreme Value Distributions. Three types of Asymptotic Extreme Value Distributions are commonly used. The Type 1 or Gumbel distribution is used when random variable can take any value between -œ to +œ. Similarly Type 2 Distribution varies between zero and -œ. Type 3 Distribution is some what different from the previous two because it is three parameter model. Type 3 Extreme Value Distribution arises from parent distributions in which the tails falls off about some finite value and similarly for minimum extreme value distributions all three extreme value can be defined. [Lewis, 1978; Ramakumar, 1993]. The CDF of type III extreme value asymptotic distribution are also given in Table 4.1.

4.1.4 Weibull Distribution

The Weibull distribution is one of the most widely used distribution in reliability calculations. Exponential distribution is the special case of Weibull distribution in which the shape factor (m) of the Weibull distribution is "1". The Weibull distribution may be formulated in either two or a three parameter form distribution [Lewis, 1978]. The CDF, mean and standard deviation of the Weibull distribution are also given in the Table 4.1. The relationship of the shape factor (m) of Weibull distribution with coefficient of variation (σ/μ) is given in Fig. 4.1 [Lewis, 1978].

4.2 Selection of Appropriate Distribution

Formally the histograms of the grouped data are first plotted with the PDFs (probability density functions) of candidate distributions. Then the CDF (cumulative distribution function) of the original data are superimposed with CDFs of candidate distributions. After visualizing the fitness of appropriate distribution the results are verified using K-S test and χ^2-test. The probability plot of the selected candidate distribution will give the characteristic prameters of that distribution [Benjamin. 1970].

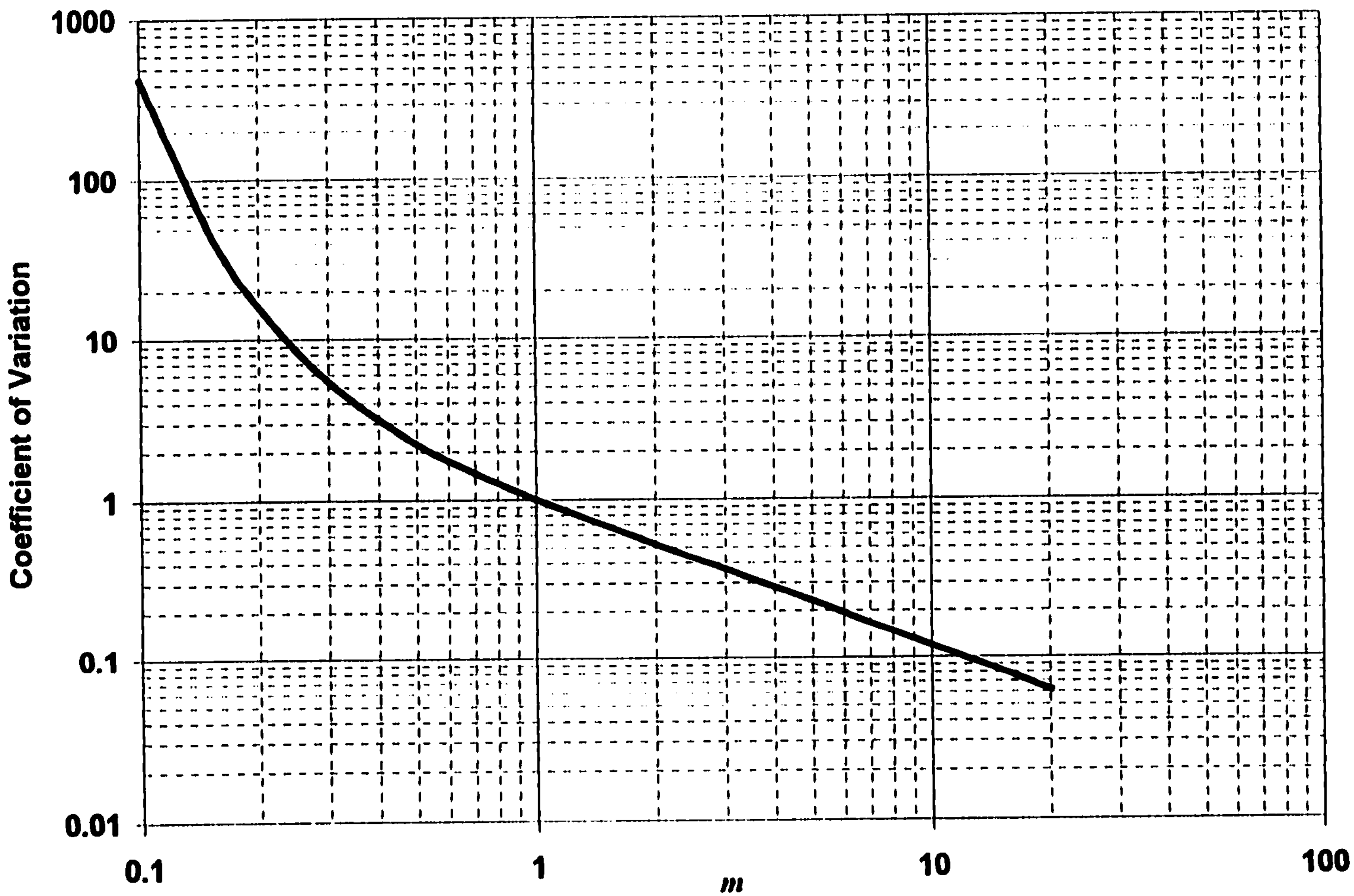

Fig. 4.1: Coefficient of Variation Vs "m" Values of Weibull Distribution (Kotz, 1995)

4.2.1 χ^2-Test

The statistics used is related to the histograms deviations from the predicted values. The test procedure requires a random sample of size "N" of the random variable "x", whose probability density function is unknown. The "N" observations are arranged in a frequency in a frequency histogram, having "k" class intervals.

Let O_i be the observed frequency in the *ith* class interval. From the hypothesized probability distribution the expected frequency is computed in the *ith* class interval, denoted by E_i. The test statistics is

$$\chi^2_o = \Sigma^K_{i=1} [O_i - E_i]/E_i \qquad (4.1)$$

The null hypothesis is rejected that conforms to the hypothesized distribution if, $\chi^2_o > \chi^2_{\alpha,k-p-1}$ [Hines and Montgomery,1990]. The χ^2- test is valid where data is enough to present in lumped form. (k-p-1) is the degree of freedom, where "p" presents the number of parameters of the hypothesized distribution estimated by sample statistics and $\chi^2_{\alpha,k-p-1}$ can be computed from available table in the statistics books [Benjamin, 1970].

4.2.2 K-S Test

A second quantitative goodness-of-fit test is based on the deviation between hypothesized cumulative distribution function, $F_x(x)$, and the observed cumulative histogram

$$F(x_i) = i/N \qquad (4.2)$$

In which x_i is the *ith* largest observed value in the random sample of size "N". The statistics is given as

$$D_{max.} = \max^{N}_{i=1} [\text{abs.}\{ i/N - F_x(x_i)\}] \qquad (4.3)$$

In words, the D_{max} is the largest of the absolute value of the "N" differences between the hypothesized CDF and the observed cumulative histograms (sometimes called empirical CDF) evaluated at the observed value in the sample. The only parameter is "N", its sample size. Knowing the statistics distribution, the critical value can be computed at the prescribed significance level (generally, α= 5%). Such test is called kolomogrov-Smirnov goodness-of-fit test. The K-S has an advantage over the χ^2-test that it does not lump the data and compare the discrete categories, but rather compares all the data in an unaltered form. The K-S test is an exact test for all sample sizes. The K-S test is valid strictly for continuous distribution [Benjamin, 1970].

4.2.3 Graphical Methods

Graphical methods are also very useful when selecting probability distribution to describe data. Probability plotting is a graphical method for determining whether data conform to a hypothesized distribution based on a subjective visual examination of the data or from coefficient of determination (R^2) value. Probability plotting requires special graph papers known as probability papers or

their linearized form of the particular distribution by transforming their scales to linear scales. Probability plotting is widely available for Normal, Lognormal, Weibull, Extreme value and Gamma distribution. To construct a probability plot, the data is needed to be ranked from smallest to largest. If the hypothesized distribution adequately describes the data, the plotted points will fall approximately along the straight line, if the plotted points deviate significantly from a straight line, the hypothesized model is not appropriate. Usually, the determination of whether or not the data plot as a straight line is subjective [Hines and Montogomery, 1990].

The choice of the distribution hypothesized to fit the data is important. Sometimes analysts can use their knowledge of the physical phenomena to choose a distribution to model the data. Sometimes previous experience can suggest the choice of the distribution. In situation where there is no previous experience or theory suggest a distribution, that describes the data, analysts must rely on other methods like K-S test, χ^2-Test and plotting histograms of probability density functions [Hines and Montogomery, 1990].

In this research the total coliform and fecal coliform concentration in tertiary effluents will be fitted on different distributions. According to "*Standard Methods for the Examination of Water and Wastewater*" the microorganisms data follow Lognormal distribution due to wide variations in their values. However, the removal efficiency data of total coliform, fecal coliform, standard plate counts and

coliphages through slow sand filtration have fitted on Normal, Lognormal, and Type III extreme value distribution. For this purpose K-S test has employed to select the most suitable distribution.

4.3 Regression Analysis

In most of the problems where two or more variables are related, it is important to model and explore the relation. Regression methods are frequently used to analyze data from unplanned experiments and this analysis is also very useful in designed experiments. Generally, the *Analysis of Variances* in a designed experiment helps to identify which factors are important and regression is used to build a quantitative model relating the important features to response. After deciding particular distribution to use in describing the data, the parameters appearing in the distribution must be estimated. In this study the most important characteristic parameter is the mean value which is used as a bench mark for subsequent analysis. The available data for filter operation is for 14 different conditions which are discussed in Chapter 5. In all conditions the controlled variables were varied to observe the effects of different factors on the removal efficiency. Important requirement in these analysis is to anticipate the removal efficiency under those conditions in which the experiment was not run. To evaluate these results a multiple non linear model is developed for all parameters.

4.3.1 Multiple Regression

Many regression problems involve more than one regression variable. The general form for fitting multiple linear regression is given as

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \cdots + \alpha_k X_k + \varepsilon \qquad (4.4)$$

is called multiple linear regression. Where X_1, X_2,.......,X_k are the designed operational factors and various interaction terms are ignored The unknown parameters "α's" are called regression coefficients and "ε" is an error. The methodology of the least square is used to estimate the regression coefficients in the above equation [Montgomery, 1991]

If the data is not well fitted by the multiple linear regression then nonlinear terms are introduced in the model given in Eq. 4.4. In this research three independent variables namely; filtration rate (q), filter sand depth (d) and effective media grain size (c) affect the removal efficiency (y) of different indicator microorganisms. For this purpose multiple regression models were developed by using "regression menu" in Microsoft Excel 7.0 and Statgraphics plus. These models contain different terms of control variables "q", "d" and "c". All types of polynomials, exponential and logarithmic terms can be incorporated and it is preferable to minimize the use of higher degree of polynomials so that the model should be less sensitive to any particular control variable and the chances of over and under estimation of removal efficiency could be minimized.

The mean values calculated from the best fitted distribution of the removal efficiency data represent the true picture of removals of different indicators. The models developed from the multiple regression are capable of predicting the efficiency of filters under different conditions of control variables but they cannot predict the extent of effect of each variable on the response (removal efficiency). These experiments were not designed according to any *Design of Experiment* technique but they can give good information about the sensitivity of response with control variables.

5. DATA ANALYSIS

5.1 Operational Details

Based on data generated from previous experiments conducted on three slow sand filters for a period of 15 months, the removal efficiencies of total coliform, fecal coliform, standard plate counts and coliphages through slow sand filter are analyzed. During that experiment two filters were operated with coarse sand of 0.5 mm effective media grain size and one filter was operated with fine sand of 0.3 mm grain size [Khan,1996; Farooq, 1996].

The Objective of that study was to see the effectiveness of various control variables on the removal efficiency of these indicator microorganisms. For this purpose the control variables filtration rate, sand bed depth and sand grain size were operated at different levels. The filtration rate was operated at 8, 10,16 and at 20 L/min, whereas, the sand bed depth was operated at 50 , 80 and at 150 cm. The sand grain size was checked at only two levels of fine and coarse grain which has already been described. The entire operation of the filter was constituted on 14 different operating conditions as given in Table 5.1 [Khan, 1996; Farooq, 1996].

Table 5.1: Operating Conditions of Slow Sand Filters with Their Corresponding Number of Observation [Khan, 1996; Farooq, 1996].

Condition No.	Grain Size (mm)	Filtration Rate (L/min)	Sand Bed Depth (cm)	*No. Of Observations			
				TC	FC	PC	CP
1	0.5	8	150	34	27	34	28
2	0.5	10	150	10	10	10	10
3	0.5	10	80	14	14	14	14
4	0.5	10	50	17	17	17	17
5	0.3	16	150	38	31	37	37
6	0.3	20	150	6	6	6	6
7	0.3	20	80	14	14	14	14
8	0.3	20	50	17	17	17	17
9	0.3	10	50	9	9	9	9
10	0.5	16	150	38	30	37	38
11	0.5	20	150	14	14	14	14
12	0.5	20	80	6	6	6	6
13	0.5	20	50	17	17	17	17
14	0.5	16	50	9	9	9	9

*TC = Total Coliform

FC = Fecal Coliform

PC = Standard Plate Counts

CP = Coliphages

Among 14 different conditions of operation, 5 conditions were operated with fine sand and remaining 9 conditions with coarse sand. The program of operation was designed in such a manner that when one condition was over the filter was adjusted to new condition with respect to sand bed depth, filtration rate and media grain size before starting the operation of filter. The data was collected upon maturation of the filter as a result of development of biological layer. Initially filter was operated at 150 cm sand depth followed by 80 cm and 50 cm respectively [Farooq *et al.*, 1996, Khan, 1996].

5.2 Risk Analysis and Selection of Distribution

To select the suitable distribution for total and fecal coliform concentration, a typical histogram for total coliform and fecal coliform condition #1 are developed and given in Figs. 5.1 and 5.2 respectively. As the data for different conditions are not enough to plot histograms for all conditions. The selected candidate distributions for this analysis are Normal, Lognormal and Weibull distributions. The histogram for the fecal coliform data shows a bell shaped skewed distribution. The Normal and Lognormal distribution probability density functions (PDFs) are plotted on this histogram to see the fit of the data. The characteristic parameter of the candidate distribution can be found out by method of moments or method of maximum likelihood. In this analysis the parameters (mean, standard deviation) are calculated from the available data of

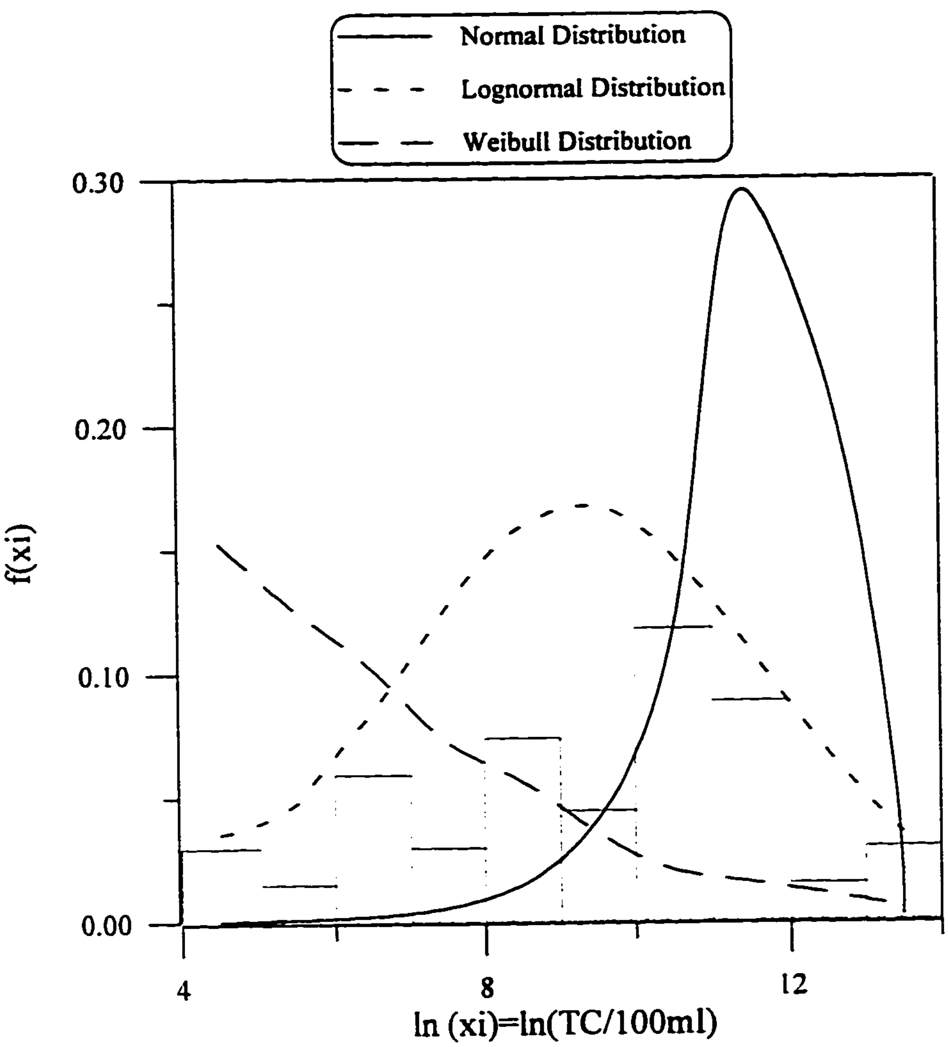

Fig. 5.1: Comparison of Histogram of Original Data and Probablity Density Functions of Candidate Distributions for Total Coliform Effluent Population, Condition # 1

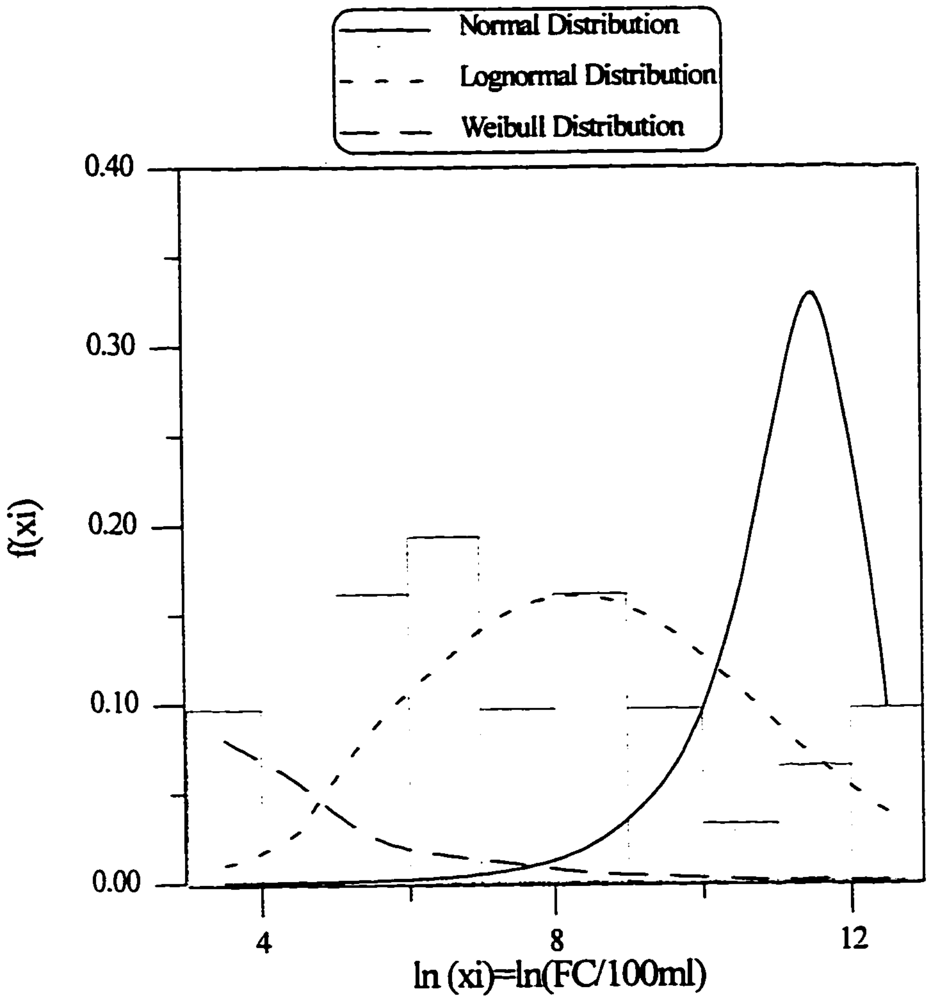

Fig. 5.2: Comparison of Histogram of Original Data and Probablity Density Functions of Candidate Distributions for Fecal Coliform Effluent Population, Condition # 1

that particular condition. The Lognormal distribution PDF gives a good compromise between the experimental data and predicted distribution.

To select the particular distribution on scientific basis K-S test is performed for all 14 conditions of total coliform and fecal coliform data. For this purpose all three distributions were compared with the experimental CDF of the data. The K-S test measures the maximum deviation of hypothesized distribution from the experimental CDF. It has one parameter statistics, i.e., number of data points.

The data points for fecal coliform condition # 5 are "31" and the corresponding K-S value is "0.238" at 5% significance level as according to standard K-S tables [Benjamin, 1970]. The CDFs of Normal, Lognormal and Weibull distributions are developed from mean and standard deviation of the original data. The maximum deviations from actual CDF for Normal, Weibull and Lognormal distribution are 0.3405, 0.2312 and 0.1232, respectively (Table 5.2). The values of deviation (D) with bold letters show the maximum deviation for different candidate distributions. To observe the results, the CDF of fecal coliform condition # 5 is plotted with the hypothesized CDF's of Normal and Lognormal distribution in Fig. 5.3. Similarly the results of total coliform for condition #4 are plotted in Fig. 5.4. The "*xi*" represents the effluent population of microorganisms per 100 ml. The data points of this condition are 17 for which K-S value at 5% significance level is 0.318.

Table 5.2: K-S Test Results on Population of Fecal Coliform in Condition #5

Serial #	Effluent.FC	Ln(FC)	CDF	Normal	Deviation,D	Lognormal	Deviation,D	Weibull	Deviation,D
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)	(Col.7)	(Col.8)	(Col.9)	(Col.10)
1	4.00E+01	3.6889	0.0323	0.3235	0.2913	0.0485	0.0162	0.054163	0.0219
2	5.00E+01	3.9120	0.0645	0.3236	0.2591	0.0583	0.0062	0.060359	0.0042
3	5.00E+01	3.9120	0.0968	0.3236	0.2268	0.0583	0.0385	0.060359	0.0364
4	1.50E+02	5.0106	0.1290	0.3242	0.1952	0.1306	0.0016	0.102222	0.0268
5	2.00E+02	5.2983	0.1613	0.3246	0.1633	0.1570	0.0043	0.117075	0.0442
6	2.10E+02	5.3471	0.1935	0.3246	0.1311	0.1618	0.0317	0.119785	0.0738
7	3.10E+02	5.7366	0.2258	0.3253	0.0995	0.2036	0.0222	0.143601	0.0822
8	3.30E+02	5.7991	0.2581	0.3254	0.0673	0.2108	0.0473	0.147807	0.1103
9	6.00E+02	6.3969	0.2903	0.3271	0.0368	0.2874	0.0030	0.193995	0.0963
10	6.00E+02	6.3969	0.3226	0.3271	0.0045	0.2874	0.0352	0.193995	0.1286
11	7.00E+02	6.5511	0.3548	0.3278	0.0271	0.3090	0.0458	0.207803	0.1470
12	8.00E+02	6.6846	0.3871	0.3284	0.0587	0.3284	0.0587	0.220443	0.1667
13	8.00E+02	6.6846	0.4194	0.3284	0.0909	0.3284	0.0910	0.220443	0.1989
14	8.00E+02	6.6846	0.4516	0.3284	0.1232	0.3284	0.1232	0.220443	0.2312
15	1.50E+03	7.3132	0.4839	0.3329	0.1510	0.4249	0.0590	0.288939	0.1949
16	2.00E+03	7.6009	0.5161	0.3362	0.1800	0.4710	0.0451	0.325477	0.1907
17	2.80E+03	7.9374	0.5484	0.3414	0.2070	0.5255	0.0229	0.372424	0.1760
18	3.50E+03	8.1605	0.5806	0.3459	0.2347	0.5613	0.0193	0.406003	0.1746
19	3.90E+03	8.2687	0.6129	0.3486	0.2643	0.5786	0.0343	0.422959	0.1899
20	4.00E+03	8.2940	0.6452	0.3492	0.2959	0.5826	0.0626	0.426987	0.2182
21	5.00E+03	8.5172	0.6774	0.3558	0.3216	0.6176	0.0599	0.463438	0.2140
22	7.00E+03	8.8537	0.7097	0.3691	0.3405	0.6684	0.0413	0.521279	0.1884
23	1.70E+04	9.7410	0.7419	0.4379	0.3041	0.7868	0.0449	0.682719	0.0592
24	1.70E+04	9.7410	0.7742	0.4379	0.3363	0.7868	0.0127	0.682719	0.0915
25	2.20E+04	9.9988	0.8065	0.4731	0.3334	0.8160	0.0095	0.729077	0.0774
26	2.60E+04	10.1659	0.8387	0.5014	0.3373	0.8335	0.0053	0.75821	0.0805
27	6.00E+04	11.0021	0.8710	0.7283	0.1426	0.9044	0.0334	0.884289	0.0133
28	6.30E+04	11.0509	0.9032	0.7457	0.1575	0.9077	0.0045	0.89029	0.0129
29	1.70E+05	12.0436	0.9355	0.9948	0.0593	0.9582	0.0227	0.973489	0.0380
30	1.70E+05	12.0436	0.9677	0.9948	0.0271	0.9582	0.0096	0.973489	0.0057
31	2.20E+05	12.3014	1.0000	0.9997	0.0003	0.9667	0.0333	0.983912	0.0161
Mean	2.58E+04	7.7786							
Stdev.	56267	2.4647							
C.V.*	2.1794								

* Coefficient of Variation

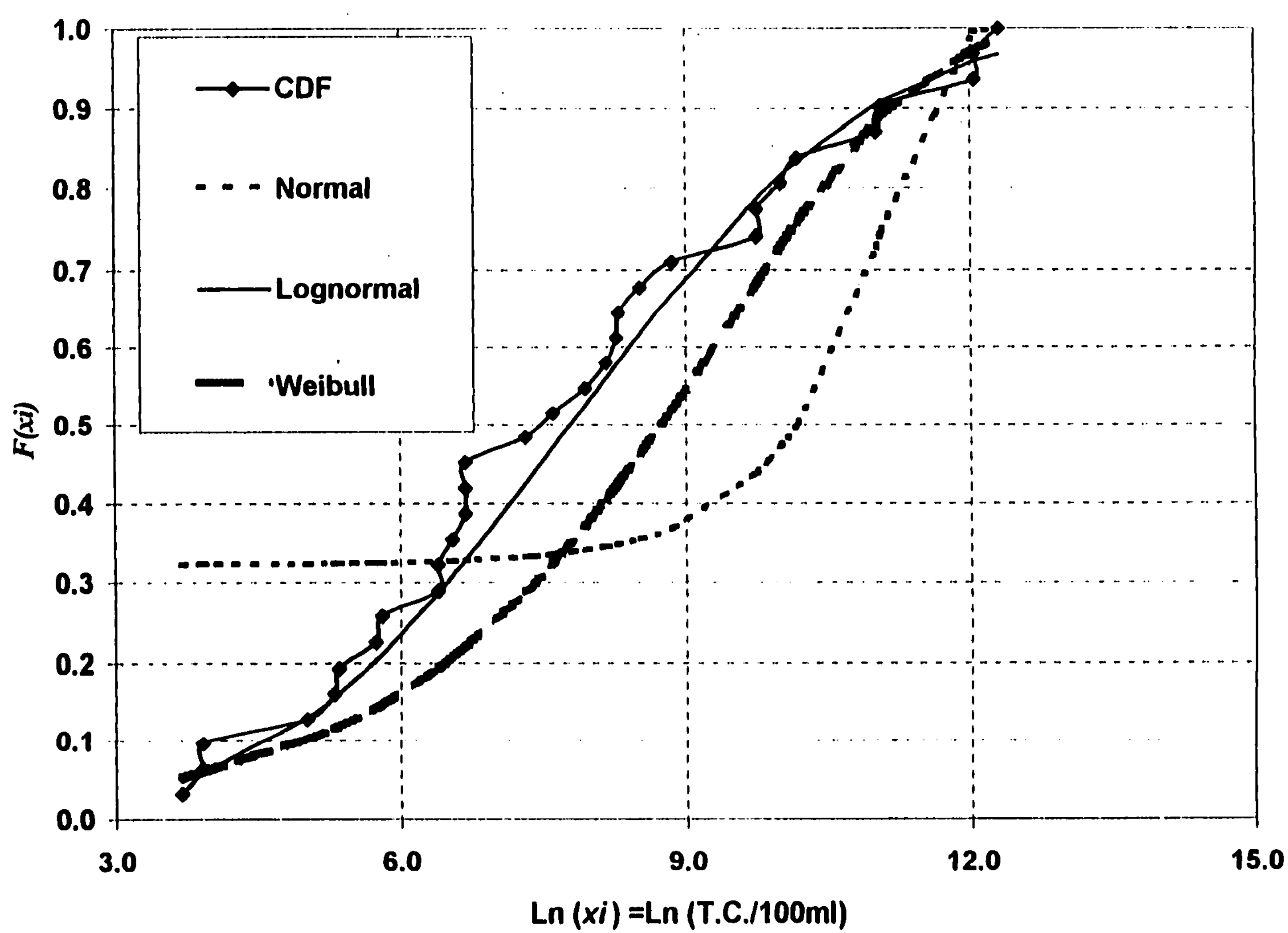

Fig. 5.3: CDF of Effluent Concentration of Fecal Coliform , Condition#5

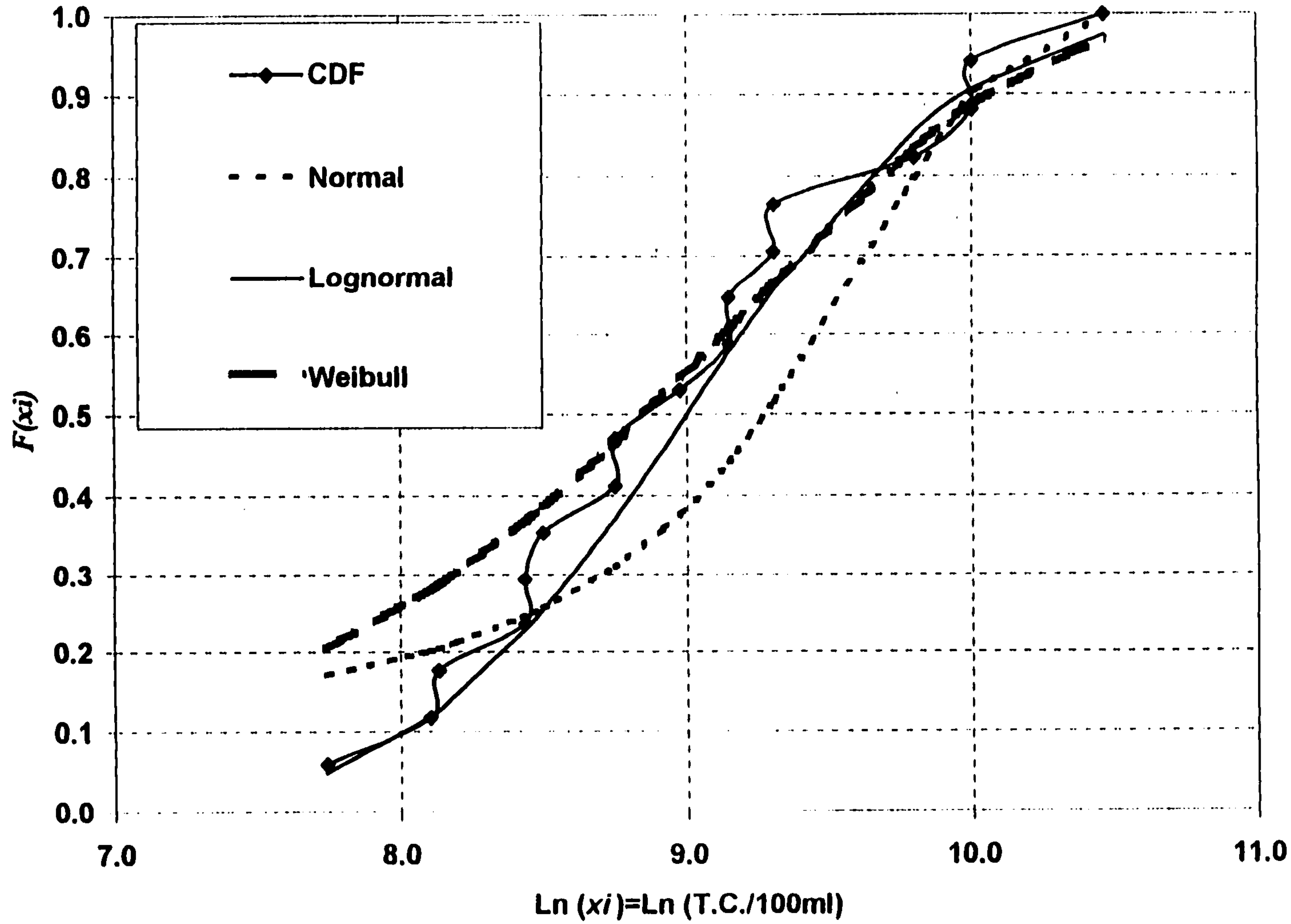

Fig. 5.4: CDF of Effluent Concentration of Total Coliform , Condition#4

The maximum deviation for Normal, Lognormal and Weibull distribution are 0.2498, 0.1074 and 0.1623, respectively. The K-S test analysis is given in Table 5.3. Although all three candidate distributions are valid in this case but the minimum deviation is again for Lognormal distribution which shows the goodness-of-fit of data on Lognormal distribution. From Table 5.4, it can be observed that out of 14 conditions of total coliform the Lognormal distribution gives the best results in 12 conditions. Similarly for 14 conditions of fecal coliform the Lognormal distribution gives the best fit for 13 conditions. To get more authentic picture of the selection of candidate distribution the conditions with data points less than 9 are not taken in to account and results are given in Table 5.5. The results show that for the valid conditions, Lognormal is the most suitable distribution to describe the effluent microbial data. For total coliform and fecal coliform the Lognormal is candidate for 83.3% and 91.7% of the valid conditions. Therefore, on the basis of K-S goodness-of-fit test the Lognormal distribution can be justified in its selection for tertiary effluent data of total and fecal coliform concentration.

5.2.1 Risk Assesment

As far as wastewater effluent standards for reuse are concerned the MEPA and MAW have given standards for total and fecal coliforms. To study the risk involved in using the wastewater coming out of the filter under different

Table 5.3: K-S Test Reults on Popuation of Total Coliform in Condintion #4

Sr.#	Effluent.FC	Ln(FC)	CDF	Normal	Deviation, D	Lognormal	Deviation, D	Weibull	Deviation, D
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)	(Col.7)	(Col.8)	(Col.9)	(Col.10)
1	2.30E+03	7.7407	0.0588	0.1704	0.1116	0.0483	0.0106	0.2046	0.1457
2	3.30E+03	8.1017	0.1176	0.2008	0.0832	0.1180	0.0003	0.2799	0.1622
3	3.40E+03	8.1315	0.1765	0.2041	0.0276	0.1260	0.0505	0.2870	0.1106
4	4.60E+03	8.4338	0.2353	0.2449	0.0096	0.2277	0.0076	0.3673	0.1320
5	4.60E+03	8.4338	0.2941	0.2449	0.0492	0.2277	0.0664	0.3673	0.0732
6	4.90E+03	8.4970	0.3529	0.2557	0.0972	0.2537	0.0993	0.3859	0.0329
7	6.30E+03	8.7483	0.4118	0.3095	0.1023	0.3703	0.0415	0.4657	0.0540
8	6.30E+03	8.7483	0.4706	0.3095	0.1611	0.3703	0.1003	0.4657	0.0049
9	7.90E+03	8.9746	0.5294	0.3763	0.1531	0.4872	0.0423	0.5444	0.0150
10	9.40E+03	9.1485	0.5882	0.4425	0.1457	0.5782	0.0100	0.6075	0.0193
11	9.40E+03	9.1485	0.6471	0.4425	0.2045	0.5782	0.0688	0.6075	0.0395
12	1.10E+04	9.3057	0.7059	0.5149	0.1909	0.6573	0.0486	0.6653	0.0406
13	1.10E+04	9.3057	0.7647	0.5149	0.2498	0.6573	0.1074	0.6653	0.0994
14	1.80E+04	9.7981	0.8235	0.7978	0.0257	0.8544	0.0309	0.8332	0.0097
15	2.20E+04	9.9988	0.8824	0.9013	0.0190	0.9067	0.0243	0.8880	0.0056
16	2.20E+04	9.9988	0.9412	0.9013	0.0399	0.9067	0.0345	0.8880	0.0532
17	3.50E+04	10.4631	1.0000	0.9972	0.0028	0.9734	0.0266	0.9693	0.0307
Mean	10670.59	8.9986							
Stdev.	8788.97	0.7572							
C.V.*	0.8237								

* Coefficient of Variation

Table 5.4: Summary of K-S Test for Risk Analysis Data for Both total & Fecal Coliform

Indicator	Condition #	Data Points	Ks, 5%	Normal	Lognormal	Weibull
T. Coliform	1	34	0.235	0.3057	0.1001	0.1401
	2	10	0.41	0.1718	0.1799	0.3103
	3	14	0.349	0.457	0.1687	0.2450
	4	17	0.318	0.2498	0.1074	0.1623
	5	38	0.221	0.3111	0.14143	0.1266
	6*	6	0.521	0.3581	0.1595	0.1990
	7	14	0.349	0.2605	0.1586	0.3175
	8	17	0.318	0.21796	0.0937	0.1782
	9	9	0.432	0.3137	0.2967	0.7811
	10	38	0.221	0.28996	0.0845	0.1083
	11	14	0.349	0.40814	0.2333	0.2728
	12*	6	0.521	0.2225	0.2158	0.4506
	13	17	0.318	0.24243	0.1534	0.2961
	14	9	0.432	0.2506	0.2449	0.7352
F. Coliform	1	27	0.26	0.4042	0.0799	0.1163
	2	10	0.41	0.3193	0.1597	0.2050
	3	14	0.49	0.3306	0.20315	0.6533
	4	17	0.318	0.2778	0.1487	0.1414
	5	31	0.238	0.3405	0.1232	0.2312
	6*	6	0.521	0.3487	0.2283	0.3229
	7	14	0.349	0.3967	0.1324	0.3900
	8	17	0.318	0.2763	0.1422	0.1661
	9	9	0.432	0.2336	0.2289	0.8189
	10	30	0.24	0.3545	0.1565	0.1935
	11	14	0.349	0.4067	0.1799	0.2291
	12*	6	0.521	0.3999	0.1819	0.2229
	13	17	0.318	0.303	0.14	0.1802
	14	9	0.432	0.1437	0.138	0.6465

* These conditions will not be considered while making final conclusions due to low number of data points

Table 5.5: Summary of Validity of Different Candidate Distributions to Effluent Microbial Data

Indicator	Total Conds.	Valid Conds.	Non Validity of K-S Test (%)	Normal (%)	Lognormal (%)	Weibull (%)
Total Coliform	14	12	0.0	8.3	83.3	8.3
Fecal Coliform	14	12	0.0	0.0	91.7	8.3

operating conditions the Lognormal distribution is found as shown previously to best-fit the effluent data of total and fecal coliforms.

5.2.2 Data Fitting on Lognormal Distribution

The level of risk in the treated wastewater can be obtained first by fitting the observed data to an appropriate probability distribution. In this study the best fitted distribution, as shown previously, follow a Lognormal distribution. The cumulative distribution function(CDF) of Lognormal distribution, is given by

$$\hat{F}(x_i) = P(X \leq x_i) = \Phi\left[\frac{1}{s}\ln\left(\frac{x}{x_o}\right)\right] \qquad (5.1)$$

Where

$P =$ probability of desired safe levels

x_o = Median values of effluent data (total or fecal coliforms/100 ml)

x = Random variable (total or coliforms/100 ml)

s = Measure of scatter of data

To plot the curve of effluent of data, linearization of Eq.(5.1) is needed and its procedure for fitting the data is given in most of the standard text books on statistics. In the linearized form of the Eq. (5.1) becomes.

$$s\Phi^{-1}[F(x_i)] = Ln(x_i) - Ln(x_o) \qquad (5.2)$$

therefore

$$Ln(x_i) = Ln(x_o) + s\Phi^{-1}[F(x_i)] \tag{5.3}$$

If Eq.(5.3) is compared with standard straight line equation, then the following relations can be developed

$$Intercept = \ln x_o \quad \text{and} \quad Slope = s$$

To plot the data of effluent densities of *total coliform* and *fecal coliform*, the natural Log of effluent values can be taken on the y-axis while the corresponding probabilities on the x-axis. The non parameteric estimate by mean rank formula is [Lewis, 1978].

$$\hat{F}(x_i) = \frac{i}{(N+1)} \tag{5.4}$$

Where "N" is the total numbers of data points in each run. The risk of violating desired safe levels can be calculated by

$$R = R(x_l)^{*100} = [1 - \hat{F}(x_l)] * 100 \tag{5.5}$$

Where

$R*100 = R(x_l) \times 100$, is the risk of violation of the standard which set an acceptable limit of X as $x \leq x_l$.

Table 5.6 gives the basic calculation results for total coliform effluent data of condition #1. The last two columns of Table 5.6, when plotted give the fit of the data as shown in Fig 5.5. This fit represents total coliform concentration in the effluent and it is also assumed that steady conditions sustain in the influent population of total coliforms. "Normsinv" is the transformation function used to

Table 5.6: Spreadsheet To Fit Lognormal Distribution To Total Coliform Effluent Data Cond. # 1

SR. # (i)	*F= i/(N+1)*	*xi*	Normsinv[F(xi)]	Ln (*xi*)
1	0.0286	5.00E+01	-1.9022	3.6889
2	0.0571	8.00E+01	-1.5792	3.6889
3	0.0857	1.30E+02	-1.3676	3.6889
4	0.1143	2.70E+02	-1.2040	4.6052
5	0.1429	3.00E+02	-1.0676	5.3936
6	0.1714	3.30E+02	-0.9485	6.3969
7	0.2000	3.40E+02	-0.8416	6.5511
8	0.2286	7.90E+02	-0.7436	6.8024
9	0.2571	1.10E+03	-0.6522	7.0031
10	0.2857	2.90E+03	-0.5659	7.6009
11	0.3143	3.00E+03	-0.4837	7.6009
12	0.3429	3.00E+03	-0.4047	7.6962
13	0.3714	3.00E+03	-0.3281	7.6962
14	0.4000	3.50E+03	-0.2533	8.0709
15	0.4286	6.00E+03	-0.1800	8.2940
16	0.4571	8.00E+03	-0.1076	8.8537
17	0.4857	8.00E+03	-0.0358	8.9872
18	0.5143	1.40E+04	0.0358	9.1050
19	0.5429	1.70E+04	0.1076	9.5468
20	0.5714	1.70E+04	0.1800	9.7410
21	0.6000	2.00E+04	0.2533	9.7410
22	0.6286	2.20E+04	0.3281	9.9988
23	0.6571	2.30E+04	0.4047	9.9988
24	0.6857	2.30E+04	0.4837	11.2898
25	0.7143	3.10E+04	0.5659	12.0436
26	0.7429	4.00E+04	0.6522	12.5062
27	0.7714	4.10E+04	0.7436	12.5062
28	0.8000	5.00E+04	0.8416	12.5062
29	0.8286	5.40E+04	0.9485	12.5062
30	0.8571	5.40E+04	1.0676	12.5062
31	0.8857	9.20E+04	1.2040	12.5062
32	0.9143	1.70E+05	1.3676	12.5062
33	0.9429	2.70E+05	1.5792	12.5062
34	0.9714	3.50E+05	1.9022	12.5062

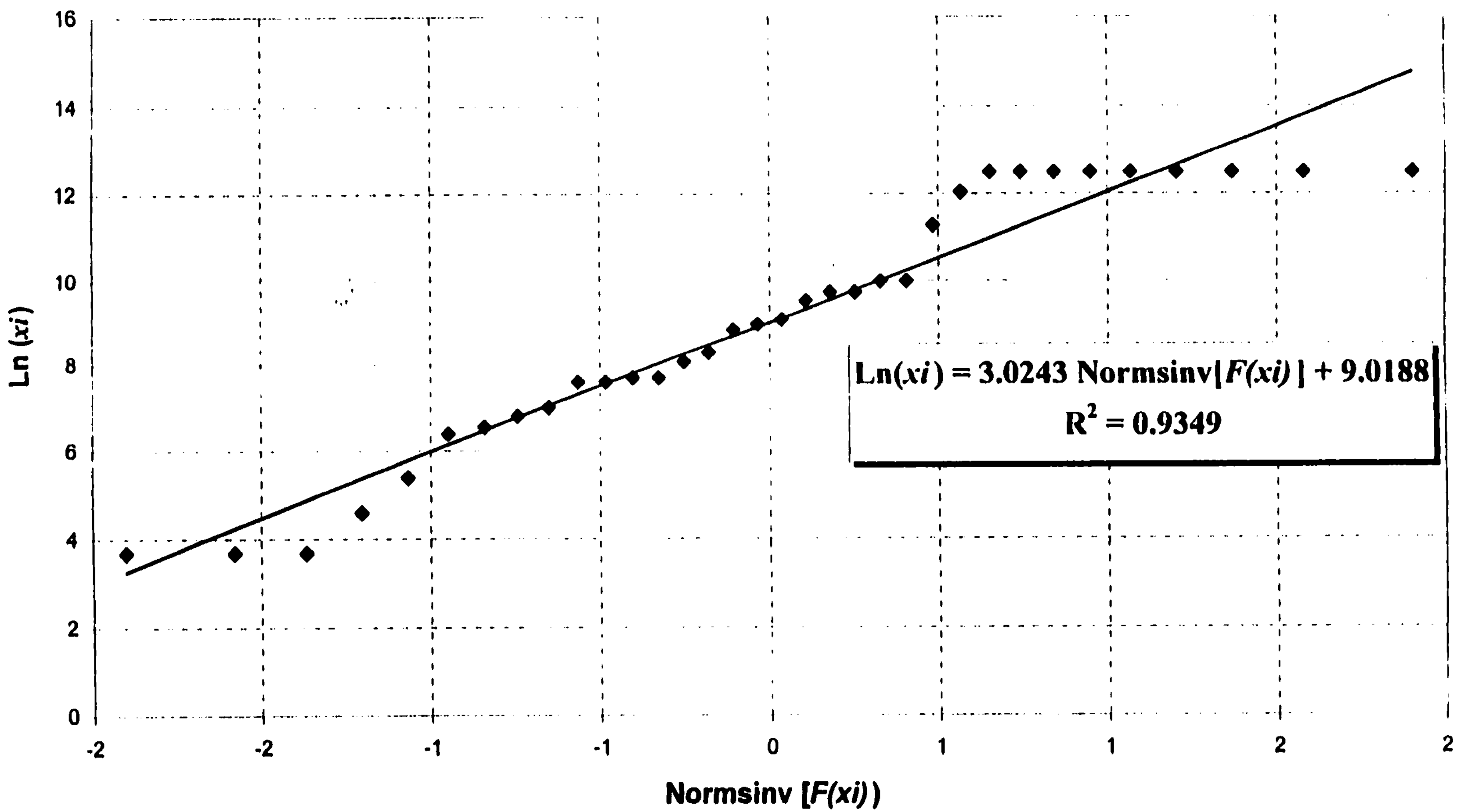

Fig.5.5: Fit of Lognormal Distribution of Total Coliform Effluent, Condition# 1

simplify the Lognormal equation and its values are given in MS-Excel 7 statistical function menu. Similarly for the other conditions the plots can be developed. Higher values of coefficient of determination represents the goodness of fit of the data to the Lognormal distribution.

Same procedure is repeated for the fecal coliform data and the results are given for condition # 1 in Table 5.7. The plot of this data is given in Fig 5.6. It has also good fit on Lognormal distribution. The property of Lognormal-distribution to take into account the large variation of the data confirms its fit to the bacterial population as bacterial measurement differences are always in order of Log scales. In case of fecal coliforms the coefficient of determination is very close to 1 as shown in Fig. 5.6.

The summary tables for the other conditions of total and fecal coliforms are given in Tables 5.8 and 5.9, respectively. There median value(x_o) and the parameter for the variation (s) are also given in these tables. Corresponding equations for each condition is being used to calculate these parameters. The effluent standards set by the Meteorological and Environmental Protection Administration (MEPA) is 1000 coliforms per 100 ml. Thus the probability of safe levels of the data is estimated at $X1$=1000 total coliform/100ml. Similarly, the Ministry of Agriculture and Water (MAW) has promulgated the effluent standards of 100 coliforms per 100 ml as designated by $X3$ in the analysis. The desired

Table 5.7: Spreadsheet To Fit Lognormal Distribution

To Fecal Coliform Effluent Data Cond. # 1

SR. # (i)	*F= i/(N+1)*	*xi*	**Normsinv[F(xi)]**	**Ln (*xi*)**
1	0.0357	4.00E+01	-1.8027	3.6889
2	0.0714	4.00E+01	-1.4652	3.6889
3	0.1071	4.00E+01	-1.2419	3.6889
4	0.1429	1.00E+02	-1.0676	4.6052
5	0.1786	2.20E+02	-0.9208	5.3936
6	0.2143	6.00E+02	-0.7916	6.3969
7	0.2500	7.00E+02	-0.6745	6.5511
8	0.2857	8.00E+02	-0.5659	6.6846
9	0.3214	9.00E+02	-0.4637	6.8024
10	0.3571	1.10E+03	-0.3661	7.0031
11	0.3929	2.00E+03	-0.2719	7.6009
12	0.4286	2.00E+03	-0.1800	7.6009
13	0.4643	2.20E+03	-0.0896	7.6962
14	0.5000	2.20E+03	0.0000	7.6962
15	0.5357	3.20E+03	0.0896	8.0709
16	0.5714	4.00E+03	0.1800	8.2940
17	0.6071	7.00E+03	0.2719	8.8537
18	0.6429	8.00E+03	0.3661	8.9872
19	0.6786	9.00E+03	0.4637	9.1050
20	0.7143	1.40E+04	0.5659	9.5468
21	0.7500	1.70E+04	0.6745	9.7410
22	0.7857	1.70E+04	0.7916	9.7410
23	0.8214	2.20E+04	0.9208	9.9988
24	0.8571	2.20E+04	1.0676	9.9988
25	0.8929	8.00E+04	1.2419	11.2898
26	0.9286	1.70E+05	1.4652	12.0436
27	0.9643	2.70E+05	1.8027	12.5062

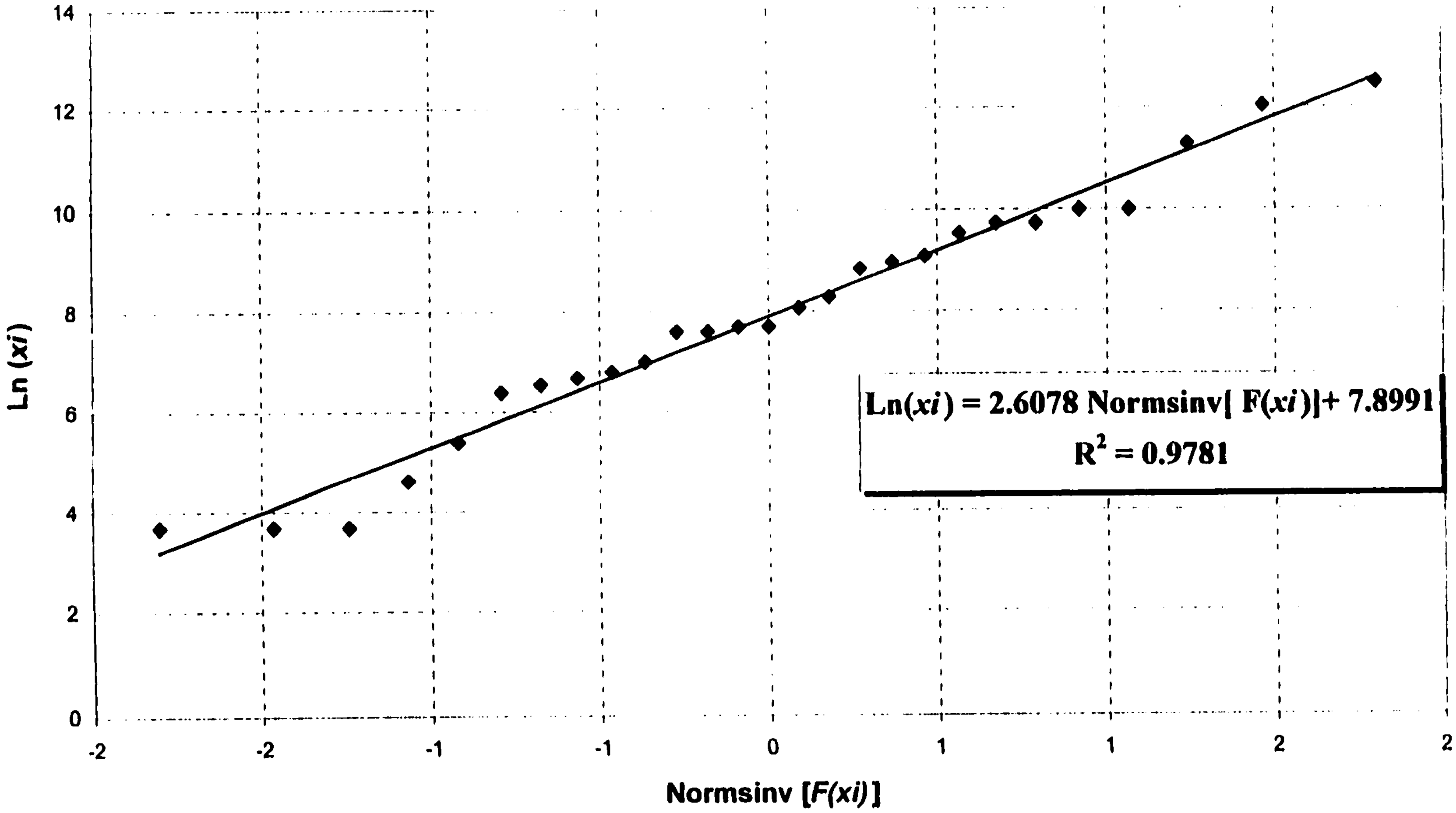

Fig.5.6: Fit of Lognormal Distribution of Fecal Coliform Effluent, Condition# 1

Table 5.8: Summary of Safe Levels and Corresponding Risks for Different Standards For Total Coliform

Condition	Flow	Depth	Size	# of obs.	Model	R^2	Median	s	Standards			Probability of SafeLevels (%)			Risk Involved (%)		
#	(L/min)	(cm)	(mm)				xo		X1	X2	X3	P[X<X1]=p1	P[X<X2]=p2	P[X<X3]=p3	R1=1-p1	R2=1-p2	R3=1-p3
1	8	150	0.5	34	3.024 Normsinv(F)+9.019	0.9349	8300	3.024	1000	200	100	24.20	10.90	7.20	75.80	89.10	92.80
2	10	150	0.5	10	1.4113 Normsinv(F)+7.837	0.8721	2500	1.4113	1000	200	100	25.81	3.68	1.13	74.19	96.32	98.87
3	10	80	0.5	14	1.699Normsinv(F)+6.735	0.9083	850	1.699	1000	200	100	53.81	19.72	10.39	46.19	80.28	89.61
4	10	50	0.5	17	0.8521Normsinv(F)+8.999	0.9786	8100	0.8521	1000	200	100	0.70	0.00	0.00	99.30	100.00	100.00
5	16	150	0.3	38	1.708Normsinv(F)+8.53	0.8611	5100	1.708	1000	200	100	17.01	2.90	1.07	82.99	97.10	98.93
6	20	150	0.3	6	2.3.13Normsinv(F)+7.6172	0.9755	2050	2.313	1000	200	100	37.81	15.72	9.58	62.19	84.28	90.42
7	20	80	0.3	14	1.906 Normsinv(F)+9.496	0.9142	13300	1.906	1000	200	100	8.73	1.38	0.51	91.27	98.62	99.49
8	20	50	0.3	17	0.828 Normsinv(F)+9.253	0.9633	10400	0.828	1000	200	100	0.23	0.00	0.00	99.77	100.00	100.00
9	10	50	0.3	9	0.357 Normsinv(F)+8.07	0.8389	3200	0.357	1000	200	100	0.06	0.00	0.00	99.94	100.00	100.00
10	16	150	0.5	38	1.386 Normsinv(F)+8.62	0.8939	5550	1.386	1000	200	100	10.81	0.82	0.19	89.19	99.18	99.81
11	20	150	0.5	14	2.004 Normsinv(F)+8.46	0.8902	4700	2.004	1000	200	100	22.00	5.76	2.74	78.00	94.24	97.26
12	20	80	0.5	6	0.598 Normsinv(F)+10.974	0.7531	58300	0.598	1000	200	100	0.00	0.00	0.00	100.00	100.00	100.00
13	20	50	0.5	17	0.784 Normsinv(F)+9.264	0.9564	10600	0.784	1000	200	100	0.13	0.00	0.00	99.87	100.00	100.00
14	16	50	0.5	9	0.414 Normsinv(F)+8.44	0.8652	4650	0.414	1000	200	100	0.01	0.00	0.00	99.99	100.00	100.00

Table 5.9: Summary of Safe Levels and Corresponding Risks for Different Standards For Fecal Coliform

Condition	Flow	Depth	Size	# of obs.	Model	R^2	Median	s	Standards			Probability of Safe Levels (%)			Risk Involved (%)		
#	(L/min)	(cm)	(mm)				x_0		X1	X2	X3	P[X<X1]=p1	P[X<X2]=p2	P[X<X3]=p3	R1=1-p1	R2=1-p2	R3=1-p3
1	8	150	0.5	27	2.608 Normsinv(F)+7.9	0.9781	2700	2.608	1000	200	100	35.17	15.91	10.32	64.83	84.09	89.68
2	10	150	0.5	10	1.513 Normsinv(F)+6.88	0.9357	1000	1.5133	1000	200	100	50.00	14.38	6.41	50.00	85.62	93.59
3	10	80	0.5	14	1.266 Normsinv(F)+6.191	0.8840	500	1.266	1000	200	100	70.80	23.46	10.18	29.20	76.54	89.82
4	10	50	0.5	17	0.9147 Normsinv(F)+8.291	0.9690	4000	0.9147	1000	200	100	6.48	0.05	0.00	93.52	99.95	100.00
5	16	150	0.3	31	2.655 Normsinv(F)+7.78	0.9801	2400	2.655	1000	200	100	37.08	17.47	11.57	62.92	82.53	88.43
6	20	150	0.3	6	2.454 Normsinv(F)+7.34	0.9583	1550	2.454	1000	200	100	42.91	20.20	13.20	57.09	79.80	86.80
7	20	80	0.3	14	2.22 Normsinv(F)+9.28	0.9299	10700	2.22	1000	200	100	14.28	3.65	1.77	85.72	96.35	98.23
8	20	50	0.3	17	1.111 Normsinv(F)+8.49	0.8938	4900	1.111	1000	200	100	7.63	0.20	0.02	92.37	99.80	99.98
9	10	50	0.3	9	.2907 Normsinv(F)+7.944	0.8864	2800	0.2907	1000	200	100	0.02	0.00	0.00	99.98	100.00	100.00
10	16	150	0.5	30	2.496 Normsinv(F)+7.408	0.9540	1650	2.496	1000	200	100	42.05	19.89	13.07	57.95	80.11	86.93
11	20	150	0.5	14	2.423 Normsinv(F)+8.118	0.9373	3350	2.423	1000	200	100	30.89	12.24	7.36	69.11	87.76	92.64
12	20	80	0.5	6	1.745 Normsinv(F)+10.13	0.8758	25150	1.745	1000	200	100	3.23	0.28	0.08	96.77	99.72	99.92
13	20	50	0.5	17	0.969 Normsinv(F)+8.564	0.9619	5250	0.969	1000	200	100	4.35	0.04	0.00	95.65	99.96	100.00
14	16	50	0.5	9	0.454 Normsinv(F)+8.189	0.9466	3600	0.454	1000	200	100	0.24	0.00	0.00	99.76	100.00	100.00

safe level of the total coliforms is calculated in all conditions of controlled variables and presented in Table 5.8.

From Tables 5.8 and 5.9 it can be observed that both total and fecal coliforms standards are violated most of the time with more than 80% risk. By relaxing standards the risk of violation decreases, but to get better quality effluent stringent standards must be preferred. The MAW effluent wastewater standards of 100 fecal coliform/100ml have the risk of violation varies from 90-100% in different operating conditions but if the standard is relaxed to 1000 fecal coliform/100ml then the variation of risk is 50-100% approximately. In MEPA standards (1000 total coliform/100ml) as given in the Table 5.8, the risk varies from 46-100% and at 100 total coliform/100ml this risk level increases to 92-100%. It can be observed that most of the time at both relaxed and stricter levels the standards are severely violated. To get higher quality effluent wastewater some additional treatment in the form of disinfection is required.

5.3 Removal Efficiency

This research is being done to study the effects of different controllable design and operated parameters on the removal efficiency of the slow sand filters as tertiary treatment units. The removal efficiency of the filters will be evaluated within a statistical framework.

In statistical literature, procedure of selecting the best fitted probability distribution of any type of data is well explained. It is customary to see the fit of the data on available distributions first. These available distributions have some particular qualities and every distribution have distinct characteristic parameters (*e.g.* shape factors and scale factors). The average removal efficiency is calculated by model's characteristic parameters (m, θ). These mean values have been used to develop a statistical regression model which can predict the removal as function of all three controlled variables.

Three distributions namely, Normal, Lognormal and Type III Asymptotic Extreme Value distributions are taken as candidate distributions to removal efficiency of microbial indicators through slow sand filters. Normal distribution is very common distribution and enough information is available in statistical books. The Lognormal distribution has already been discussed. Before using Type III distribution a brief description is given below.

5.3.1 Type III Maximum Extreme Value Asymptotic Distribution Model

The extreme value theory is a blend of an enormous variety of applications involving natural phenomena such as rain fall, floods, wind dusts, air pollution and corrosion, and delicate mathematical results on point processes and regularly varying functions [Kotz, 1995]. Fisher and Tippett [1928] showed that extreme limit distribution can only be of three types.

Generally "*N*" values are quite large, therefore sometimes they are defined as infinity and then a new distribution is developed, called "**asymptotic**" extreme value distribution. Asymptotic extreme value distribution are of three types. To model the bacterial removal data, Type III extreme value distribution which is similar to Weibull 3-parameter distribution is being used. In this model upper limit is specified. These three parameters are "y_m", "θ" and "**m**". "y_m " is the maximum value of the removal efficiency. In this study the removal efficiency is the design variable and its maximum value has been defined as 100%.

The CDF of Type III maxima is given by

$$F_y(y) = \exp\left[-\left(\frac{y_m - y}{\theta}\right)^m\right] \quad (5.6)$$

The "m" and "θ" are the two unknown parameters of the distribution. Where "m" is the shape factor which gives information about the scatter of the data and "θ" is the scale factor.

The mean or expected value of the distribution is given by

$$E(y) = \mu_y = \int_{-\alpha}^{y_m} y\, f(y)\, dy \quad (5.7)$$

After simplification

$$Mean = \mu_y = y_m - \theta\Gamma\left(1 + \frac{1}{m}\right) \quad (5.8)$$

The median value which reflect the value below 50% of the data is given by

$$Median = y_{0.5} = y_m - \theta[Ln(2)]^{1/m} \qquad (5.9)$$

Variance of the distribution reflects scatter in the data, and given by

$$\text{Var} = \sigma^2 = \theta^2 \left[\Gamma\left(1+\frac{2}{m}\right) - \Gamma^2\left(1+\frac{1}{m}\right)\right] \qquad (5.10)$$

[Raudkivi,1979].

where $\Gamma(y)$ is a complete gamma function, also known as the factorial function [Lewis,1978]. It is defined as

$$\Gamma(y) = \int_0^{\alpha} t^{x-1} e^{-t} dt, \qquad y > 0 \qquad (5.11)$$

5.3.2 Selection of Appropriate Distribution for Removal Efficiency

The removal efficiency of bacterial indicators through slow sand filter is fitted on different candidate distributions namely; Normal, Lognormal and Type III maximum extreme value asymptotic distribution. Under steady state conditions the maximum removal efficiency is expected and there is less variation with respect to average response.

The method of moment technique is used to calculate the mean and standard deviation of the experimental data and these parameters were used to develop the PDF and CDF of the hypothesized distributions. The Type III asymptotic distribution is 3-parameter model. To calculate its characteristic parameters a plot was developed (Fig. 5.7) between shape factor "m" and "(y_m-

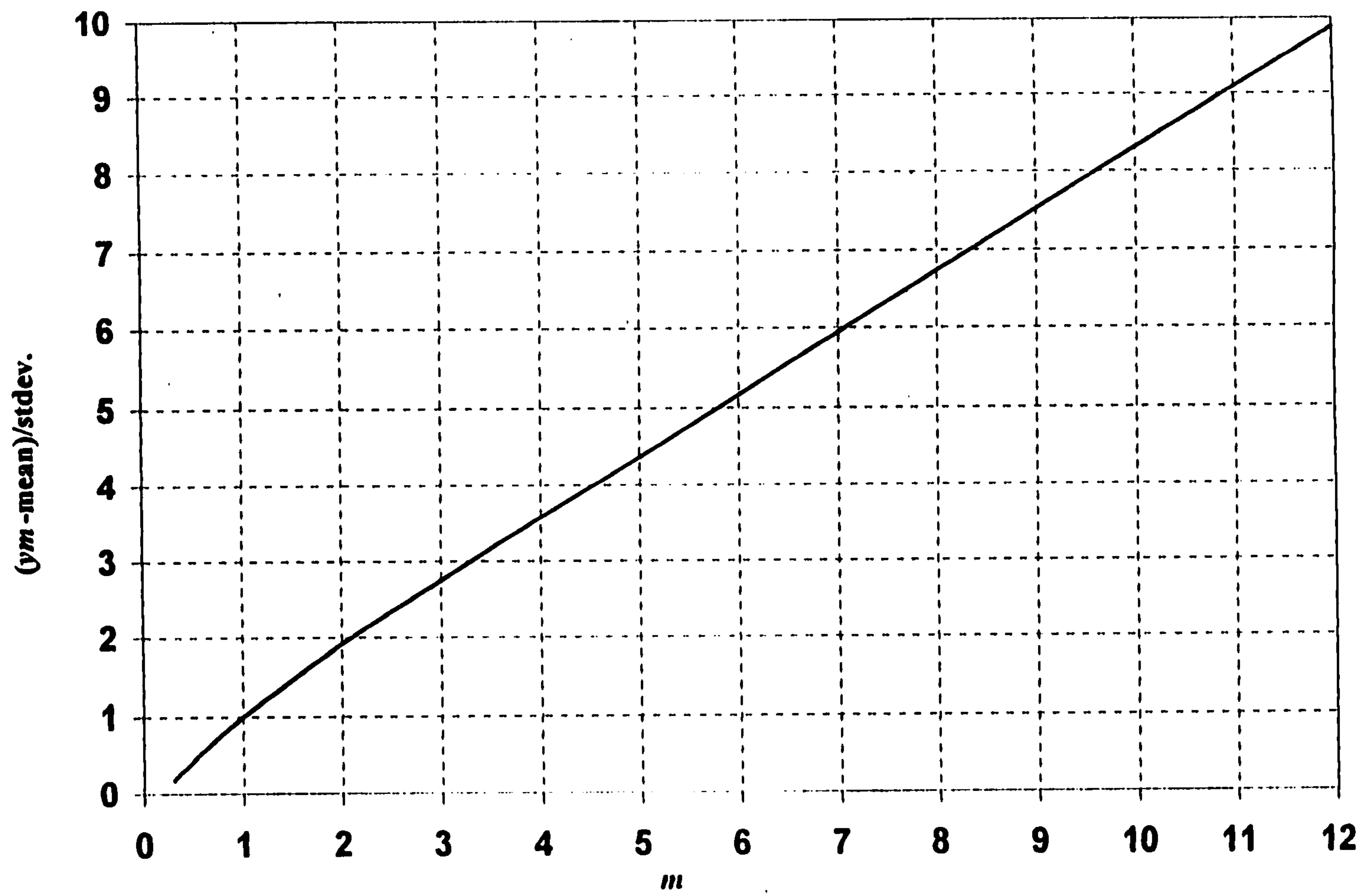

Fig. 5.7: (ym-mean)/stdev. Vs "m" of Type III Asymptotic Distribution

mean)/stand.dev.". This plot gives the shape factor value at known values of mean and standard deviation [Kotz, 1995].

The Eq. 5.8 can be modified as

$$y_m - mean = \theta\Gamma\left(1+\frac{1}{m}\right) \tag{5.12}$$

The standard deviation is given as

$$\sigma = \theta \sqrt{\left[\Gamma\left(1+\frac{2}{m}\right) - \Gamma^2\left(1+\frac{1}{m}\right)\right]} \tag{5.13}$$

Dividing equations 5.12 and 5.13 side by side the following relation is obtained

$$\left(\frac{y_m - mean}{\sigma}\right) = \frac{\Gamma\left(1+\frac{1}{m}\right)}{\sqrt{\Gamma(1+\frac{2}{m}) - \left[\Gamma(1+\frac{1}{m})\right]^2}} \tag{5.14}$$

Now by assuming different values of "m" the L.H.S. factor can be calculated. Then Fig. 5.7 has developed, which gives the relationship between "m" and (y_m-mean)/stand.dev. The Fig. 5.7 is the graphical representation of Equation 5.14. Now under the given condition of data, mean and standard deviation can be calculated by method of moments. So knowing the value of mean and standard deviation "m" can be calculated from Fig. 5.7. After calculating the "m" value from graph the scale factor "θ" can be computed from relationship of mean, as given in equation 5.8.

The total coliform removal efficiency data of condition # 1 is used to develop the histogram as given in Fig. 5.8. One data point is missing for influent reading of total coliform therefore total removal efficiency data points for total coliform are 33 instead of 34. The Normal distribution PDF is plotted on this histogram to see the fit of this distribution. Similarly Lognormal and Type III distribution is also plotted on the same histogram. It can be observed the best fit was obtained for Type III asymptotic distribution. To confirm these results, K-S test was performed on all 14 conditions of total coliform, fecal coliform, standard plate counts and coliphages. The CDFs of three distributions; Normal, Lognormal and Type III, are developed from the available data as given in Table 5.10. The CDF of total coliform condition #1 is plotted in Fig. 5.9. On the same figure the CDF of all three hypothesized distributions are also plotted. The K-S value at 5% significance level is approximately "0.234" The maximum deviation (D_{max}.) calculated for Normal, Lognormal and Type III distribution are 0.289, 0.335 and 0.1000, respectively (Table 5.10). These results confirms the assumption of goodness-of-fit of Type III distribution.

The CDFs for different distributions for total coliform condition # 5 are also calculated from the available data by the estimated mean and standard deviation. In Fig. 5.10 the total coliform removal efficiency data is plotted with its hypothesized distributions. Under this condition there are 38 data points and the corresponding K-S value at 5% significance level is 0.221. The maximum deviation (D_{max}) calculated for Normal, Lognormal and Type III asymptotic

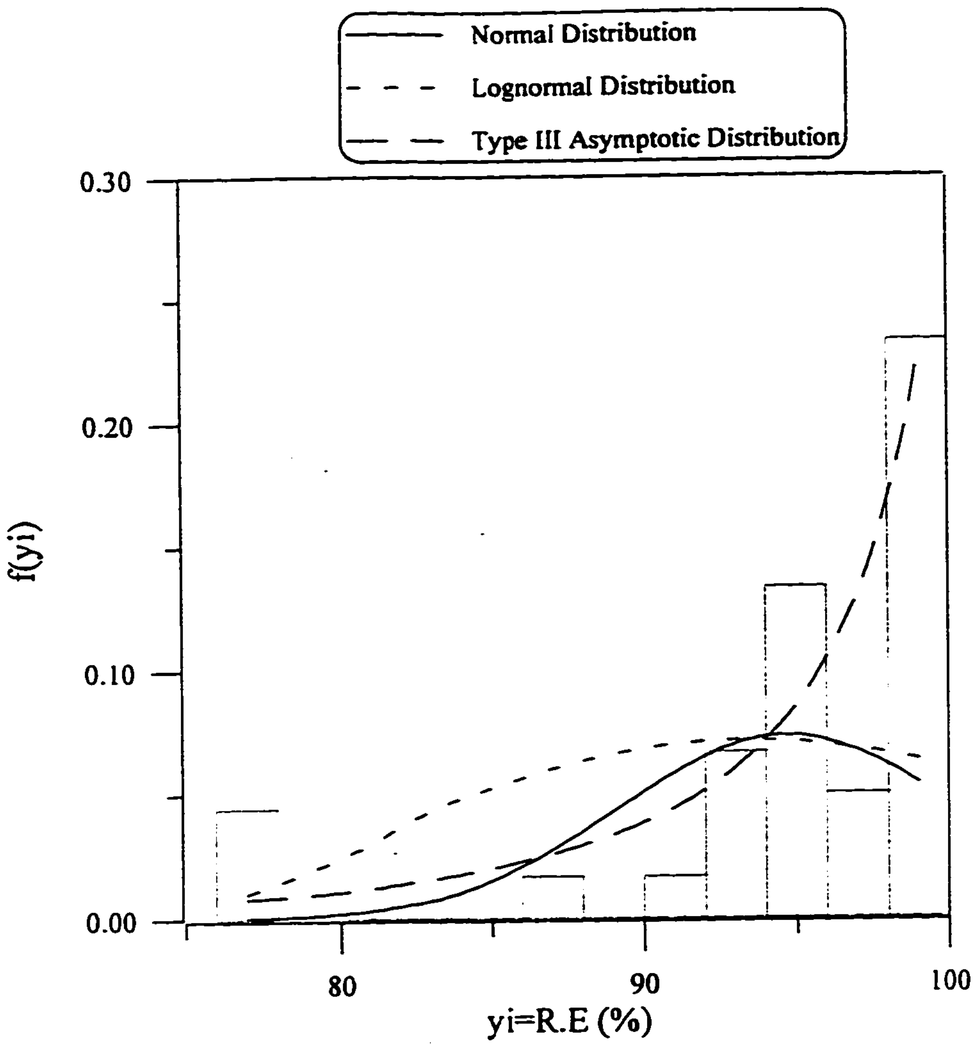

Fig. 5.8: Comparison of Histogram of Original Data and Probablity Density Functions of Candidate Distributions for Total Coliform Removal Efficiency, Condition # 1

Table 5.10: K-S Test Reults for Total Coliform Removal Efficiency Condition #1

Sr. #	*RE=y_i	Ln(RE)	CDF	Normal	Deviation, D	Lognormal	Deviation, D	Type III	Deviation, D
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)	(Col.7)	(Col.8)	(Col.9)	(Col.10)
1	20.588	3.025	0.030	0.000	0.030	0.000	0.030	0.011	0.019
2	34.615	3.544	0.061	0.001	0.060	0.002	0.059	0.018	0.043
3	73.330	4.295	0.091	0.166	0.075	0.294	0.203	0.096	0.005
4	82.581	4.414	0.121	0.330	0.208	0.433	0.312	0.163	0.042
5	83.871	4.429	0.152	0.357	0.205	0.452	0.300	0.177	0.025
6	85.000	4.443	0.182	0.381	0.199	0.468	0.287	0.190	0.008
7	85.397	4.447	0.212	0.390	0.178	0.474	0.262	0.195	0.017
8	87.600	4.574	0.242	0.460	0.218	0.500	0.258	0.217	0.025
9	90.000	4.500	0.273	0.494	0.221	0.540	0.267	0.272	0.000
10	90.000	4.500	0.303	0.494	0.191	0.540	0.237	0.272	0.031
11	90.435	4.505	0.333	0.504	0.170	0.546	0.212	0.282	0.052
12	93.492	4.538	0.364	0.573	0.210	0.586	0.223	0.366	0.002
13	93.529	4.538	0.394	0.574	0.180	0.587	0.193	0.367	0.027
14	94.286	4.546	0.424	0.591	0.167	0.597	0.172	0.395	0.030
15	94.733	4.551	0.455	0.601	0.147	0.602	0.148	0.413	0.042
16	95.000	4.554	0.485	0.607	0.122	0.606	0.121	0.424	0.061
17	95.400	4.558	0.515	0.616	0.101	0.611	0.096	0.442	0.073
18	95.741	4.562	0.545	0.623	0.078	0.615	0.070	0.459	0.087
19	96.076	4.565	0.576	0.631	0.055	0.619	0.044	0.476	**0.100**
20	97.143	4.576	0.606	0.653	0.047	0.632	0.026	0.541	0.065
21	97.419	4.579	0.636	0.659	0.023	0.636	0.001	0.561	0.075
22	98.125	4.586	0.667	0.674	0.007	0.644	0.023	0.621	0.046
23	98.542	4.590	0.697	0.683	0.014	0.649	0.048	0.664	0.033
24	98.667	4.592	0.727	0.685	0.042	0.651	0.077	0.678	0.049
25	99.444	4.600	0.758	0.701	0.057	0.660	0.098	0.795	0.037
26	99.625	4.601	0.788	0.704	0.084	0.662	0.126	0.834	0.046
27	99.646	4.602	0.818	0.705	0.113	0.662	0.156	0.839	0.021
28	99.746	4.603	0.848	0.707	0.142	0.663	0.185	0.866	0.018
29	99.792	4.603	0.879	0.708	0.171	0.664	0.215	0.880	0.002
30	99.898	4.604	0.909	0.710	0.199	0.665	0.244	0.920	0.011
31	99.931	4.604	0.939	0.710	0.229	0.665	0.274	0.936	0.003
32	99.939	4.605	0.970	0.711	0.259	0.665	0.304	0.941	0.029
33	99.946	4.605	1.000	0.711	**0.289**	0.665	**0.335**	0.945	0.055
Mean	**89.986**	**4.468**							
Stdev.	**17.391**	**0.320**							
C.V.	**0.193**								

*R.E.=Removal Efficiency (%) = y_i

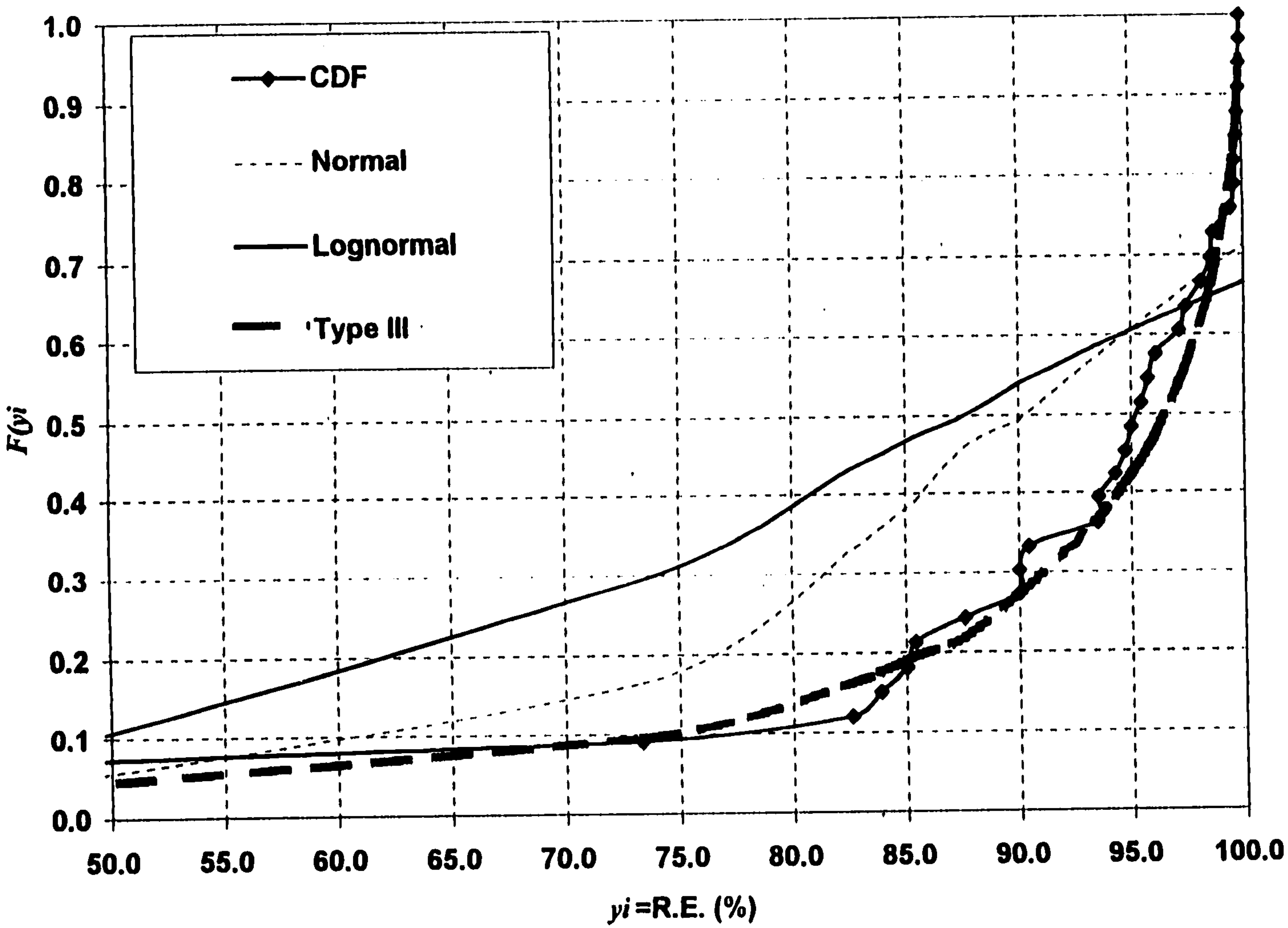

Fig. 5.9: CDF of Removal Efficiency of Total Coliform Condition #1

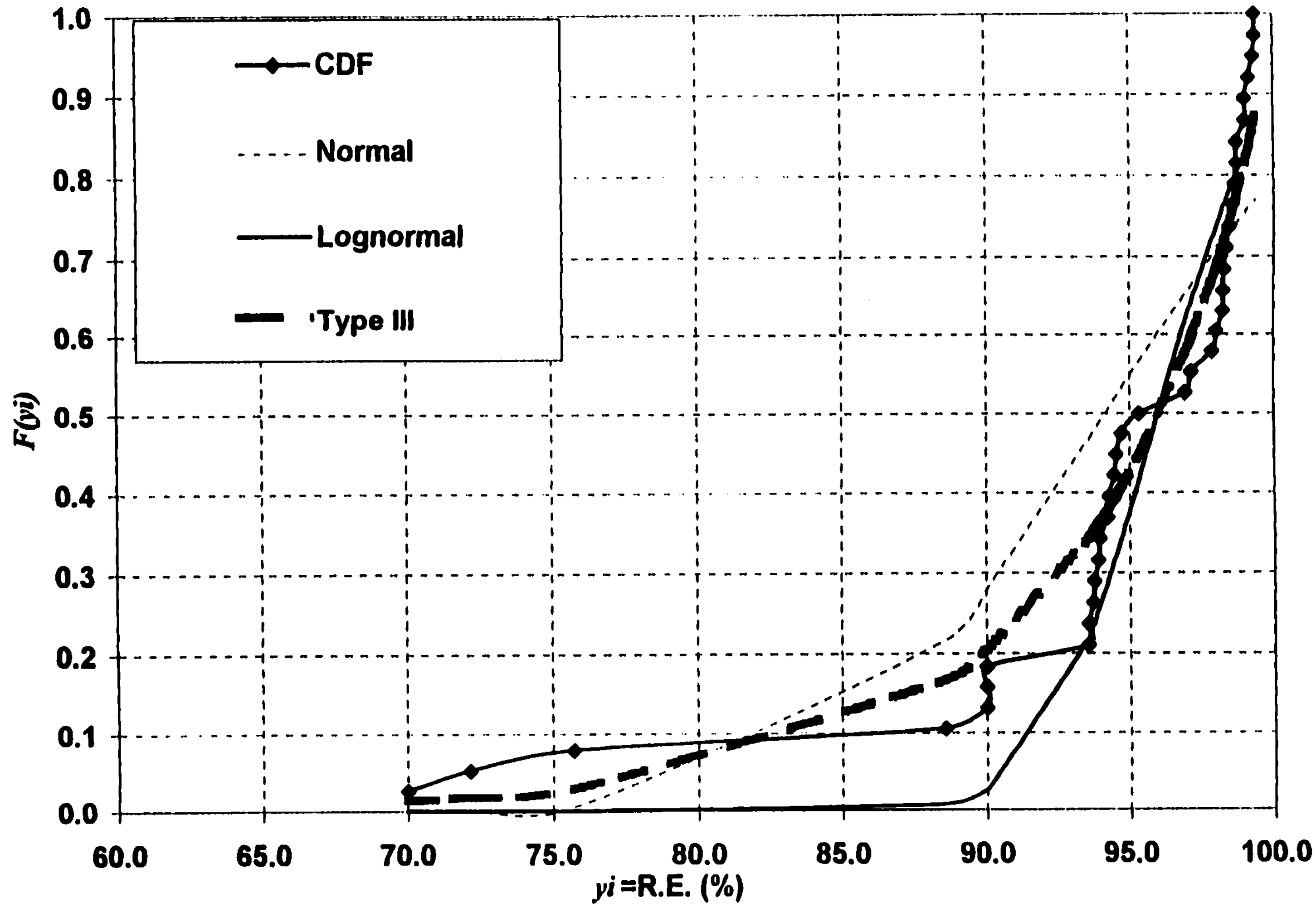

Fig. 5.10: CDF of Removal Efficiency of Total Coliform Condition#5

distribution are 0.2552, 0.1583 and 0.1319, respectively (Table 5.11). Although Lognormal and Type III distribution both are candidate for that data but the minimum deviation is obtained from Type III distribution.

The summary of K-S test results are given in Table 5.12. These results show that Type III asymptotic distribution is candidate for total coliform data in 8 conditions out of 14. And in other conditions it was within the limit of K-S critical value of 5% significance level. The fecal coliform data is best fitted on 12 conditions out of available 14 conditions. Similarly the standard plate count data confirm its best fit for 8 conditions and in the remaining 6 conditions the maximum deviation of Type III distribution was within 5% K-S value. For the coliphages removal efficiency the Type III distribution was proved to be best distribution for 6 conditions, whereas, Lognormal distribution was the best distribution for 4 conditions and Normal distribution for remaining 4 conditions. But the Type III distribution was again within the permissible critical value of K-S at 5 % significance level.

To visualize the suitability of candidacy of any particular distribution, Table 5.13 have been developed. The conditions with data points lees than 9 are not taken into account to make results more authentic and acceptable. According to this summary 12 conditions are valid conditions for all microorganisms. For total coliform 25% conditions are best represented by Normal Distribution. Similarly, 16.7% by Lognormal and 50% by Type III distribution. In case of fecal coliform 0, 0, and 83.3% are best fitted on Normal, Lognormal and Type III Distributions,

Table 5.11: K-S Test Reults for Total Coliform Removal Efficiency Condition #5

Sr. #	*RE=y_i	L(RE)	CDF	Normal	Deviation,	Lognormal	Deviation, D	Type III	Deviation, D
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)	(Col.7)	(Col.8)	(Col.9)	(Col.10)
1	70.000	4.248	0.0263	0.0003	0.0260	0.0000	0.0263	0.0140	0.0123
2	72.152	4.279	0.0526	0.0010	0.0517	0.0000	0.0526	0.0184	0.0342
3	75.714	4.327	0.0789	0.0047	0.0743	0.0000	0.0789	0.0293	0.0496
4	88.57	4.484	0.1053	0.2161	0.1108	0.0075	0.0977	0.1667	0.0615
5	90.00	4.500	0.1316	0.2796	0.1481	0.0259	0.1057	0.2042	0.0727
6	90.00	4.500	0.1579	0.2796	0.1217	0.0259	0.1320	0.2042	0.0464
7	90.00	4.500	0.1842	0.2796	0.0954	0.0259	**0.1583**	0.2042	0.0200
8	93.53	4.538	0.2105	0.4657	**0.2552**	0.2178	0.0073	0.3418	**0.1313**
9	93.55	4.538	0.2368	0.4667	0.2299	0.2197	0.0172	0.3428	0.1059
10	93.71	4.540	0.2632	0.4761	0.2129	0.2359	0.0273	0.3514	0.0882
11	93.75	4.541	0.2895	0.4781	0.1886	0.2394	0.0500	0.3533	0.0638
12	93.89	4.542	0.3158	0.4859	0.1701	0.2536	0.0622	0.3607	0.0449
13	93.93	4.543	0.3421	0.4881	0.1460	0.2577	0.0844	0.3629	0.0208
14	94.20	4.545	0.3684	0.5034	0.1350	0.2867	0.0817	0.3780	0.0096
15	94.26	4.546	0.3947	0.5067	0.1120	0.2932	0.1015	0.3814	0.0133
16	94.44	4.548	0.4211	0.5171	0.0961	0.3140	0.1070	0.3922	0.0288
17	94.52	4.549	0.4474	0.5212	0.0738	0.3222	0.1251	0.3965	0.0508
18	94.69	4.551	0.4737	0.5311	0.0574	0.3429	0.1308	0.4074	0.0663
19	95.31	4.557	0.5000	0.5653	0.0653	0.4171	0.0829	0.4475	0.0525
20	96.92	4.574	0.5263	0.6527	0.1264	0.6181	0.0918	0.5770	0.0507
21	97.14	4.576	0.5526	0.6640	0.1114	0.6440	0.0914	0.5979	0.0452
22	97.85	4.583	0.5789	0.6994	0.1205	0.7217	0.1427	0.6711	0.0921
23	98.00	4.585	0.6053	0.7069	0.1017	0.7374	0.1321	0.6886	0.0833
24	98.24	4.587	0.6316	0.7182	0.0867	0.7605	0.1290	0.7165	0.0849
25	98.25	4.588	0.6579	0.7189	0.0610	0.7619	0.1041	0.7183	0.0604
26	98.26	4.588	0.6842	0.7195	0.0352	0.7630	0.0788	0.7196	0.0354
27	98.35	4.589	0.7105	0.7237	0.0131	0.7714	0.0609	0.7306	0.0201
28	98.46	4.590	0.7368	0.7288	0.0081	0.7814	0.0445	0.7444	0.0075
29	98.57	4.591	0.7632	0.7338	0.0294	0.7911	0.0279	0.7584	0.0047
30	98.62	4.591	0.7895	0.7361	0.0534	0.7953	0.0059	0.7649	0.0246
31	98.69	4.592	0.8158	0.7396	0.0762	0.8020	0.0138	0.7752	0.0405
32	98.70	4.592	0.8421	0.7399	0.1022	0.8026	0.0395	0.7763	0.0658
33	99.00	4.595	0.8684	0.7535	0.1149	0.8272	0.0413	0.8188	0.0497
34	99.00	4.595	0.8947	0.7535	0.1413	0.8272	0.0676	0.8188	0.0760
35	99.13	4.596	0.9211	0.7594	0.1617	0.8374	0.0837	0.8388	0.0823
36	99.30	4.598	0.9474	0.7666	0.1807	0.8496	0.0978	0.8650	0.0824
37	99.35	4.599	0.9737	0.7687	0.2050	0.8530	0.1207	0.8727	0.1009
38	99.35	4.599	1.0000	0.7690	0.2310	0.8535	0.1465	0.8739	0.1261
Mean	**94.14**	**4.542**							
Stdev.	**7.09**	**0.083**							
C.V.	**0.0753**								

*R.E.=Removal Efficiency (%) = y_i

Table 5.12: Summary of K-S Test for Removal Efficiency Data

Indicator	Condition #	Data points	K-S, 5%	Normal	Lognormal	Type III
T. Coliform	1	33	0.234	0.289	0.335	0.100
	2	10	0.41	0.1364	0.1311	0.1576
	3	14	0.349	0.35318	0.2665	0.3345
	4	17	0.318	0.1443	0.1466	0.1589
	5	38	0.221	0.2552	0.1583	0.1313
	6*	6	0.521	0.2115	0.2102	0.21262
	7	14	0.349	0.1245	0.1256	0.1264
	8	17	0.318	0.2424	0.2538	0.2567
	9	9	0.412	0.2299	0.3307	0.12244
	10	38	0.221	0.274	0.3023	0.2505
	11	14	0.349	0.2989	0.3073	0.2026
	12*	6	0.521	0.1613	0.1583	0.15074
	13	17	0.318	0.1998	0.1906	0.1676
	14	9	0.432	0.2229	0.2186	0.21274
F. Coliform	1	27	0.255	0.3187	0.2578	0.222
	2	10	0.41	0.157	0.1608	0.1562
	3	14	0.349	0.4999	0.256	0.2376
	4	17	0.318	0.1092	0.1082	0.1071
	5	31	0.238	0.3405	0.3593	0.2714
	6*	6	0.521	0.1925	0.198	0.1625
	7	14	0.349	0.128	0.1385	0.1147
	8	17	0.318	0.1629	0.1625	0.1541
	9	9	0.432	0.2999	0.2936	0.2724
	10	30	0.24	0.2699	0.2955	0.2858
	11	14	0.349	0.3089	0.3344	0.2948
	12*	6	0.521	0.2716	0.2952	0.289
	13	17	0.318	0.1426	0.1425	0.1381
	14	9	0.432	0.1397	0.1419	0.1367

* These conditions will not be considered while making final conclusions due to low number of data points

Table 5.12: (Contd.) Summary of K-S Test for Removal Efficiency Data

Indicator	Condition #	Data points	Ks, 5%	Normal	Lognormal	Type III
S.P.Counts	1	34	0.232	0.1232	0.1274	0.0735
	2	10	0.41	0.2066	0.2071	0.162
	3.	14	0.349	0.1425	0.1524	0.1342
	4	17	0.318	0.1354	0.1388	0.1597
	5	37	0.2236	0.2904	0.31	0.2879
	6*	6	0.521	0.15708	0.146	0.2401
	7	14	0.349	0.207	0.197	0.2381
	8	17	0.318	0.147	0.157	0.1685
	9	9	0.432	0.142	0.1547	0.189
	10	37	0.2236	0.1647	0.1619	0.1454
	11	14	0.349	0.1299	0.3088	0.1745
	12*	6	0.521	0.1842	0.1832	0.1708
	13	17	0.318	0.1009	0.473	0.0908
	14	9	0.432	0.1229	0.1235	0.1215
Coliphage	1	28	0.25	0.20617	0.2608	0.2295
	2	10	0.41	0.1787	0.1655	0.17464
	3	14	0.349	0.19296	0.1862	0.1832
	4	17	0.318	0.178	0.1752	0.1616
	5	37	0.223	0.1037	0.1033	0.1132
	6*	6	0.521	0.1832	0.1865	0.1753
	7	14	0.349	0.228	0.2153	0.1989
	8	17	0.318	0.2332	0.2576	0.2633
	9	9	0.432	0.162	0.1706	0.1142
	10	38	0.2206	0.1984	0.1916	0.2188
	11	14	0.349	0.1849	0.195	0.1999
	12*	6	0.521	0.15796	0.1634	0.1522
	13	17	0.318	0.1787	0.4738	0.229
	14	9	0.432	0.2002	0.199	0.22

* These conditions will not be considered while making final conclusions due to low number of data points

Table 5.13: Summary of Validity of Different Candidate Distributions to Removal Efficiency Data

Indicator	Total Conds.	Valid Conds.	Non Validity of K-S Test (%)	Normal (%)	Lognormal (%)	Type III (%)
Total Coliform	14	12	8.3	25.0	16.7	50.0
Fecal Coliform	14	12	16.7	0.0	0.0	83.3
S.Plate Counts	14	12	8.3	33.3	8.3	50.0
Coliphage	14	12	0.0	33.3	33.3	33.3

respectively. 16.7% of the conditions were not fitted to any distribution at 5% significance level. For standard plate counts the percent fitness of Normal, Lognormal and Type III distributions are 33.3%, 8.3% and 50%, respectively to removal efficiency data. In case of coliphages Normal, Lognormal and Type III distributions are representing respectively 33.3%, 33.3% and 33.3% of the valid conditions

5.3.3 Modeling of Slow Sand Filter Removal Efficiency

In addition to K-S test coupled with parameter estimation by method of moments, the selected distribution was fitted to the data by regression analysis to further provide the confidence on the fit of the distribution through the observed R^2 value. The estimated parameters of the distribution with this method will later be used to develop mean response model as function of operating conditions.

5.3.3.1 Computational Procedure

To plot the data on the Type III distribution, linearization of Eq. (5.6) is required. The linearized form of the Eq. is

$$\mathrm{Ln}\,\mathrm{Ln}\,(1/F(y)) = m\,\mathrm{Ln}\,(y_m - y) - m\,\mathrm{Ln}\,\theta \qquad (5.15)$$

If Ln Ln$(1/F(y))$ is taken on y-axis and Ln $(y_m - y)$ on the x-axis then characteristic parameters "m" and "θ" can be calculated from intercept and slope.

The following steps are being used to fit the data on the extreme value distribution.

- The probability of the data is calculated by mean rank formula [Lewis,1978].

$$\hat{F} = \hat{i}/(N+1) \tag{5.16}$$

where "N" is the total no. of data points in the distribution

- The removal efficiency (y) is then calculated by

$$y = \left(\frac{I-E}{I}\right)100 \tag{5.17}$$

Where "I" is the influent concentration of pollutants and "E" is the effluent concentration.

(y_m–y)and Ln (y_m–y) are then calculated and ordered.

- Calculate LnLn $\left(\frac{1}{F}\right)$

- The plot of LnLn $\left(\frac{1}{F}\right)$ vs. Ln (y_m–y) is drawn.

Same types of plots are made for all different conditions of operation.

The characteristics parameters "m" and "θ" are calculated by the equation of straight line. These parameters are then used to calculate the mean, mode, median and variance. The coefficient of determinations (R^2) gives the indication of goodness of the fit of data. Therefore the other two parameters, i.e., shape factor (m) and scale factor (θ) can be calculated using probability plots.

5.3.4 Probability Plotting of Removal Efficiency

Total coliform, fecal coliform, total plate counts and coliphages are studied as indicator microorganisms in this study. All four microorganisms were sampled on weekly basis, therefore, due to different filter run lengths the number of data points for all 14 different conditions were different.

The analysis of condition # 1 for total coliform removal efficiency is given in Table 5.14. The mean ranking formula is used to calculate the plotting positions of the data points (Col. 2). The 6th col. of Table 5:14 shows the removal efficiency of the filter in ascending order. The last two columns, i.e., col 8 and 9 of the same table when plotted, gave a good fit of the data as shown by a straight line in Fig. 5.11. The criteria for the fitting of the data is the coefficient of determination (R^2) which should be closer to "1" for good fit, but if the R^2 value is small then it implies that the data lack in fit. The R^2 value of fit for total coliform in condition #1 was approximately 0.97 which is very high indicating good fit.

When this procedure is repeated for other conditions, similar results were obtained. The summary of these results are given in Table 5.15. The "m" and "θ" values were calculated by equating the Eq. 5.15 with equation of straight line shown in Fig. 5.11. Table 5.15 gives the details of median, mean and variance of data. The standard deviation of the data was 10.6 for condition #1 of the total coliform and the mean value was 96.5%. In all other conditions the removal efficiencies of total coliform were more than 90% except for conditions # 4, # 8, #

Table 5.14: Spreadsheet to Fit Extreme Value Distribution to Total Coliform Removal Efficiency Cond. #1

Sr. # (i)	*F=i/(N+1)*	*INFL. (I)*	*Effl. (E)*	*R.E*.(y)*	*Ordered Eff."y"*	*(ym-y)*	*Ln(ym-y)*	*LnLn[1/F(y)]*
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)	(Col.7)	(Col.8)	(Col.9)
1	0.0294	2.40E+05	3.50E+03	98.542	20.588	79.412	4.375	1.260
2	0.0588	1.70E+04	1.10E+03	93.529	34.615	65.385	4.180	1.041
3	0.0882	5.40E+05	5.40E+04	90.000	73.333	26.667	3.283	0.887
4	0.1176	3.10E+03	8.00E+01	97.419	82.581	17.419	2.858	0.761
5	0.1471	2.40E+05	1.30E+02	99.946	83.871	16.129	2.781	0.651
6	0.1765	1.30E+05	2.70E+02	99.792	85.000	15.000	2.708	0.551
7	0.2059	4.90E+05	3.40E+02	99.931	85.397	14.603	2.681	0.458
8	0.2353	1.50E+04	7.90E+02	94.733	86.923	13.077	2.571	0.369
9	0.2647	4.90E+04	5.00E+01	99.898	90.000	10.000	2.303	0.285
10	0.2941	1.30E+05	3.30E+02	99.746	90.000	10.000	2.303	0.202
11	0.3235	2.60E+05	1.70E+05	34.615	90.435	9.565	2.258	0.121
12	0.3529	2.30E+05	2.20E+04	90.435	93.492	6.508	1.873	0.041
13	0.3824	3.40E+05	2.70E+05	20.588	93.529	6.471	1.867	-0.039
14	0.4118	1.70E+05	1.70E+04	90.000	94.286	5.714	1.743	-0.120
15	0.4412	2.80E+05	1.40E+04	95.000	94.733	5.267	1.661	-0.201
16	0.4706	5.40E+05	2.30E+04	95.741	95.000	5.000	1.609	-0.283
17	0.5000	1.30E+05	1.70E+04	86.923	95.400	4.600	1.526	-0.367
18	0.5294	3.10E+05	5.40E+04	82.581	95.741	4.259	1.449	-0.453
19	0.5588	6.30E+05	9.20E+04	85.397	96.076	3.924	1.367	-0.541
20	0.5882	5.00E+05	2.30E+04	95.400	97.143	2.857	1.050	-0.634
21	0.6176	7.90E+05	3.10E+04	96.076	97.419	2.581	0.948	-0.730
22	0.6471	6.30E+05	4.10E+04	93.492	98.125	1.875	0.629	-0.832
23	0.6765	5.40E+05	3.00E+03	99.444	98.542	1.458	0.377	-0.939
24	0.7059	3.20E+05	6.00E+03	98.125	98.667	1.333	0.288	-1.055
25	0.7353	8.20E+05	2.90E+03	99.646	99.444	0.556	-0.588	-1.179
26	0.7647	8.00E+05	3.00E+03	99.625	99.625	0.375	-0.981	-1.316
27	0.7941	7.00E+05	4.00E+04	94.286	99.646	0.354	-1.039	-1.467
28	0.8235	3.10E+05	5.00E+04	83.871	99.746	0.254	-1.371	-1.639
29	0.8529	2.00E+04	3.00E+03	85.000	99.792	0.208	-1.572	-1.838
30	0.8824	3.00E+04	8.00E+03	73.333	99.898	0.102	-2.282	-2.078
31	0.9118	6.00E+05	8.00E+03	98.667	99.931	0.069	-2.668	-2.382
32	0.9412	4.90E+05	3.00E+02	99.939	99.939	0.061	-2.793	-2.803
33	0.9706	7.00E+05	2.00E+04	97.143	99.946	0.054	-2.916	-3.511

*R.E.= Removal Efficiency (%) = y_i

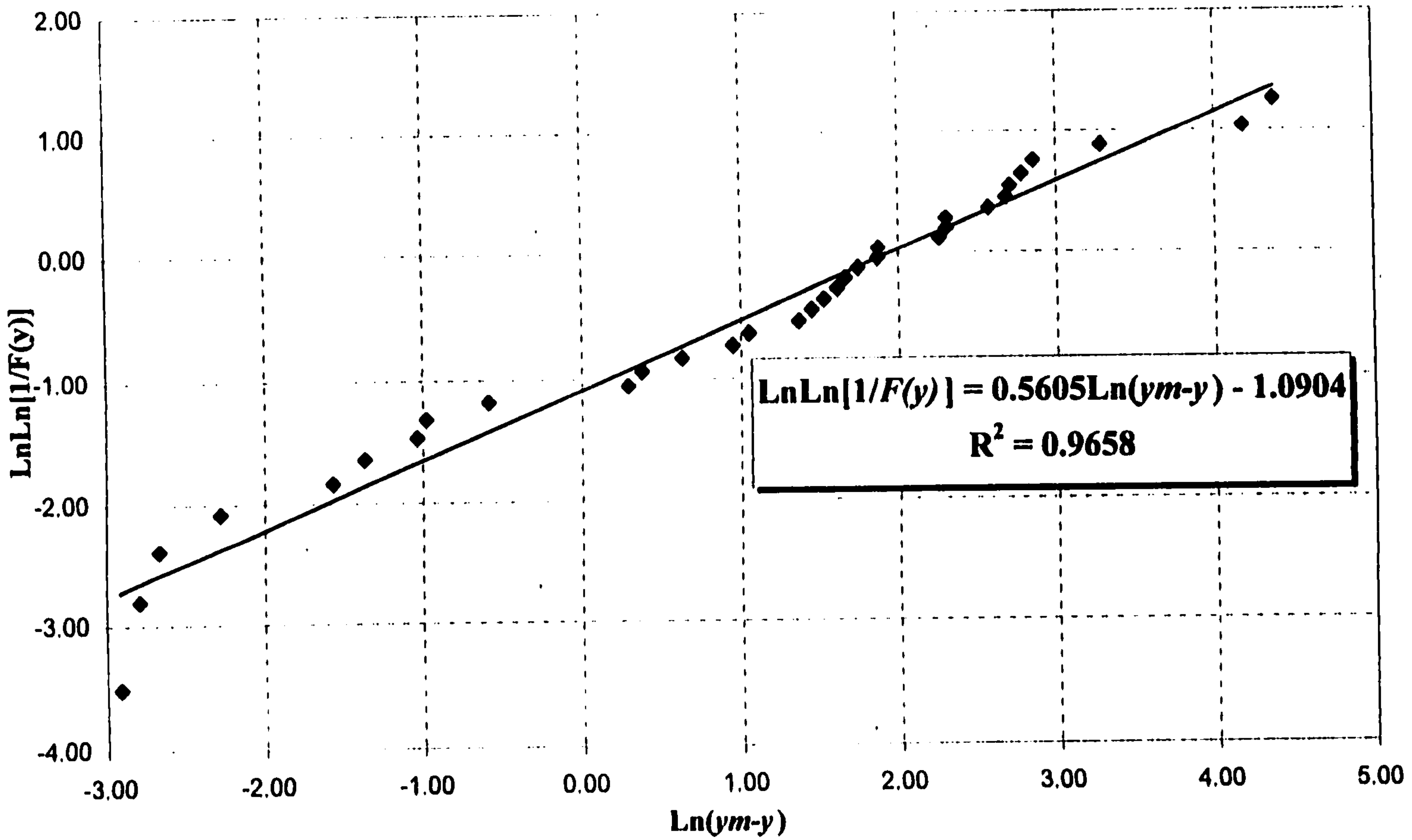

Fig. 5.11: Fit of Type III Asymptotic Maximum Extreme Value Distribution To Characterize the Removal Efficiency of Total Coliform, Condition# 1

Table 5.15: Removal Efficiency of Total Coliform At Various Operational Conditions

Condition #	q (L/min)	d (cm)	c (mm)	R^2	# of Observations	m	θ	*y med.*	*y mean*	VAR.	Standev.
1	8	150	0.5	0.966	33	0.56	7.00	96.36	96.48	112.38	10.60
2	10	150	0.5	0.886	10	2.06	2.96	97.52	97.38	1.78	1.33
3	10	80	0.5	0.988	14	4.44	2.72	97.50	97.52	0.40	0.63
4	10	50	0.5	0.894	17	4.93	17.51	83.75	83.94	13.90	3.73
5	16	150	0.3	0.926	38	0.96	5.49	96.25	94.40	34.09	5.84
6	20	150	0.3	0.920	6	1.11	2.49	98.21	97.61	4.66	2.16
7	20	80	0.3	0.938	14	2.11	6.31	94.70	94.41	7.77	2.79
8	20	50	0.3	0.779	17	4.19	23.00	78.93	79.10	31.61	5.62
9	10	50	0.3	0.922	9	4.84	12.32	88.58	88.71	7.10	2.66
10	16	150	0.5	0.823	38	1.30	5.44	95.90	94.98	15.19	3.90
11	20	150	0.5	0.948	14	1.24	5.93	95.59	94.47	20.17	4.49
12	20	80	0.5	0.970	6	2.82	10.00	91.22	91.09	11.74	3.43
13	20	80	0.5	0.943	17	5.73	22.44	78.95	79.24	17.62	4.20
14	16	50	0.5	0.882	9	6.30	1.15	98.91	98.93	0.04	0.20

9 and # 13. In these conditions either flow rate was very high or sand depth was very low (Table 5.15). The analysis of data for these conditions showed that in all these cases the standard deviation values were smaller than 10. Lower variation in the data for other conditions implied that removal efficiency fluctuations were not significant over time. The reason of very high standard deviation in cond. #1 of total coliform is that in two readings the removal efficiency was even less than 40%. Whereas in remaining 31 readings (data points) the removal efficiency was varying from 73 to 99.95% as shown in Table 5.14. These readings could possibly imparted by human error. The fits of the data were good in all conditions and coefficient of determination values were satisfactorily high (0.78-0.99), indicating the good fit of Type III distribution.

Removal efficiency of fecal coliform data when plotted, gave, satisfactory fit to Type III distribution. The data of Table 5.16, plotted for condition # 1 are shown in Fig 5.12 and its results are quite similar to total coliform results. The summary of all 14 conditions for fecal coliform are given in Table 5.17. Generally the average removal efficiency for fecal coliform was less than total coliform efficiency. In secondary wastewater effluent generally the total coliform population is not much different from fecal coliforms, but the data obtained in this study revealed that total coliforms were more than twice in numbers than fecal coliforms [Khan,1996]. The standard deviation of the fecal coliform data indicated more variation than the total coliform in most of the cases.

Table 5.16: Spreadsheet to Fit Extreme Value Distribution to Fecal Coliform Removal Efficiency Cond. #1

Sr. # (i)	*F= i/(N+1)*	*R.E.*(%)*	*(ym-y)*	*Ln(ym-y)*	*LnLn[1/F(y)]*
1	0.0357	55.0000	45.0000	3.8067	1.2036
2	0.0714	66.0000	34.0000	3.5264	0.9704
3	0.1071	77.1429	22.8571	3.1293	0.8036
4	0.1429	90.0000	10.0000	2.3026	0.6657
5	0.1786	90.0000	10.0000	2.3026	0.5439
6	0.2143	90.0000	10.0000	2.3026	0.4321
7	0.2500	90.0000	10.0000	2.3026	0.3266
8	0.2857	90.0000	10.0000	2.3026	0.2254
9	0.3214	90.2174	9.7826	2.2806	0.1266
10	0.3571	92.6667	7.3333	1.9924	0.0292
11	0.3929	92.9032	7.0968	1.9596	-0.0679
12	0.4286	93.3333	6.6667	1.8971	-0.1657
13	0.4643	93.4615	6.5385	1.8777	-0.2649
14	0.5000	93.5294	6.4706	1.8673	-0.3665
15	0.5357	94.5000	5.5000	1.7047	-0.4714
16	0.5714	94.5161	5.4839	1.7018	-0.5805
17	0.6071	94.8837	5.1163	1.6324	-0.6952
18	0.6429	95.5000	4.5000	1.5041	-0.8168
19	0.6786	95.6000	4.4000	1.4816	-0.9474
20	0.7143	95.6522	4.3478	1.4697	-1.0892
21	0.7500	95.8824	4.1176	1.4153	-1.2459
22	0.7857	96.0000	4.0000	1.3863	-1.4223
23	0.8214	96.0000	4.0000	1.3863	-1.6260
24	0.8571	96.3636	3.6364	1.2910	-1.8698
25	0.8929	96.7742	3.2258	1.1712	-2.1775
26	0.9286	98.0000	2.0000	0.6931	-2.6022
27	0.9643	98.0000	2.0000	0.6931	-3.3141

*R.E.=Removal Efficiency (%) = y_i

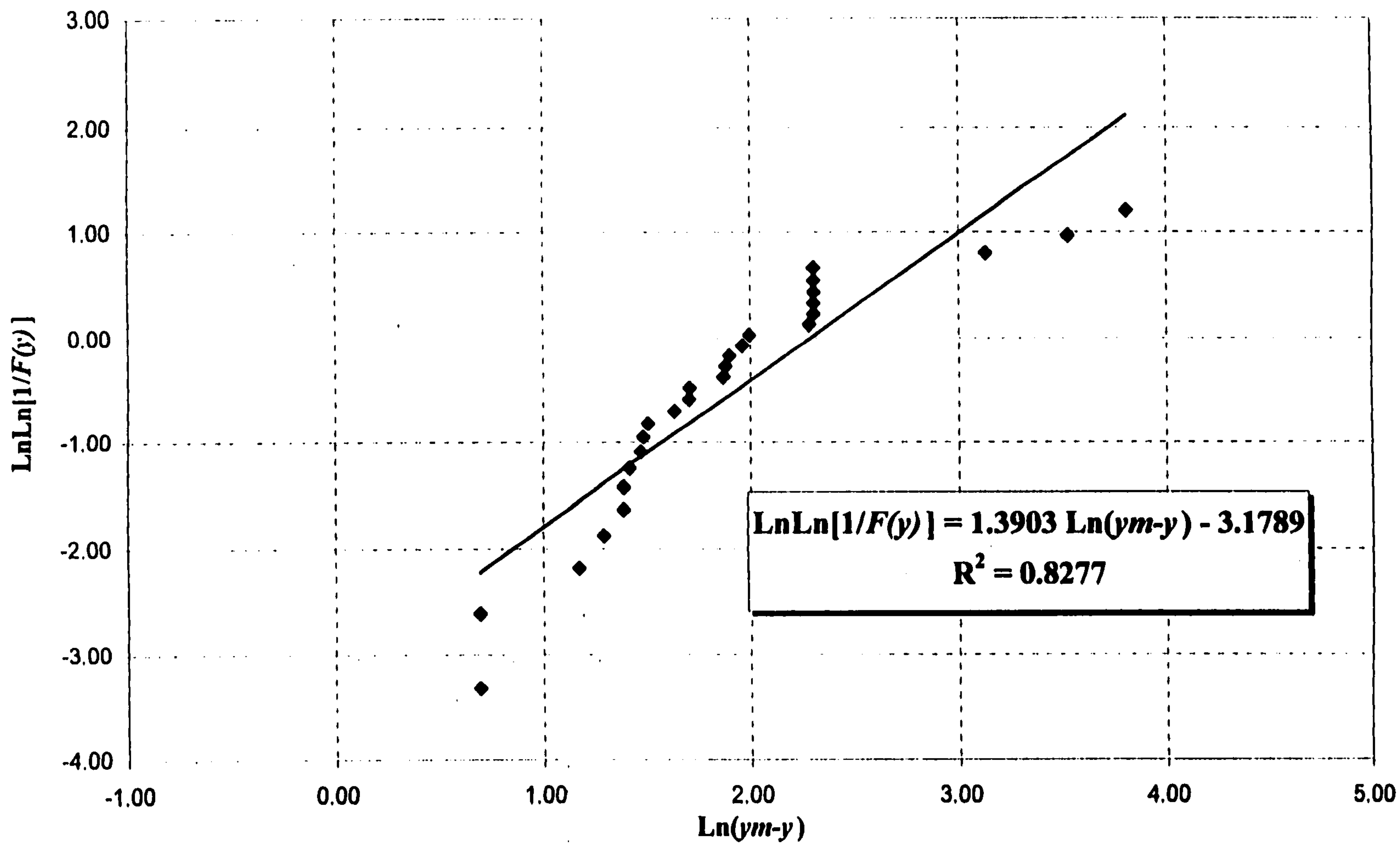

Fig. 5.12: Fit For Type III Asymptotic Maximum Extreme Value Distribution To Charcterize The Removal Efficiency of Fecal Coliform, Condition # 1

Table 5.17: Removal Efficiency Of Fecal Coliform at Various Operational Conditions

Condition #	q (L/min)	d (cm)	c (mm)	R^2	# of Observations	m	θ	y med.	y mean	VAR.	Standev.
1	8	150	0.5	0.828	27	1.39	9.85	92.44	91.02	42.84	6.55
2	10	150	0.5	0.894	10	2.39	2.89	97.52	97.44	1.31	1.14
3	10	80	0.5	0.807	14	1.41	1.75	98.65	98.40	1.32	1.15
4	10	50	0.5	0.952	17	4.38	16.11	85.18	85.32	14.39	3.79
5	16	150	0.3	0.732	31	1.25	9.92	92.60	90.77	54.95	7.41
6	20	150	0.3	0.948	6	1.17	3.45	97.48	96.73	7.90	2.81
7	20	80	0.3	0.949	14	1.67	11.78	90.55	89.47	42.19	6.50
8	20	50	0.3	0.963	17	2.75	21.11	81.52	81.22	54.48	7.38
9	10	50	0.3	0.883	9	4.12	14.09	87.11	87.21	12.23	3.50
10	16	150	0.5	0.796	30	1.29	7.32	94.50	93.23	28.12	5.30
11	20	150	0.5	0.815	14	0.84	7.60	95.09	91.65	100.66	10.03
12	20	80	0.5	0.733	6	0.96	23.19	84.16	76.40	603.56	24.57
13	20	80	0.5	0.979	17	3.69	21.62	80.42	80.49	34.59	5.88
14	16	50	0.5	0.946	9	6.60	17.28	83.65	83.89	8.18	2.86

The analysis of condition #1 of standard plate count is given in Table 5.18. Its corresponding plot is given in Fig.5.13. The summary results of standard plate counts for all other conditions are given in Table 5.19. High removal efficiencies were observed in most of the conditions. Mean removal efficiency was again used as the criteria of filter performance over a complete filter run. In statistical terms the mean values are generally referred to as expected values of the results, that implies if the data is very large, this calculated mean could be the possible expected result. So mean values could be the best estimate and indicator of the filter's overall performance. The results of standard plate counts are similar to total coliform. The standard deviation in condition # 6 is higher (40.74), whereas, in remaining 13 conditions, the data showed smaller variations (less than 6.6) with respect to mean response. This could possibly due to lesser number of data points.

The analysis of condition #1 of the coliphage is given in Table 5.20. The corresponding probability plot for condition #1 is given in Fig.5.14. The summary of all 14 conditions of the fitted distribution of coliphage are given in Table 5.21. The coliphage were the only virus group studied in this research. The mean removal efficiency in all conditions was higher than the 82%. Higher removals of viruses are the indicator of the fact that mechanisms of removal other than straining are also present. The smaller particles usually with the size of 0.01 μm (this is the average size of virus) are removed by diffusion or Brownian motion

Table 5.18: Spreadsheet to Fit Extreme Value Distribution to Standard Plate Counts Removal Efficiency Cond. #1

SR. # (i)	*F= i/(N+1)*	*R.E.*(%)*	*(ym-y)*	*Ln(ym-y)*	*LnLn[1/F(y)]*
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)
1	0.0286	82.9268	17.0732	2.8375	1.2685
2	0.0571	89.0244	10.9756	2.3957	1.0516
3	0.0857	90.2439	9.7561	2.2779	0.8988
4	0.1143	91.2195	8.7805	2.1725	0.7743
5	0.1429	92.5000	7.5000	2.0149	0.6657
6	0.1714	92.5000	7.5000	2.0149	0.5674
7	0.2000	93.5000	6.5000	1.8718	0.4759
8	0.2286	93.8889	6.1111	1.8101	0.3893
9	0.2571	94.1975	5.8025	1.7583	0.3061
10	0.2857	94.3889	5.6111	1.7247	0.2254
11	0.3143	94.4444	5.5556	1.7148	0.1462
12	0.3429	94.5000	5.5000	1.7047	0.0681
13	0.3714	95.0000	5.0000	1.6094	-0.0096
14	0.4000	95.0000	5.0000	1.6094	-0.0874
15	0.4286	95.0820	4.9180	1.5929	-0.1657
16	0.4571	95.6250	4.3750	1.4759	-0.2449
17	0.4857	95.7692	4.2308	1.4424	-0.3255
18	0.5143	95.8621	4.1379	1.4202	-0.4080
19	0.5429	96.1667	3.8333	1.3437	-0.4928
20	0.5714	96.2264	3.7736	1.3280	-0.5805
21	0.6000	96.2500	3.7500	1.3218	-0.6717
22	0.6286	96.2500	3.7500	1.3218	-0.7672
23	0.6571	96.5000	3.5000	1.2528	-0.8678
24	0.6857	96.7347	3.2653	1.1834	-0.9747
25	0.7143	96.8675	3.1325	1.1418	-1.0892
26	0.7429	97.2222	2.7778	1.0217	-1.2132
27	0.7714	97.5194	2.4806	0.9085	-1.3490
28	0.8000	97.6271	2.3729	0.8641	-1.4999
29	0.8286	97.7586	2.2414	0.8071	-1.6710
30	0.8571	98.3750	1.6250	0.4855	-1.8698
31	0.8857	98.4444	1.5556	0.4418	-2.1090
32	0.9143	98.6667	1.3333	0.2877	-2.4123
33	0.9429	98.6875	1.3125	0.2719	-2.8329
34	0.9714	99.0000	1.0000	0.0000	-3.5409

*R.E.= Removal Efficiency (%) = y_i

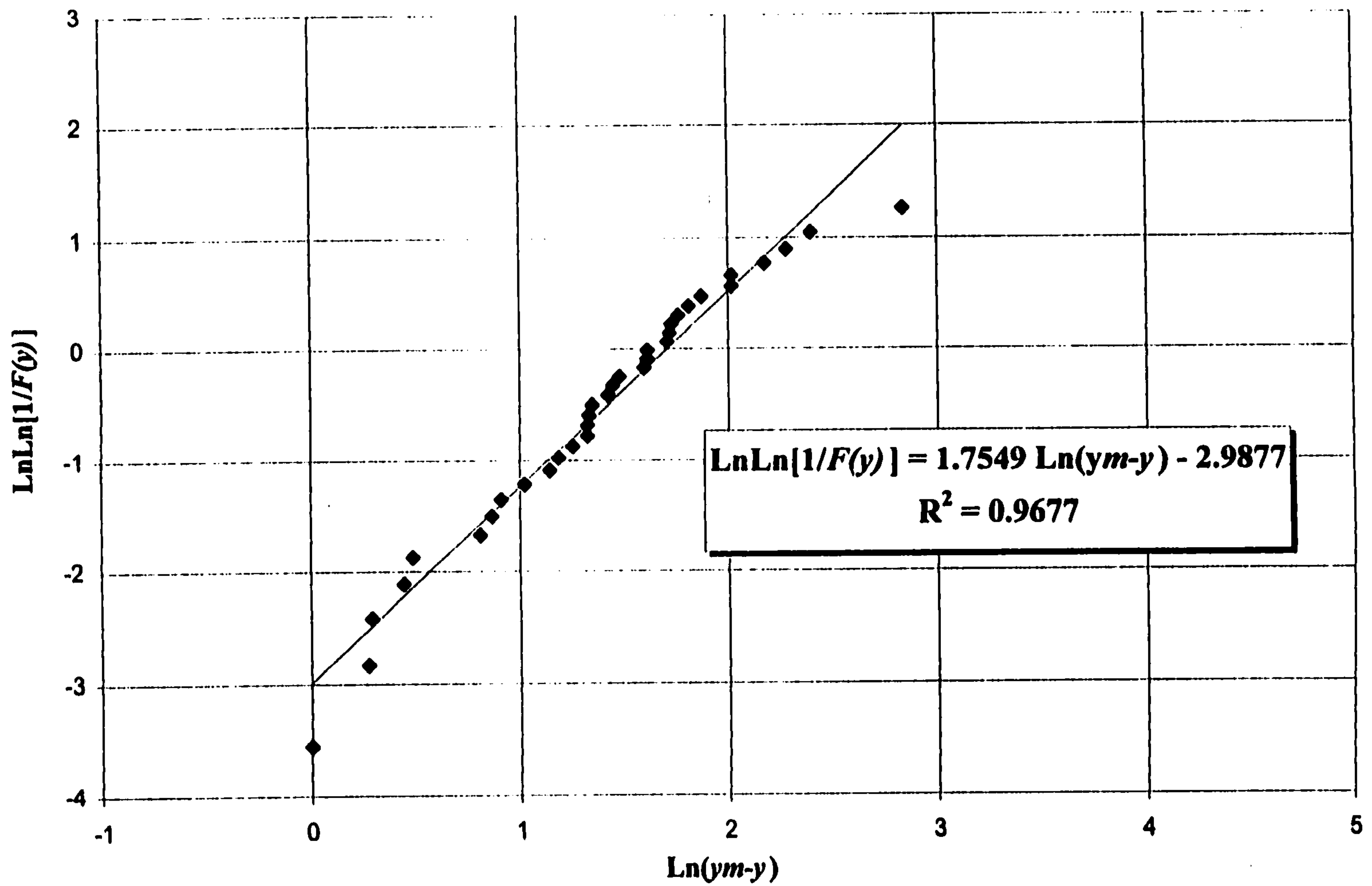

Fig. 5.13: Fit For Type III Asymptotic Maximum Extreme Value Distribution to Charcterize the Removal Efficiency of Standard Plate Counts, Condition #1

Table 5.19: Removal Efficiency Of Standard Plate Counts At Various Operational Conditions

Condition #	q (L/min)	d (cm)	c (mm)	R^2	# of Observations	m	θ_i	*y med.*	*y mean*	VAR.	Standev.
1	8	150	0.5	0.9677	34	1.755	5.49	95.5447	95.1113	8.2692	2.8756
2	10	150	0.5	0.907	10	0.956	6.15	95.8084	93.7249	43.1108	6.5659
3	10	80	0.5	0.9174	14	2.96	1.285	98.8647	98.8532	0.1780	0.4218
4	10	50	0.5	0.91	17	4.812	14.72	86.3595	86.5145	10.2325	3.1988
5	16	150	0.3	0.782	37	1.623	3.93	96.8644	96.4809	4.9403	2.2227
6	20	150	0.3	0.8377	6	0.5412	11.624	94.0947	79.7046	1659.6865	40.7392
7	20	80	0.3	0.8854	14	1.525	8.624	93.2184	92.2298	26.9989	5.1960
8	20	50	0.3	0.8371	17	4.72	18.45	82.9284	83.1163	16.6137	4.0760
9	10	50	0.3	0.8568	9	9.56	10.7	89.7025	89.8402	1.6264	1.2753
10	16	150	0.5	0.8433	37	2.913	5.13	95.4765	95.4248	2.9148	1.7073
11	20	150	0.5	0.9139	14	1.648	1.74	98.6070	98.4439	0.9394	0.9692
12	20	80	0.5	0.947	6	3.465	14.186	87.2379	87.2430	16.5955	4.0738
13	20	80	0.5	0.9536	17	4.796	19.19	82.2219	82.4228	17.4898	4.1821
14	16	50	0.5	0.9338	9	11.323	14.25	86.2039	86.3746	2.1239	1.4574

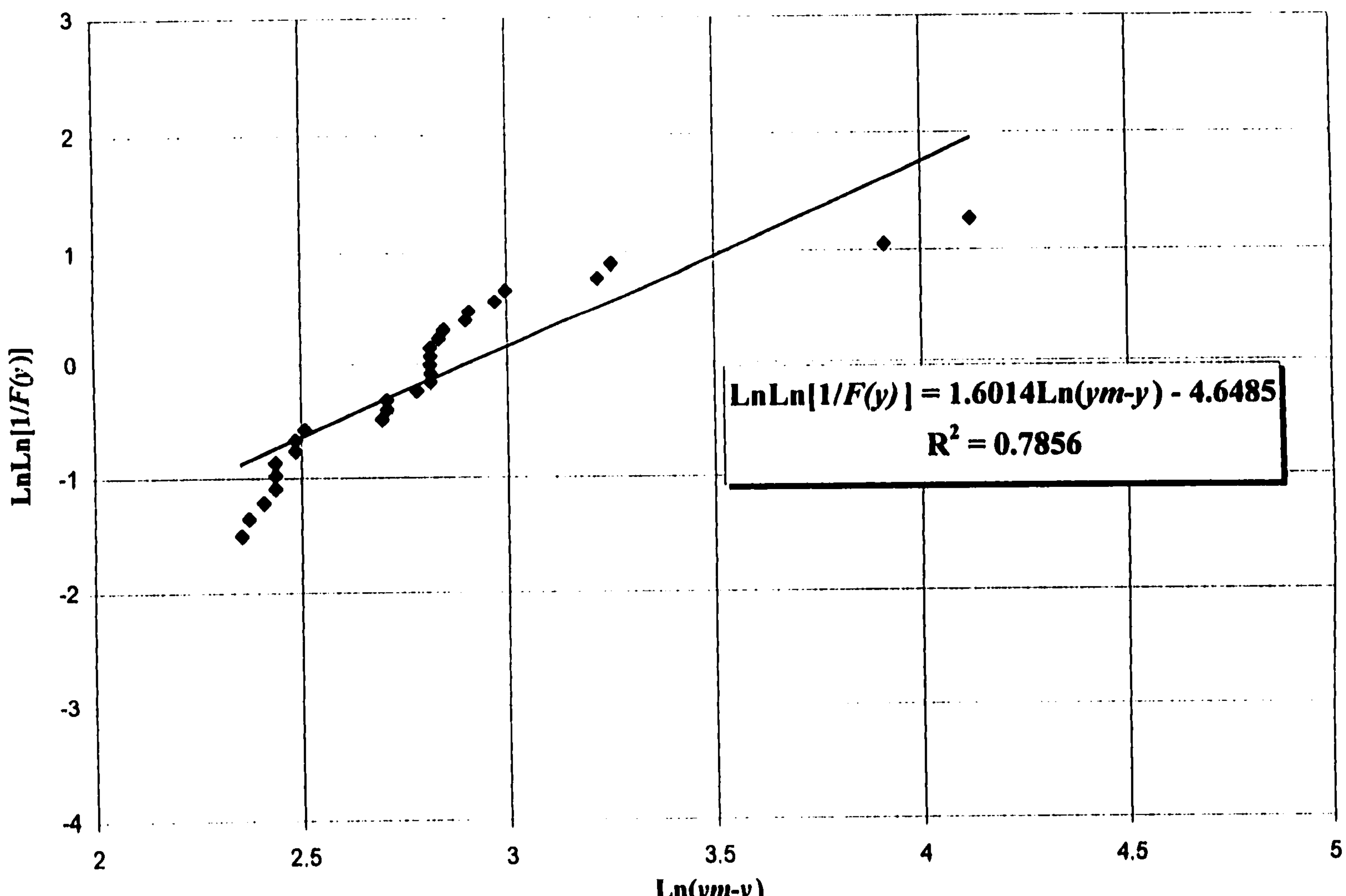

Fig. 5.14: Fit for Type III Asymptotic Maximum Extreme Value Distribution to Characterize the Removal Efficiency of Coliphages, Condition #1

Table 5.20: Spreadsheet to Fit Extreme Value Distribution to Coliphages Removal Efficiency Cond. #1

Sr. # (i)	*F= i/(N+1)*	*R.E.*(%)*	*(ym-y)*	*Ln(ym-y)*	*LnLn[1/F(y)]*
(Col.1)	(Col.2)	(Col.3)	(Col.4)	(Col.5)	(Col.6)
1	0.0345	38.4615	61.5385	4.1197	1.2685
2	0.0690	50.0000	50.0000	3.9120	1.0516
3	0.1034	74.1667	25.8333	3.2517	0.8988
4	0.1379	75.0000	25.0000	3.2189	0.7743
5	0.1724	80.0000	20.0000	2.9957	0.6657
6	0.2069	80.4878	19.5122	2.9710	0.5674
7	0.2414	81.6667	18.3333	2.9087	0.4759
8	0.2759	81.8182	18.1818	2.9004	0.3893
9	0.3103	82.7586	17.2414	2.8473	0.3061
10	0.3448	83.0000	17.0000	2.8332	0.2254
11	0.3793	83.3333	16.6667	2.8134	0.1462
12	0.4138	83.3333	16.6667	2.8134	0.0681
13	0.4483	83.3333	16.6667	2.8134	-0.0096
14	0.4828	83.3333	16.6667	2.8134	-0.0874
15	0.5172	83.3333	16.6667	2.8134	-0.1657
16	0.5517	83.8710	16.1290	2.7806	-0.2449
17	0.5862	85.0000	15.0000	2.7081	-0.3255
18	0.6207	85.0000	15.0000	2.7081	-0.4080
19	0.6552	85.1852	14.8148	2.6956	-0.4928
20	0.6897	87.7193	12.2807	2.5080	-0.5805
21	0.7241	88.0000	12.0000	2.4849	-0.6717
22	0.7586	88.0000	12.0000	2.4849	-0.7672
23	0.7931	88.5714	11.4286	2.4361	-0.8678
24	0.8276	88.5714	11.4286	2.4361	-0.9747
25	0.8621	88.5714	11.4286	2.4361	-1.0892
26	0.8966	88.8889	11.1111	2.4079	-1.2132
27	0.9310	89.2857	10.7143	2.3716	-1.3490
28	0.9655	89.4737	10.5263	2.3539	-1.4999

*R.E.= Removal Efficiency (%) = *yi*

Table 5.21: Removal Efficiency Of Coliphages At Various Operational Conditions

Condition #	q (L/min)	d (cm)	c (mm)	R^2	# of Observations	*m*	θ	*y med.*	*y mean*	VAR.	Standev.
1	8	150	0.5	0.786	28	5.49	95.63	97.02	95.08	9.91	3.15
2	10	150	0.5	0.925	10	6.15	94.62	94.78	94.53	4.63	2.15
3	10	80	0.5	0.872	14	1.29	98.83	98.80	98.83	0.10	0.32
4	10	50	0.5	0.889	17	14.72	85.91	85.50	86.11	3.93	1.98
5	16	150	0.3	0.749	37	3.93	96.94	98.22	96.44	6.16	2.48
6	20	150	0.3	0.809	6	11.62	89.12	88.79	89.27	5.02	2.24
7	20	80	0.3	0.917	14	8.62	91.98	91.75	92.08	3.28	1.81
8	20	50	0.3	0.617	17	18.45	82.72	82.19	82.95	12.39	3.52
9	10	50	0.3	0.953	9	10.70	89.58	89.36	89.70	0.84	0.92
10	16	150	0.5	0.800	38	5.13	96.16	98.53	95.23	14.52	3.81
11	20	150	0.5	0.823	14	1.74	98.41	98.37	98.42	0.18	0.43
12	20	80	0.5	0.873	6	14.19	86.46	86.06	86.65	4.08	2.02
13	20	80	0.5	0.752	17	19.19	81.52	81.02	81.76	5.02	2.24
14	16	50	0.5	0.919	6	14.25	86.12	85.83	86.28	1.47	1.21

[Yao *et al.*, 1971]. The variation of the data could be visualized from the standard deviation results as given in Table 5.21. The shape factor "m" in most of the cases is more than 4 which confirms that the shape of the curve is more or less like normal distribution curve. The lower value of standard deviation showed that whole of the data were placed closely.

5.4 Regression Model Development

Instead of considering all data sets in developing regression model, in this research the focal point is to analyze the average (mean) behavior of the filter for various pollutants under different operating conditions, although, there is not much difference in the mean and median values. If the data available is large (N>30) then the population mean of the available data can be obtained, but the fitting of the distribution can also provide better estimate of the available results and approaches towards the true mean of the data.

To develop meaningful relationships among control variables (regressors) and response (removal efficiency) Statgraphics plus and Microsoft Excel-7 were used. In the literature many models have been developed for the removal efficiency of slow sand filters on analytical and empirical basis. Generally available models provide the removal efficiency of the clean filter and also some equations are available for the filter removal efficiency throughout its filter run.

Most of the equations are quite complex and they require lot of data to predict the efficiency of filter.

Most of the investigators used macroscopic and microscopic approaches in the development of their models and they have taken into account many uncontrolled variables like ambient temperature and influent water quality etc. In this research the uncontrolled variables are considered as *noise-to-signal* and the equations contain only controlled variables. This approach is undertaken to make the procedure simple and handy so as to help predict the average expected removals in field conditions. The most suitable equation for controlled variables are obtained even though the noise factors are present. The developed equations can help find the expected removals of given parameters in those conditions of controlled variables which were even not studied.

5.4.1 Regression Statistics

One of the oldest problems in statistics is fitting a straight line to data points in the plane. To make the procedure rigorous, a particular model is employed and the method of least square estimation is developed around the model. The principle of least squares is to minimize the vertical distance of the plotted points to the fitted line. The result is the least square estimators for the model parameters. Using the properties of these estimators, it is possible to make inferences regarding the parameters in the underlying model.

The minimization of SSE (sum of squares of error) results in a regression line that **best fits** the observational data. SSE provides a measure of the variation between the data points and the fitted regression line. Algebraic summation shows that

$$S_{YY} = \sum_{i=1}^{n}(Y_i - \bar{Y})^2 + \sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2 \qquad (5.18)$$

where

$\hat{Y}$ = estimated or predicted value

$\bar{Y}$ = expected or mean of given value

Yi= experimental given response value

letting

$$SS_R = \sum_{i=1}^{n}(Y_i - \bar{Y})^2 \qquad (5.19)$$

where SS_R, called the regression sum of squares. This equation yields the decomposition

$$S_{YY} = SS_R + SSE \qquad (5.20)$$

"S_{YY}" measures the total variation of observations $Y_1, Y_2, \ldots, Y_n$ about their mean. The degree of freedom (df) of S_{YY} is (N-1) that is "total data points minus 1" whereas the df for SSE is N-(p+1) in which "p" is the number of regressors or control variables.

To get the authenticity of the regression equations F-test statistics is determined, which is given by the following relationship

$$F = \frac{MSR}{MSE} \tag{5.21}$$

where

MSR= regression mean square, SSR/df

MSE= error mean square, SSE/df

The value calculated, F_{cal}. should be more than the value given in standard table value of F_{tab}. at some significant level. Normally this value is taken for 95% confidence interval and it is in built function of all regression analysis packages. Another important statistic which evaluates the authenticity of the regressed equation is **P-value**. The P-value corresponding to an observed value of test statistic, is the lowest level of significance for which the test-statistic value results in rejection of null hypothesis. An advantage of the p-value is that it gives the investigator some insight in to degree of significance of test result. All of the statistical packages include the p value corresponding to given set of data.

Coefficient of determination (R^2) measures the proportion of the total variation attribute to regression. R^2 for regression analysis is given as

$$R^2 = \frac{SS_R}{S_{YY}} \tag{5.22}$$

Since SS_R measures the variation attributable to regression and S_{YY} measures the total variation, R^2 is near "1" when most variability attribute to regression and near "0" when the most variation is random. R^2 values can be

improved by taking more regressors in the regression equation, to counter this problem adjusted R^2 is defined

$$R^2_{adjust} = 1 - \left(\frac{n-1}{n-p}\right)\left(1 - R^2\right) \qquad (5.23)$$

Advantage of the adjusted $R^2{}_{adjust}$ value is that it does not automatically increase as the regressors are inserted in to the model.

The objective of checking all these "statistics" is to make the regression equations reliable for the prediction of results. Microsoft Excel 7, Statgraphics plus have in-built functions under multiple regression.

5.4.1.1 Stepwise Regression

To develop the relationships between removal efficiency and the control variables different trials have been made to get the best equation. For this purpose stepwise regression technique was employed. First the relationship between filtration rate (q) and removal efficiency was tried, then a new variable sand bed depth (d) was introduced. The increase in the coefficient of determination shows that it is a significant independent variable and can not be ignored. This procedure was repeated again for sand grain size (c). As there were only three control variables, nonlinear models were tried as a combination of these variables.

The stepwise regression results of total coliform removal efficiency are tabulated in Table 5.22. Similarly Models 2, 3 and 4 were developed for fecal coliform, standard plate counts and coliphages, respectively. The summary of these models are given in Table 5.23.

Table 5.22: Stepwise Regression For Total Coliform (Model 1)

Trial	Equation	R^2
1	96.14+0.276q	0.0396
2	87.23-0.236q+0.0835d	0.3851
3	85.76-0.219q+0.0833d+2.88c	0.387
4	$85.29-0.00864q^2+0.831d^2+3.03c^2$	0.395
5	63.17-2.658q+8.22ln(d)+1.1504c	0.424

Model-1 (T.C.)	$-107.5-4.5*10^{-8}\exp(q)+55.8\ln(d)+0.556c+0.64q-0.57d+2.47*10^{-10}[d*\exp(q)]$	0.81

Table 5.23: Final Regression Models of Microorganisms

Models	Equation	R^2
Model 2	$-87.5-19.66\ln(d)-11.9c-6.8q-0.14d+1.45*10^{-10}[d*\exp(q)]+77.07\ln(q)$	0.74
Model 3	$-62.9-1.3*10^{-8}\exp(q)+50.45\ln(d)-32.9c-0.565q-0.57d+0.324[qdc^2]$	0.76
Model 4	$-66.77+40.1\ln(d)-21.1c-2.64q-0.43d+22.9\ln(q)+0.0133[qdc]$	0.86

5.4.2 Discussion of Results

The developed four models for total coliform, fecal coliform, standard plate counts and coliphage were used to predict the removal efficiency under known conditions of control variables. Table 5.24 gives the actual and predicted values of removal efficiency of indicator microorganisms under given conditions of sand bed depth, filtration rate and sand grain size. The plot of comparison of predicted and measured values are given in Fig. 5.15-5.18 for total coliform, fecal coliform, total plate counts and coliphages, respectively. While developing these models the higher degrees of polynomials were avoided to reduce the sensitivity of the equations under high/low values of this particular parameter. The reason of lesser fit is that only three major control variables were considered and all other uncontrolled variables/noise factors like temperature, influent water quality etc. could influence the results also. The coefficient of determination (R^2) value for all the indicator's removal efficiency vary from 0.74 to 0.86.

It can be noted from the Table 5.22 and 5.23 that different terms of all models are quite similar to each other and the small difference might be due to different mechanisms of removal, active in case of different indicators. The other reason could be that all these equations of different parameters are based on their mean results, therefore skewness of the data present in the distribution might cause different results. These models are non linear equations and in

Table 5.24: Comparison of Actual and Predicted Mean Values of Indicator Microorganisms

Condition #	Flow (L/min)	Depth (cm)	Size (mm)	Total Coliform Model-1		Fecal Coliform Model-2		Standard Plate Counts Model-3		Coliphages Model-4	
				Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	8	150	0.5	96.480	97.931	91.017	96.954	95.111	97.482	95.078	97.962
2	10	150	0.5	97.378	97.494	97.438	95.801	93.725	96.585	94.527	97.212
3	10	80	0.5	97.521	91.666	98.403	89.226	98.853	92.255	98.834	91.323
4	10	50	0.5	83.939	89.169	85.321	86.408	86.515	90.400	86.110	88.799
5	16	150	0.3	94.403	95.605	90.770	94.843	96.481	92.152	96.439	95.079
6	20	150	0.3	97.609	94.730	96.730	92.538	79.705	90.358	89.265	93.579
7	20	80	0.3	94.413	88.902	89.474	85.963	92.230	86.029	92.081	87.690
8	20	50	0.3	79.101	86.405	81.215	83.145	83.116	84.174	82.949	85.167
9	10	50	0.3	88.710	88.593	87.208	88.909	89.840	88.658	89.697	88.917
10	16	150	0.5	94.976	96.181	93.228	92.343	95.425	93.894	95.231	94.962
11	20	150	0.5	94.467	95.306	91.646	90.037	98.444	92.100	98.419	93.461
12	20	30	0.5	91.094	89.478	76.396	83.462	87.243	87.771	86.654	87.573
13	20	50	0.5	79.235	86.981	80.491	80.644	82.423	85.916	81.761	85.049
14	16	50	0.5	98.930	87.856	83.886	82.950	86.375	87.710	86.276	86.549

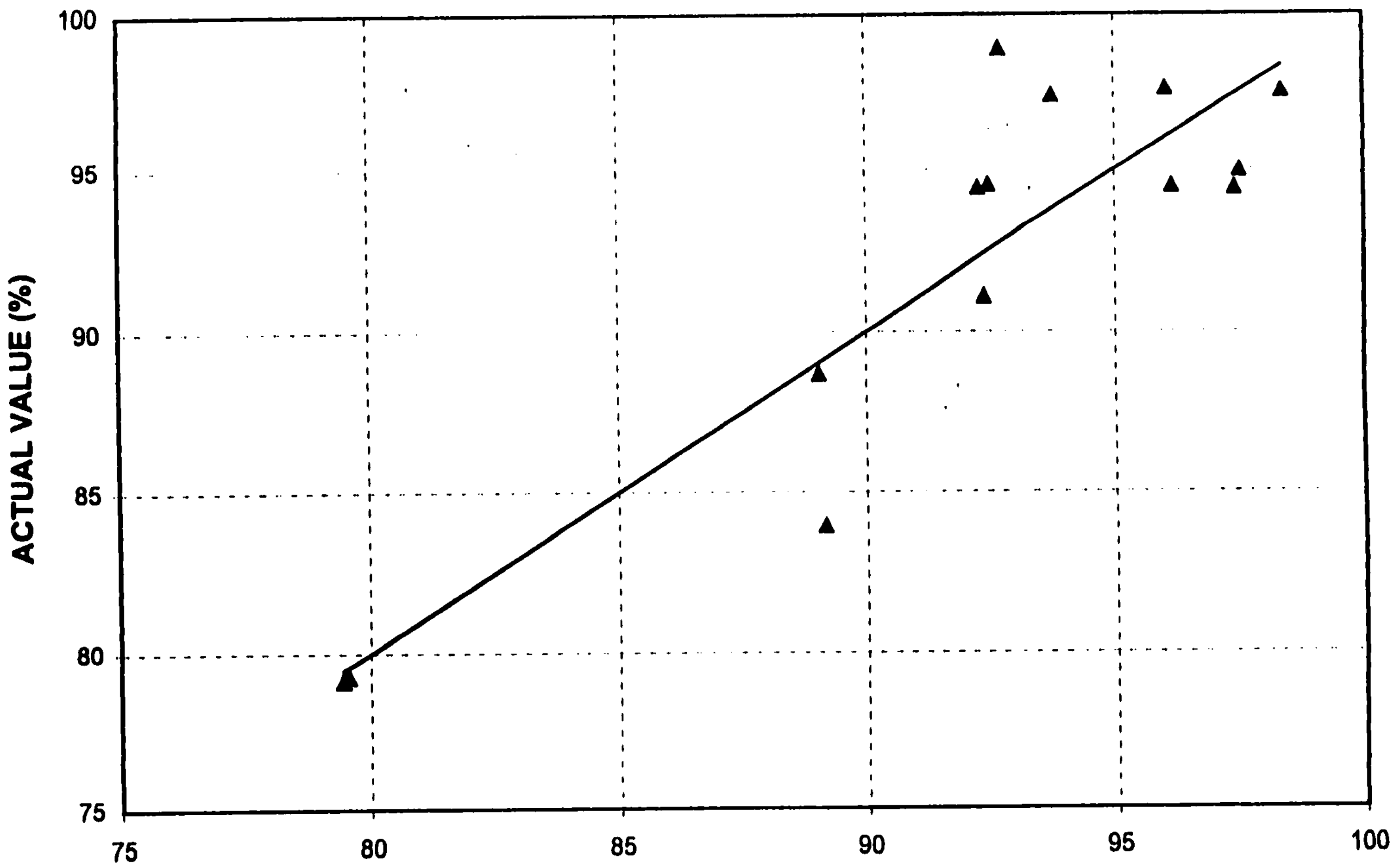

Fig 5.15: Comparison of Predicted and Measured Values of Total Coliform.
(Model-1)

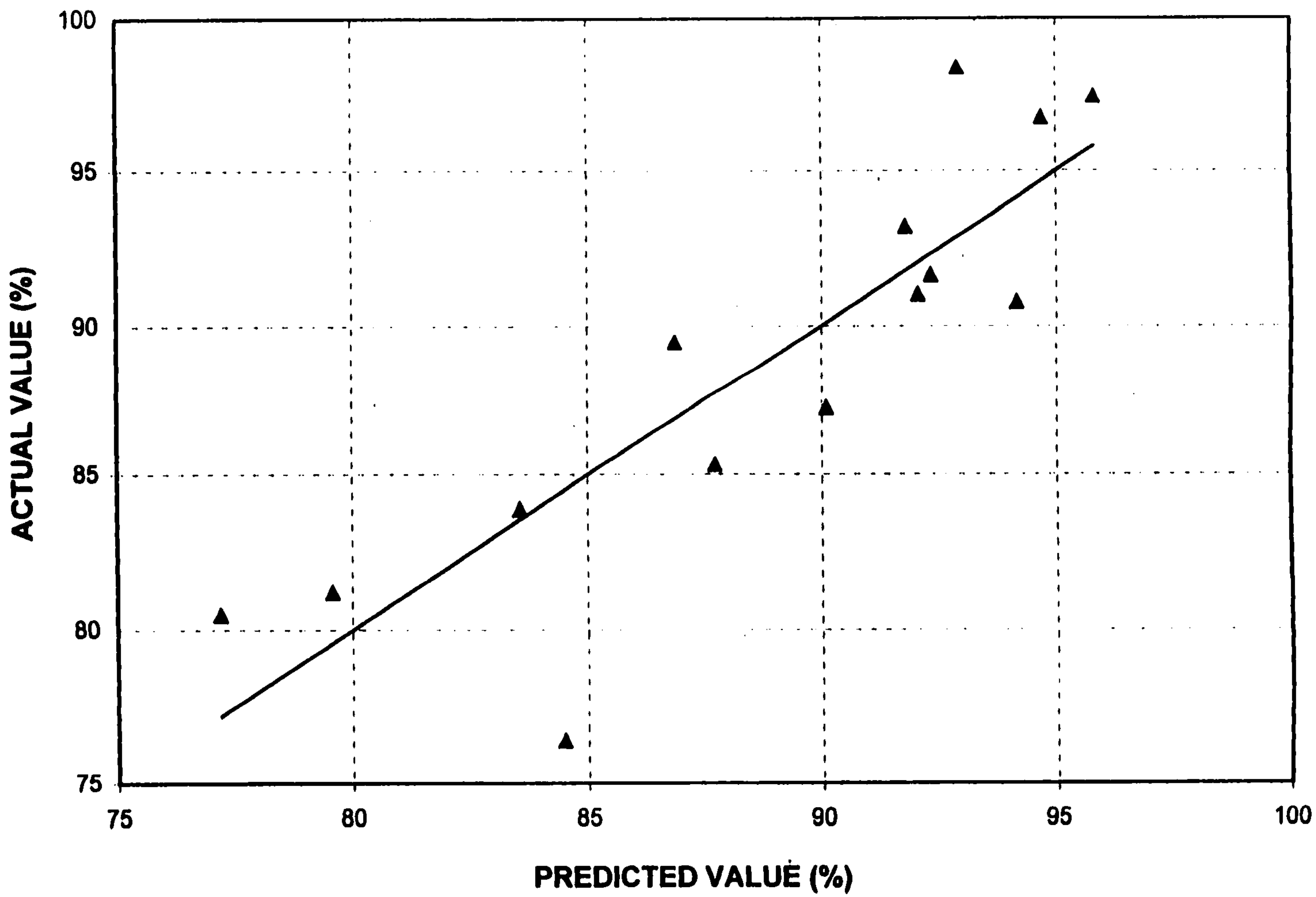

Fig. 5.16: Comparison of Predicted and Measured Values of Fecal Coliform (Model-2)

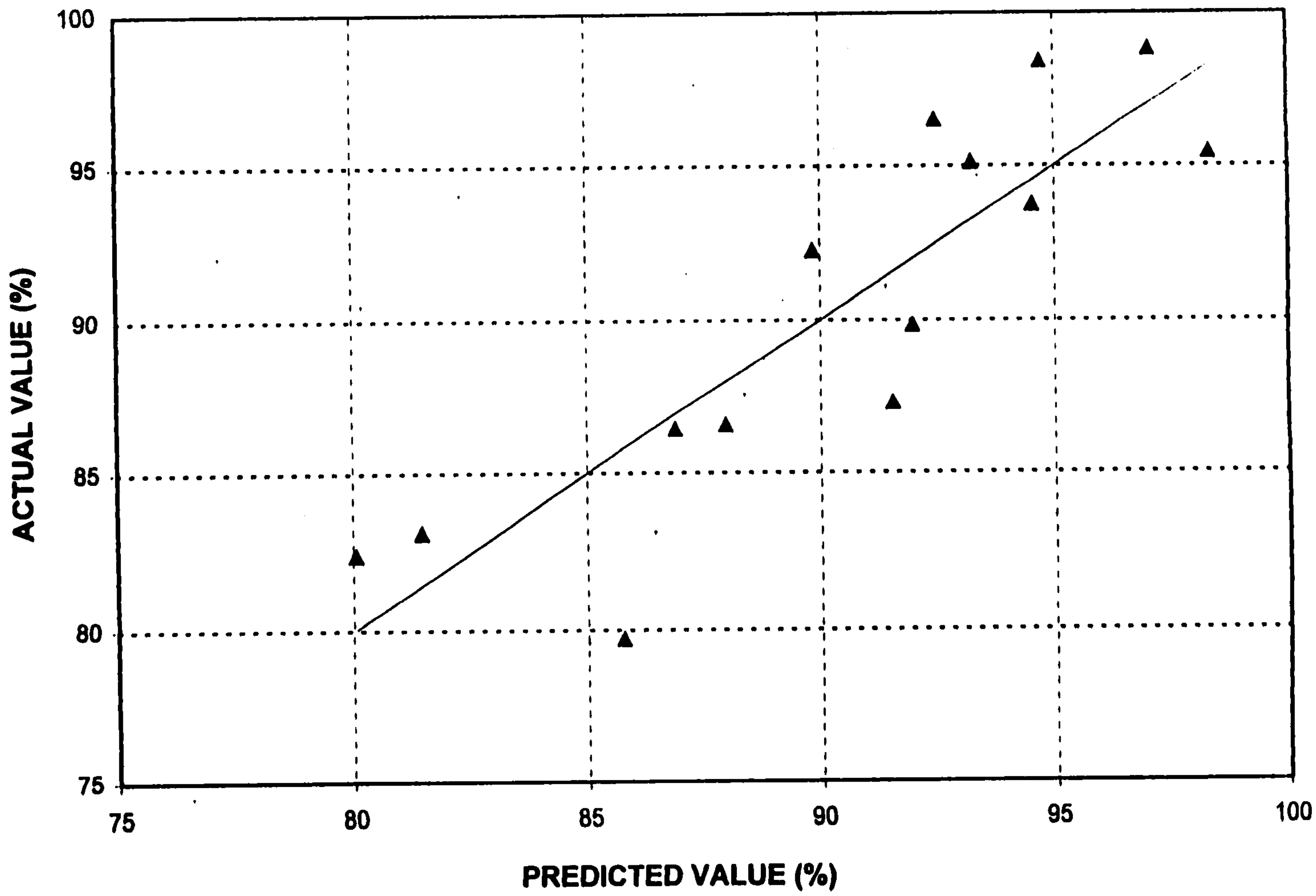

Fig 5.17: Comparison of Predicted and Measured Values of Standard Plate Counts (Model-3)

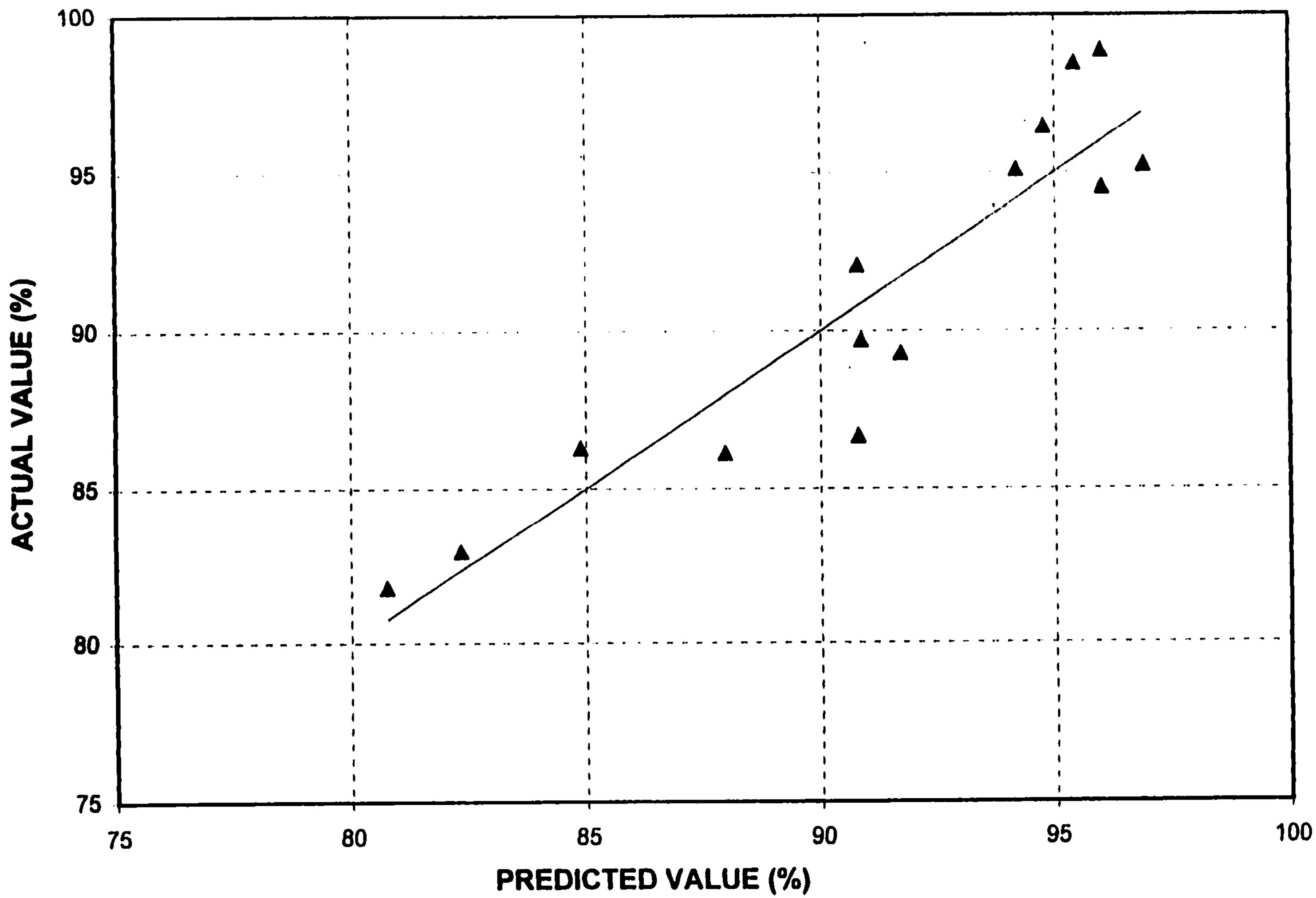

Fig. 5.18: Comparison of Predicted and Measured Values of Coliphages (Model-4)

almost all models the filtration rate (q) and sand depth (d) terms are predominant in comparison to filter media grain size(c) terms.

In regression analysis of indicator total coliform, R^2 statistic indicates that the model-1 explains 80.70 % of the variability of independent variable. The $R^2_{adjusted}$ statistic which is more suitable for comparing models with different numbers of independent variables, is 64.16%. The standard error of the estimate shows the standard deviation of the residuals to be 3.99. The mean absolute error (MAE) of 2.29 is the average value of the residuals. Since the p-value in the ANOVA (regression analysis of variances) table is less than 0.05, there is significant relationship between the variables at more than 95% confidence interval. The $F_{cal.}$ value is 4.88 which is more than the $F_{0.05,6,7}$=3.87, given in the standardized tables. The "0.05" is the confidence interval and "6" and "7" are the degree of freedom for the regression and error, respectively. The $F_{cal.}$ value of 4.88 corresponds to 97.2% of confidence interval.

The results of regression statistic of all microorganism indicators are given in the Table 5.25. There are many factors which caused fluctuations in the results but these equations are statistically sound to predict the results under some confidence band.

Table 5.25: Statistic of Regression Analysis for Various Indicators

Indicator	F-cal.	P-value	Confidence Level (%)	R^2	R^2_{adjust}	Std. Error	Average Residual
T.Coliform	4.88	0.0283	97.17	0.817	0.642	3.99	2.229
F.Coliform	3.33	0.0706	92.94	0.74	0.518	4.663	2.264
S.P.Counts	3.69	0.0558	94.42	0.76	0.554	4.174	2.575
Coliphages	7.11	0.0010	99.90	0.86	0.738	2.888	1.82

5.5 Verification Of Regression Models at Different Values of Control Variables

The regression equations which have already been developed can be verified under various conditions of control variables. Different researchers have experimented and observed the slow sand filtration removal efficiency for different pollutants under varying values of control variables. Regression models can predict the response under specific range and its prediction interval widens as it moves away from the mean values [Montgomery, 1991].

As 2m diameter filters were used in this study and the unit of flow rate (q) was "L/min/area". Therefore, to use the regression equations, given in Tables 5.22 and 5.23, filtration rate need to be converted into corresponding unit. If the units of filtration rates are given in (m/hr) then the q values must be divided by factor of "0.019" to use the model equations for prediction of removal efficiency.

5.5.1 Indicator Microorganisms

The results of comparison of experimental and modeled values are given in Table 5.26. The percentage error is also calculated in the last column of the table which represents the departure of the predicted values from experimental results. Chances of errors always exist in predicting the results in running the

Table 5.26: Comparison of Modeled and Expermental Values of Microbial Indicators

Author	Study Details	Indicator	Filt. Rate (m/hr)	Depth (cm)	Grain Size (mm)	Experimental Result (%)	Modeled Results (%)	% Error (%)
Al-Yousaf [1990]	Pilot-Scale (Dia-1m)	T.Coliform	0.16	139	0.31	82	94.62	13.34
			0.16	140	0.56	80.25	94.59	15.16
			0.16	135	0.31	99.76	95.26	-4.72
			0.16	105	0.31	97.82	98.24	0.43
			0.16	55	0.31	93.46	90.51	-3.26
			0.16	135	0.56	99.39	95.4	-4.18
			0.16	105	0.56	97.26	98.38	1.14
			0.16	55	0.56	93.03	90.65	-2.63
Bellamy (*et al*.,1985)	Pilot-Scale (Dia-0.3m)		0.12	48	0.29	92	85.52	-7.58
			0.12	97	0.29	98.5	96.99	-1.56
			0.12	97	0.62	96.5	97.17	0.69
Cleasby (*et al*.,1984)			0.12	94	0.32	99	96.5	-2.59
Ellis [1987]	Pilot-Scale (Dia-0.14m)		0.15	95	0.30	97	97.97	0.99
			0.30	95	0.60	99	100	1.00
			0.15	95	0.60	99	97.97	-1.05
Poynter (*et al*.,1977)	Lab. Scale		0.40	60	0.30	99.6	93.85	-6.13
			0.10	75	0.28	100	94.44	-5.89
			0.15	90	0.30	97	97.66	0.68
Al-Yousaf [1990]	Pilot-Scale (Dia-1m)	S.P.Counts	0.16	139	0.31	69.71	95.55	27.04
			0.16	140	0.56	78.92	95.43	17.30
			0.16	135	0.31	92.99	96.26	3.40
			0.16	105	0.31	90.94	99.89	8.96
			0.16	55	0.31	88.07	94.46	6.76
			0.16	135	0.56	92.13	96.03	4.06
			0.16	105	0.56	89.87	97.88	8.18
			0.16	55	0.56	87.46	89.49	2.27
Bellamy (*et al*.,1985)	Pilot-Scale (Dia-0.3m)		0.12	97	0.29	99.90	100.00	0.10
			0.12	97	0.62	99.90	96.29	-3.75
B.J.Lloyd (*et al*.,1988)	Field-Scale	F.Coliform & E.Coli	0.28	50	0.30	98.00	86.50	-13.29
Poynter (*et al*.,1977)	Lab. Scale		0.20	60	0.30	99.50	91.24	-9.05
B.J.Lloyd (*et al*.,1988)	Field-Scale	Coliphages (Bacteriophages)	0.28	50	0.30	99.03	88.00	-12.53

experiment or finding the best fitted distribution. The positive percent error means that model is overestimating the results and vice versa.

If the results of Al-Yousef (1990) are compared with total coliform model values at the same condition, the percentage error is less than 5% in 6 conditions out of 8. In some conditions results were overestimated and in some other conditions the results were underestimated. Similarly the results of Bellamy *et al.*(1985) are underestimated in two conditions and overestimated in one condition. The percentage error is less than 2% in two of the conditions. The variations in the results depend upon the varying conditions of control variables. If the experiment was conducted within the regression variables range then chances of good prediction are increased. The regression equations are based on the experiments which were conducted in the field where it was very difficult to control all the variables. The results of experiments compared, were mostly conducted at smaller scale where the conditions can be controlled easily. The efficiency calculated in the field is generally less then those observed in the laboratory or pilot scale. The results of Ellis (1987) are also very close to predicted values. At some points the model predicts the values more than 100% which is maximum possible value, in that case the values are taken as 100%. Similarly the results of Poynter and Slade (1977) are predicted by the Model-1 (total coliform). Of all the 18 comparisons the percentage error was less than 5% in 13 comparisons.

The standard plate counts results are also overestimated in all the cases. The removal efficiency calculated by Al-Yousaf (1990) is less than 10% in 6 comparisons out of 8. Results of Bellamy *et al.* (1985) are very close to the predicted results. The percent error is less than 5% in case of plate counts in 5 comparisons out of 10.

When results of E-coli and fecal coliforms both were compared with results of fecal coliform model, there was approximately 10% underestimation with respect to observed value. The coliphages results are compared with the experiments conducted by Llyod (1988) on 4 different bacteriophages. The results were different by 12.5% when compared with the calculated values of coliphages model given in Table 5.26.

There are different factors that cause variation between model and experimental results. These reasons could be environmental factors not being considered like temperature etc., shortage of data, difference between laboratory controlled conditions and pilot scale.

5.6 Effect of Control Variables

To see the effect of control variables; sand bed depth, filtration rate, and sand grain size on the removal efficiency of microorganisms through slow sand filtration, the contours maps were developed. These contours have been plotted at fixed grain sizes of 0.5 mm and 0.3 mm.

To develop the contour maps of removal efficiency, regression models were used. Table 5.27 shows the data generated from Model-1 under different conditions of sand bed depth and flow rate. This table is generated at 0.5mm fixed grain size. Fig. 5.19 shows the corresponding contour of removal efficiency as a function of flow rate and sand bed depth. The X-axis represents the variation of flow rate from 8 to 20 L/min (0.15 to 0.4m/hr). This range was selected on the basis of available data as the regression models can predict the response more accurately within the range of regressors. Similarly on Y-axis the sand bed depth varies from 50 to 150 cm which is the experimental range for bed depth of slow sand filter. Fig. 5.19 shows that change in flow rate is not significantly affecting the removal efficiency, whereas, smaller change in depth increases the removal efficiency appreciably. For instance at 15 L/min flow rate and 50 cm bed depth the removal efficiency of total coliform was 92% but by increasing the depth to 80cm the removal efficiency was increased to more than 98%. Same behavior can be observed at other flow rates. Table 5.28 gives the details of generated removal efficiency data for 0.3 mm grain size under various conditions of sand bed depth and filtration rate. A plot of this data gave similar trend when compared to 0.5mm grain size as can be seen from Fig. 5.20. There was no change in removal efficiency by changing the grain size. Fig. 5.20 have the same optimum range of removal efficiency as was in case of 0.5 mm grain size contour plot.

Table 5.27: The Removal Efficiency Data Generated from Model-1 (Total Coliform) at 0.5 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	87.88	97.10	98.21	97.04	92.48
10	89.16	98.37	99.49	98.32	93.76
12	90.43	99.65	99.99	99.60	95.04
14	91.68	99.99	99.99	99.99	96.31
16	92.71	99.99	99.99	99.99	97.53
18	92.14	99.99	99.99	99.99	98.36
20	79.72	92.53	96.04	97.27	96.30

Table 5.28: The Removal Efficiency Data Generated from Model-1 (Total Coliform) at 0.3 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	87.77	96.98	98.10	96.93	92.37
10	89.05	98.26	99.37	98.21	93.65
12	90.32	99.54	99.99	99.49	94.93
14	91.57	99.99	99.99	99.99	96.20
16	92.60	99.99	99.99	99.99	97.42
18	92.02	99.99	99.99	99.99	98.25
20	79.61	92.42	95.93	97.16	96.19

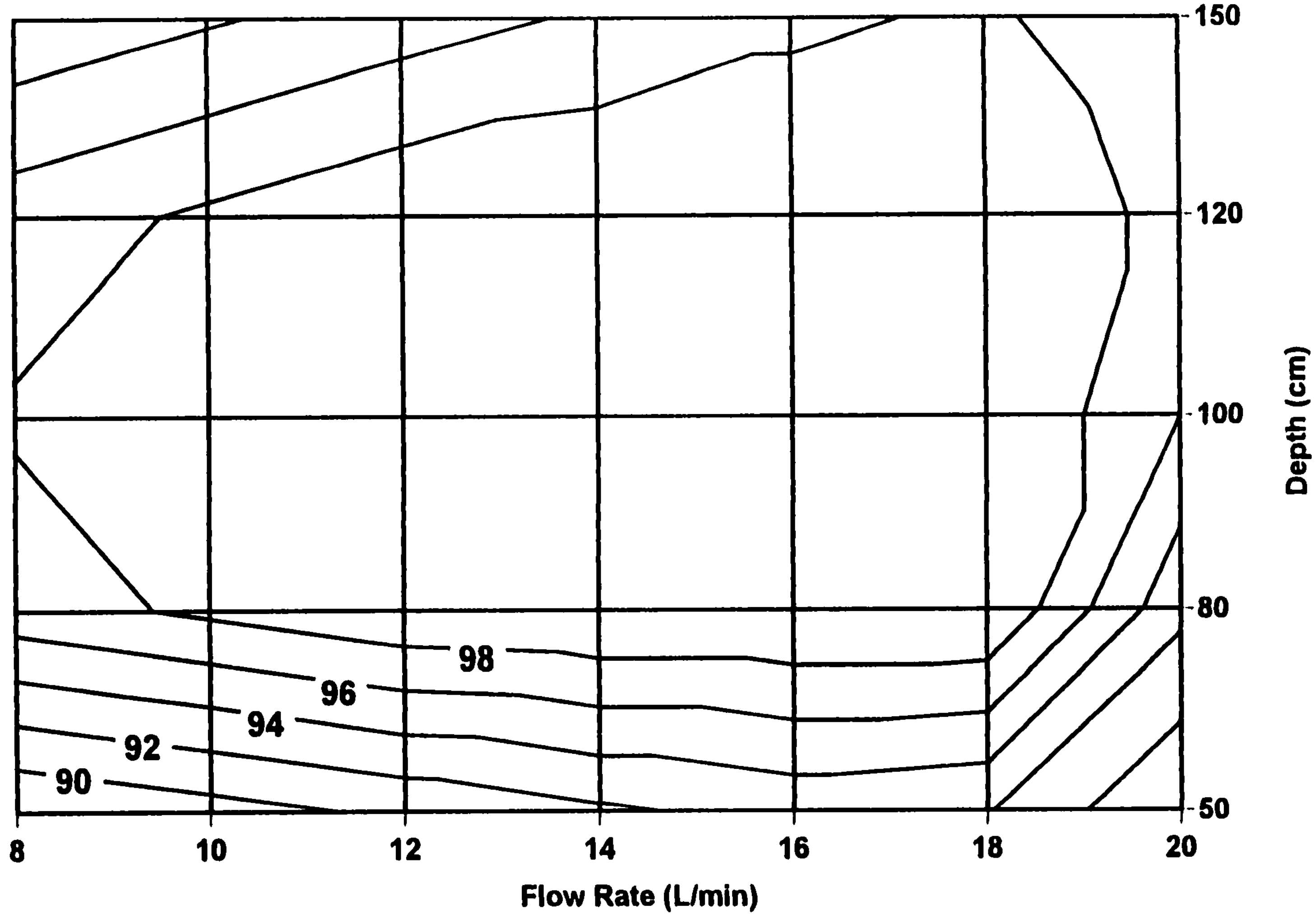

Fig. 5.19: Contours for Total Coliform Showing Percent Removal at 0.5 mm Grain Size

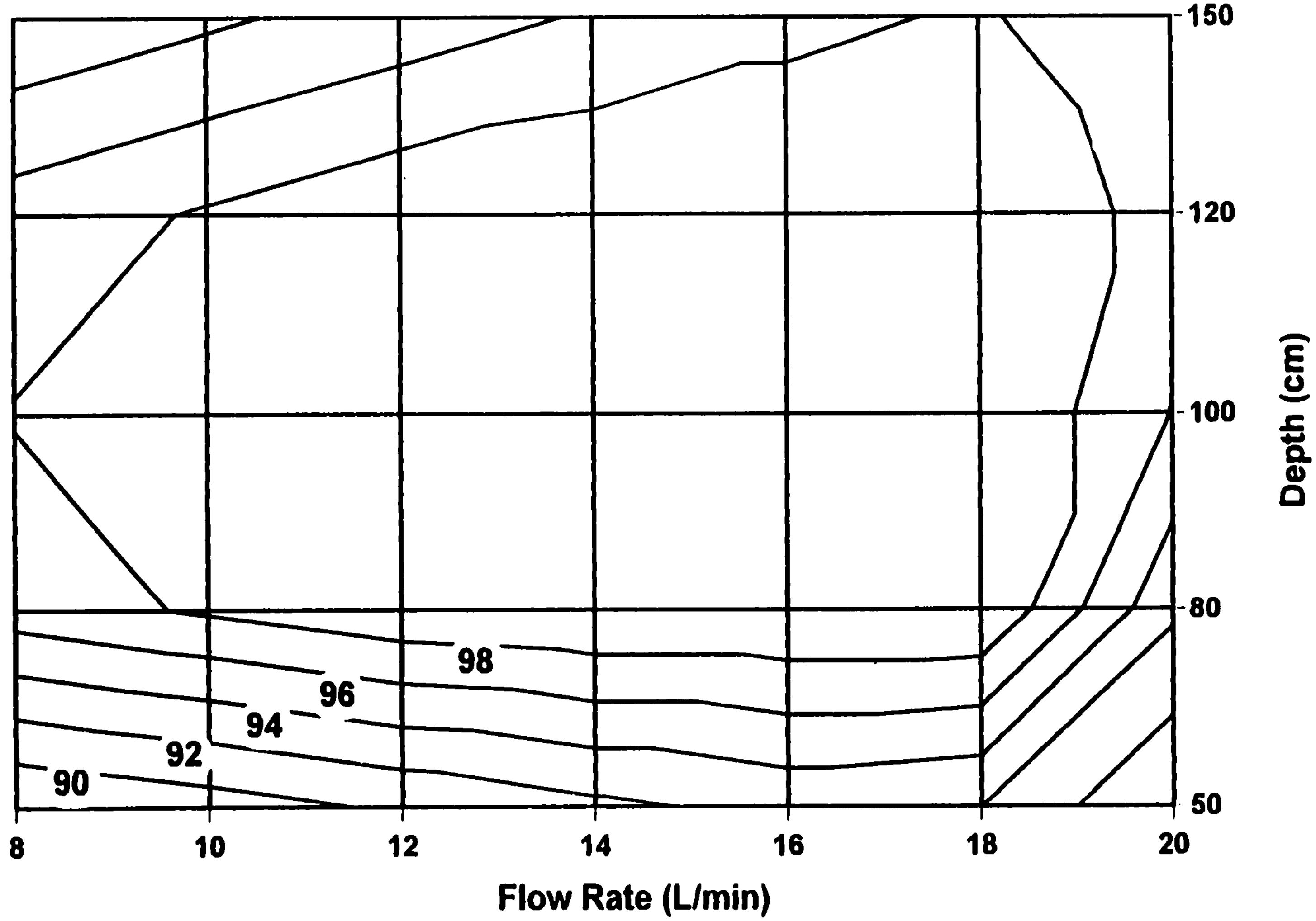

Fig. 5.20: Contours for Total Coliform Showing Percent Removal at 0.3 mm Grain Size

Table 5.29 was developed from the regression Model-2 (fecal coliform). The plot of this table is given in Fig. 5.21. As can be revealed from the figure, the removal efficiency is sensitive to the change in the flow rate. For example, at a bed depth of 80 cm and a flow rate of 12 L/min the removal efficiency is approximately 92%. By increasing the flow rate to 14 L/min, while keeping the bed depth fixed at 80 cm, the removal efficiency decreases to 90%. Similarly at fixed flow rate of 12 L/min and 60cm bed depth the removal efficiency became 88%. The removal efficiency became 90% when the bed depth increases to 70 cm and then increases to 92% at 80 cm bed depth. Lower removal efficiencies were observed in case of fecal coliform when compared to total coliform. The range for optimum results of removal efficiency for the case of fecal coliform can be achieved with flow rate range of 10-12 L/min and bed depths range of 120-150 cm. Table 5.30 gives detail of generated data for fecal coliform with 0.3 mm grain size filter. In case of fecal coliform removal efficiency, it was observed that smaller grain size give better removals as can be observed from Fig. 5.22. The expected removal efficiency increased to more than 96%. The optimum range for sand bed depth increased from 120-150cm to 100-150cm when sand grain size was changed from 0.5mm to 0.3mm.

The Table 5.31 was developed from Model-3 which was for standard plate counts. This table was developed at fixed grain size of 0.5mm. The corresponding removal efficiency contour plot was similar to total coliform contour at 0.5 mm grain size as shown in Fig. 5.23. There was no appreciable

Table 5.29: The Removal Efficiency Data Generated from Model-2 (Fecal Coliform) at 0.5 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	82.67	87.86	89.55	90.43	90.77
10	86.29	91.48	93.16	94.05	94.38
12	86.76	91.95	93.64	94.52	94.86
14	85.07	90.26	91.95	92.84	93.18
16	81.83	87.06	88.77	89.69	90.06
18	77.74	83.22	85.10	86.17	86.79
20	75.32	82.62	85.72	88.01	90.46

Table 5.30: The Removal Efficiency Data Generated from Model-2 (Fecal Coliform) at 0.3 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	85.04	90.23	91.92	92.80	93.14
10	88.66	93.85	95.54	96.42	96.76
12	89.13	94.32	96.01	96.90	97.23
14	87.44	92.64	94.33	95.21	95.56
16	84.21	89.44	91.15	92.06	92.43
18	80.12	85.59	87.47	88.54	89.17
20	77.70	85.00	88.09	90.38	92.83

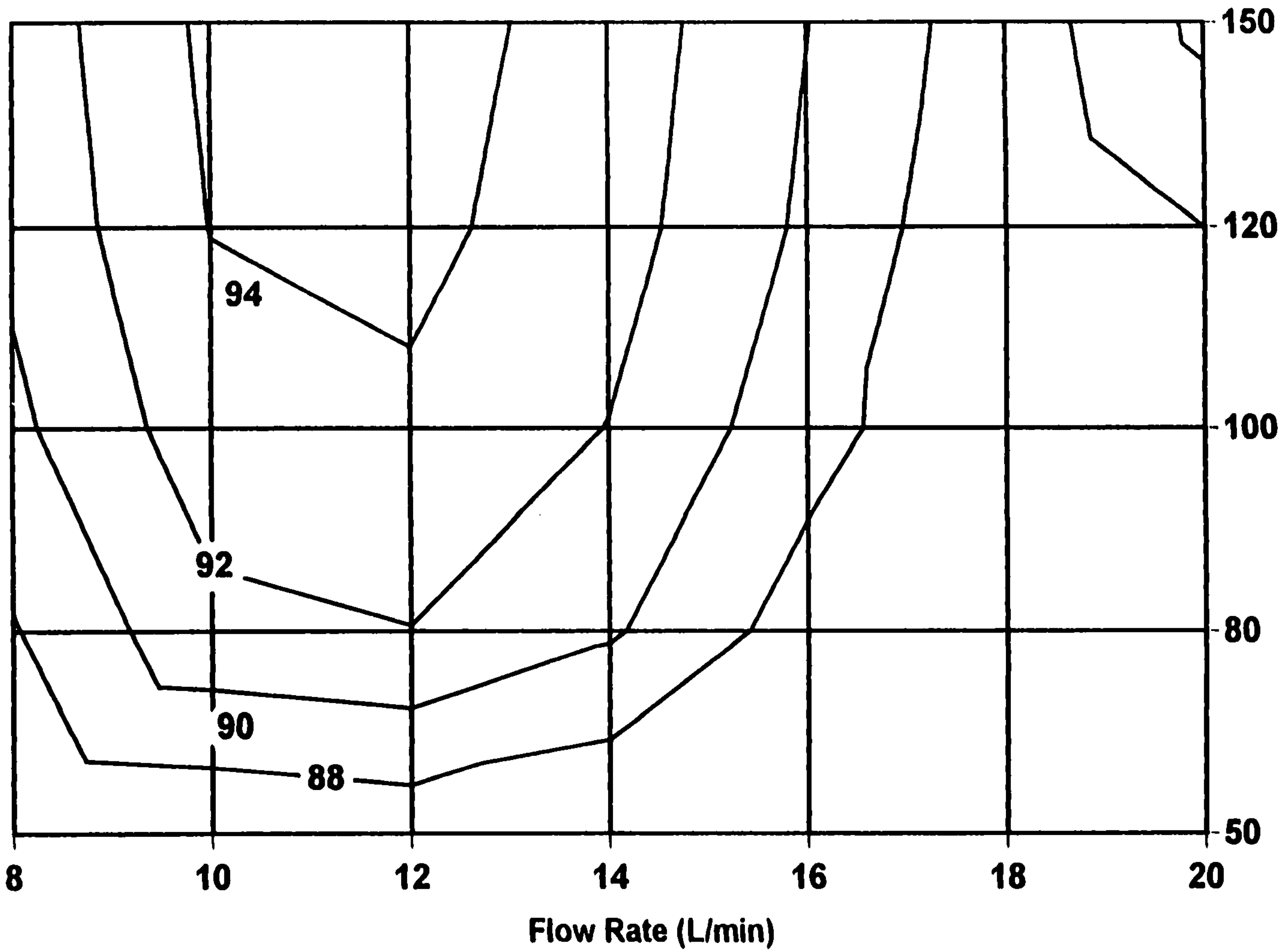

Fig.5.21: Contours for Fecal Coliform Showing Percent Removal at 0.5 mm Grain Size

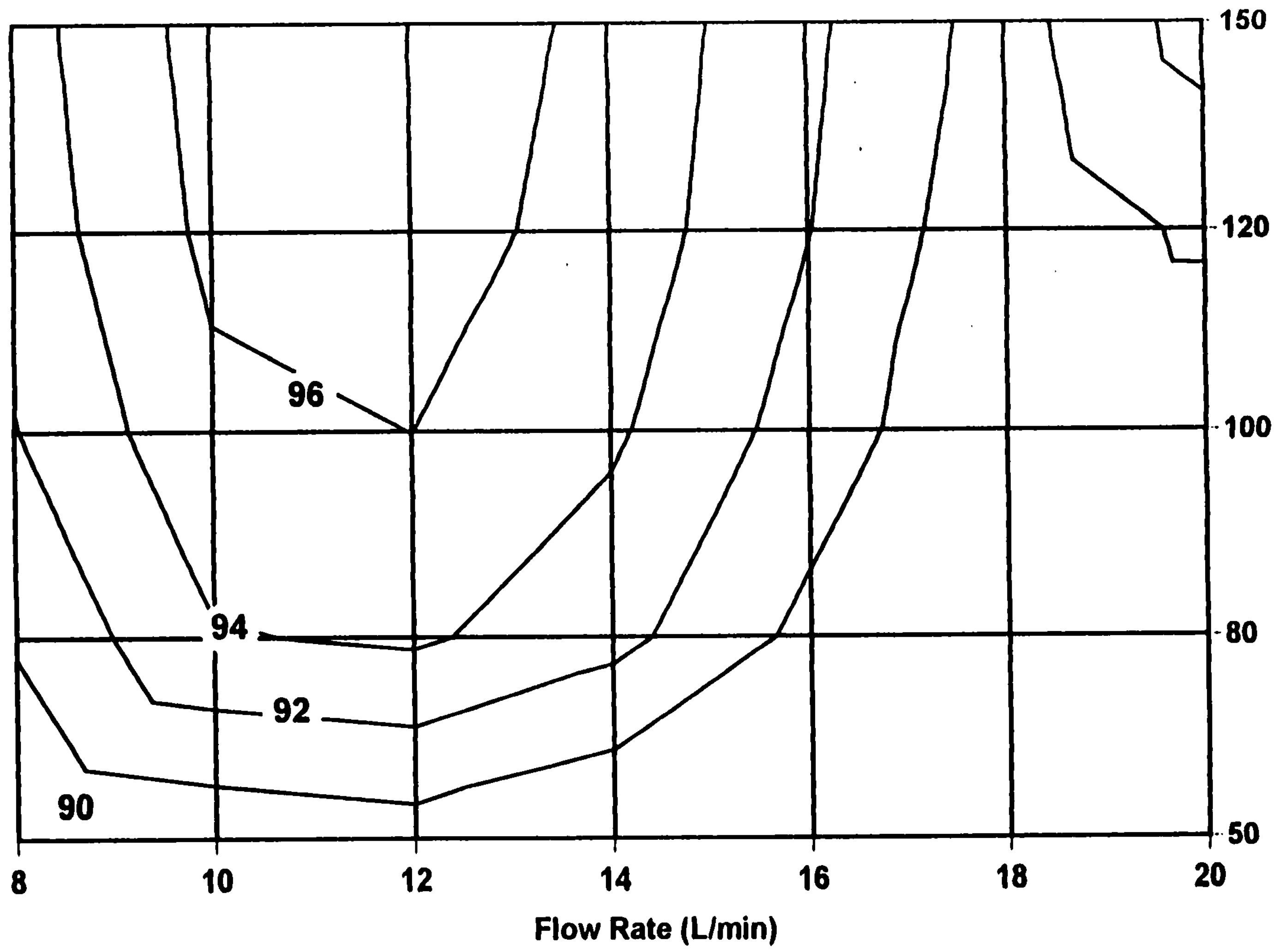

Fig. 5.22: Contours for Fecal Coliform Showing Percent Removal at 0.3 mm Grain Size

Table 5.31: The Removal Efficiency Data Generated from Model-3 (Standard Plate Counts) at 0.5 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	82.67	87.86	89.55	90.43	90.77
10	86.29	91.48	93.16	94.05	94.38
12	86.76	91.95	93.64	94.52	94.86
14	85.07	90.26	91.95	92.84	93.18
16	81.83	87.06	88.77	89.69	90.06
18	77.74	83.22	85.10	86.17	86.79
20	75.32	82.62	85.72	88.01	90.46

Table 5.32: The Removal Efficiency Data Generated from Model-3 (Standard Plate Counts) at 0.3 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	92.79	99.99	99.99	98.69	93.55
10	91.95	99.43	99.87	98.26	93.29
12	91.09	98.75	99.31	97.81	93.01
14	90.12	97.95	98.63	97.24	92.62
16	88.28	96.29	97.08	95.81	91.37
18	80.06	88.25	89.15	88.00	83.73
20	24.69	33.05	34.07	33.04	28.94

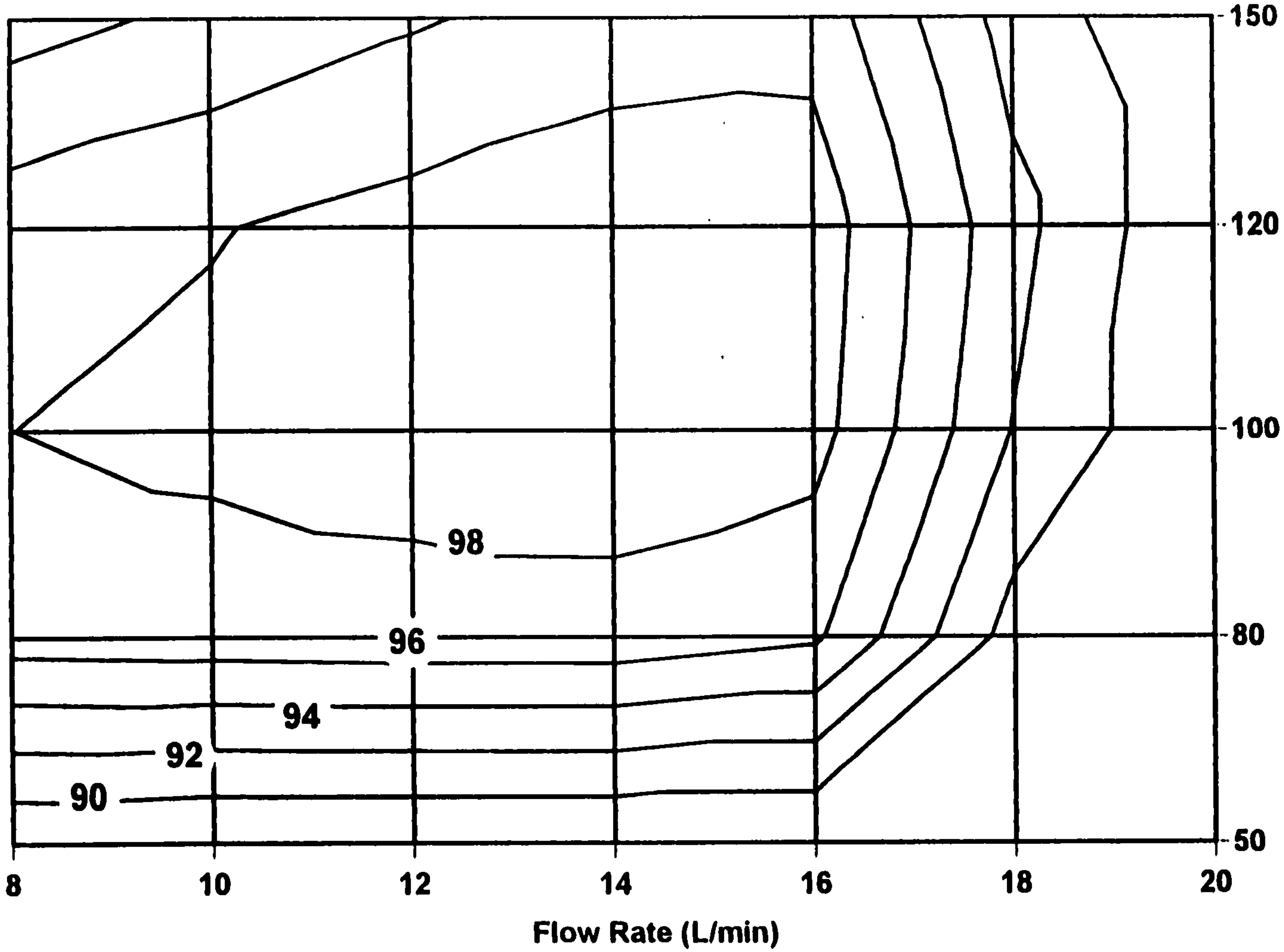

Fig. 5.23: Contours for S.PlateCounts Showing Percent Removal at 0.5 mm Grain Size

change in removal efficiency with increase in flow rate from 8-16 L/min at fixed bed depth. But at a constant flow rate significant improvement in removal efficiency can be observed by increasing the bed depth. The optimum range of removal efficiency will be achieved within the bed depth range 90-130 cm. At 12 L/min flow rate and 50 cm bed depth the removal efficiency was less than 90%. The removal efficiency will increase when bed depth increases, i.e., at 55cm it became 90%, then 92% at 65 cm and improved to 96% at depth of 80cm. The optimum results of removal efficiency can be achieved within the filtration rate of 10-16 L/min and bed depth of 90-120cm. Similarly Table 5.32 was developed for 0.3mm grain size filter under variable conditions of sand bed depth and filtration rate. Fig. 5.24 shows the contour plot for 0.3mm grain size, standard plate count removal efficiency. This plot showed that at 10 L/min flow rate and 50 cm bed depth, the removal efficiency was 92% and it increases to 98% when the bed depth was increased to 80 cm at the same flow rate. In comparison to this, at fixed bed depth of 50 cm the removal efficiency decreased from 92% to 90% with increase in flow rate from 10 to 18 L/min. It can be observed that bed depth greater than 80 cm a rapid change in removal efficiency of standard plate counts at fixed flow rate. At approximately 17 L/min flow rate, the change of depth from 80 to 130 cm did not bring any change in removal efficiency. The working range of filtration should be from 8-14 L/min and the bed depth should be from 80-120 cm to get the optimum results of removal efficiency. The filtration rate lesser than 8 L/min are not generally recommended for the operation of slow sand filters.

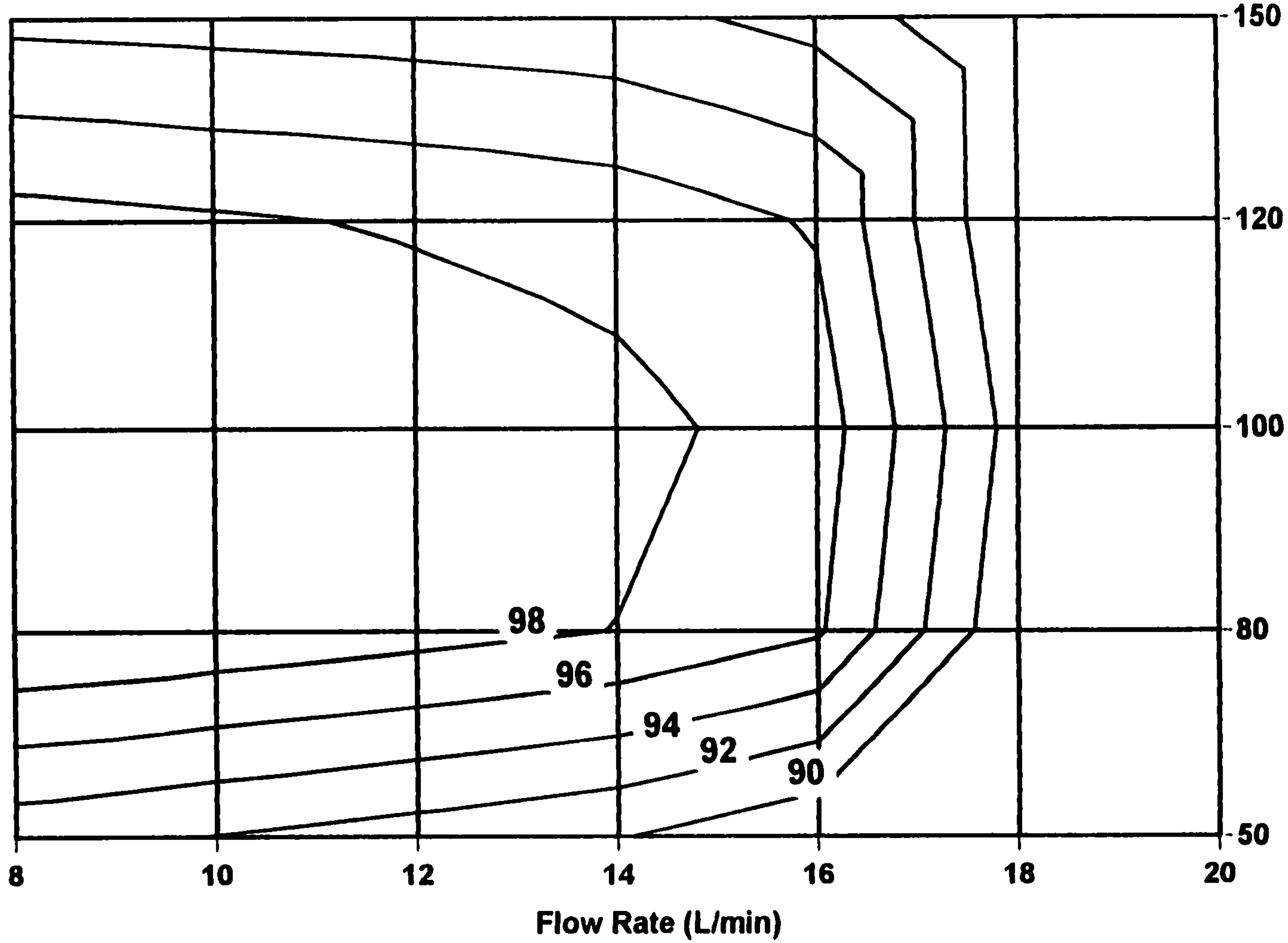

Fig. 5.24: Contours for S. Plate Counts Showing Perceny Removal at 0.3 mm Grain Size

There is no significant change in optimum range of removal efficiency by changing the sand grain size.

The data generated for coliphage contour is given in Table 5.33 for 0.5 mm grain size. Regression Model-4 has been used to develop this table. The corresponding plot for this condition is given in Fig. 5.25. This plot also showed the similar trend, i.e., fixed bed depth and decrease of flow rate did not bring any appreciable change in removal efficiency. From 8 to16 L/min flow rate the removal efficiency curves were parallel to X-axis. But the removal efficiency of coliphages is quite sensitive with variation in bed depth of sand. At 60 cm bed depth, if the filtration rate was varied from 8 to16 L/min the removal efficiency remained the same at 90%. But if at fixed flow rate of 12 L/min, the bed depth was changed from 50 to 90 cm the removal efficiency improved from less than 90% to 96%. The optimum range of control parameters should be 10-16 L/min and 90-130 cm for filtration rate and sand bed depth, respectively. Table 5.34 shows the details of removal efficiency of coliphage at 0.3 mm grain size and under various conditions of flow rate and sand bed depth. The trend of contour plot in case of 0.3 mm grain size as observed in Fig. 5.26 does not vary from the contour map generated for the case of 0.5 mm grain size. The optimum results of removal efficiency can be achieved at flow rate of 8-12 L/min and 90-120 cm bed depth.

From the above discussion it can be concluded that maximum removal efficiency of different indicator microorganisms vary negligibly except for fecal

Table 5.33: The Removal Efficiency Data Generated from Model-4 (Coliphage) at 0.5 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	87.28	94.82	96.24	96.01	93.66
10	87.78	95.72	97.40	97.44	95.48
12	87.34	95.68	97.62	97.93	96.37
14	86.25	94.99	97.20	97.77	96.62
16	84.69	93.83	96.31	97.15	96.39
18	82.78	92.31	95.06	96.16	95.80
20	80.57	90.51	93.52	94.89	94.93

Table 5.34: The Removal Efficiency Data Generated from Model-4 (Coliphage) at 0.3 mm Grain size

Flow(L/min)	Depth(cm)				
	50	80	100	120	150
8	90.44	97.34	98.33	97.68	94.68
10	90.67	97.81	98.96	98.47	95.71
12	89.96	97.34	98.65	98.32	95.80
14	88.61	96.23	97.70	97.53	95.25
16	86.79	94.65	96.27	96.26	94.22
18	84.60	92.70	94.49	94.64	92.84
20	82.13	90.48	92.42	92.73	91.17

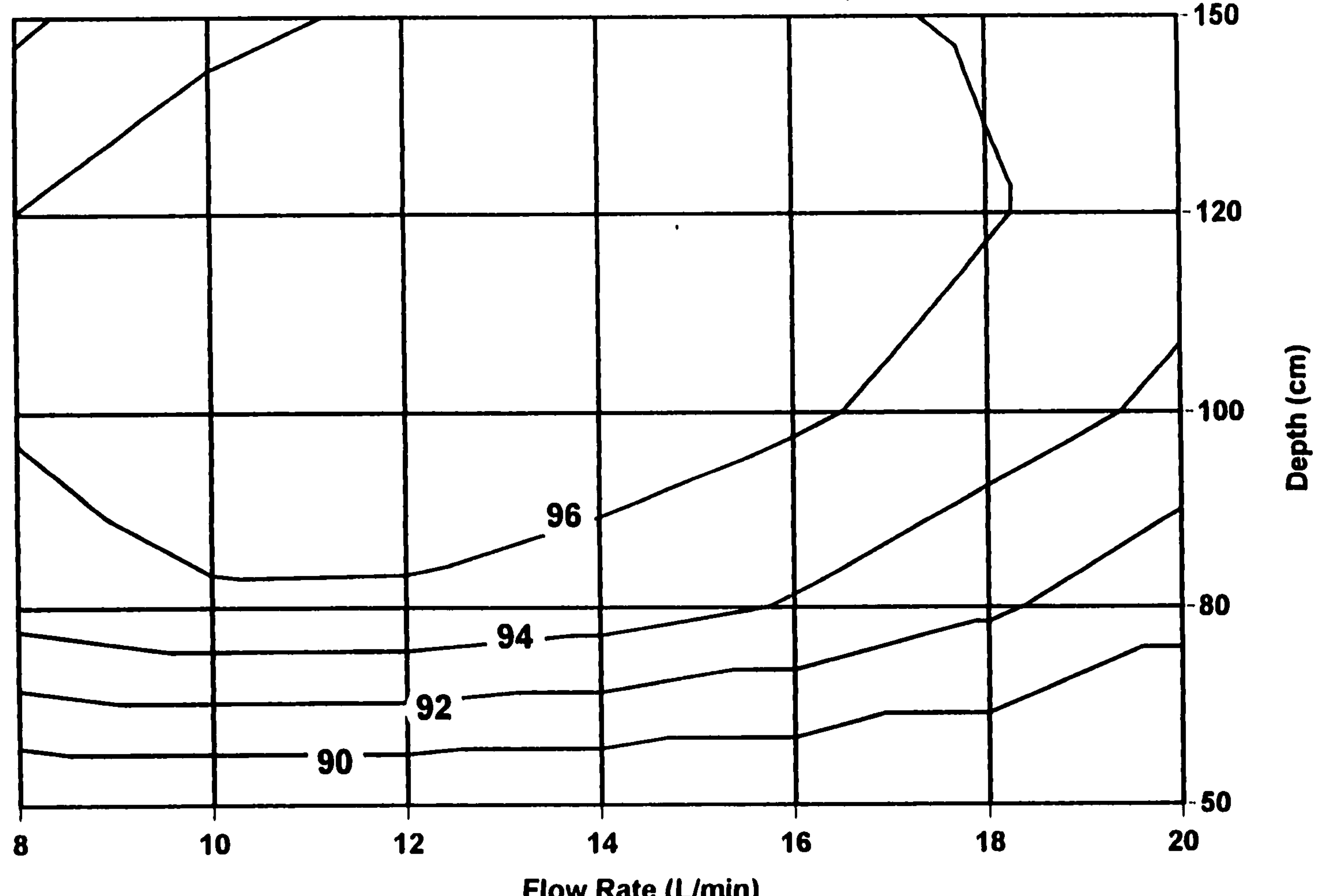

Fig. 5.25: Contours for Coliphages Showing Percent Removal at 0.5 mm Grain Size

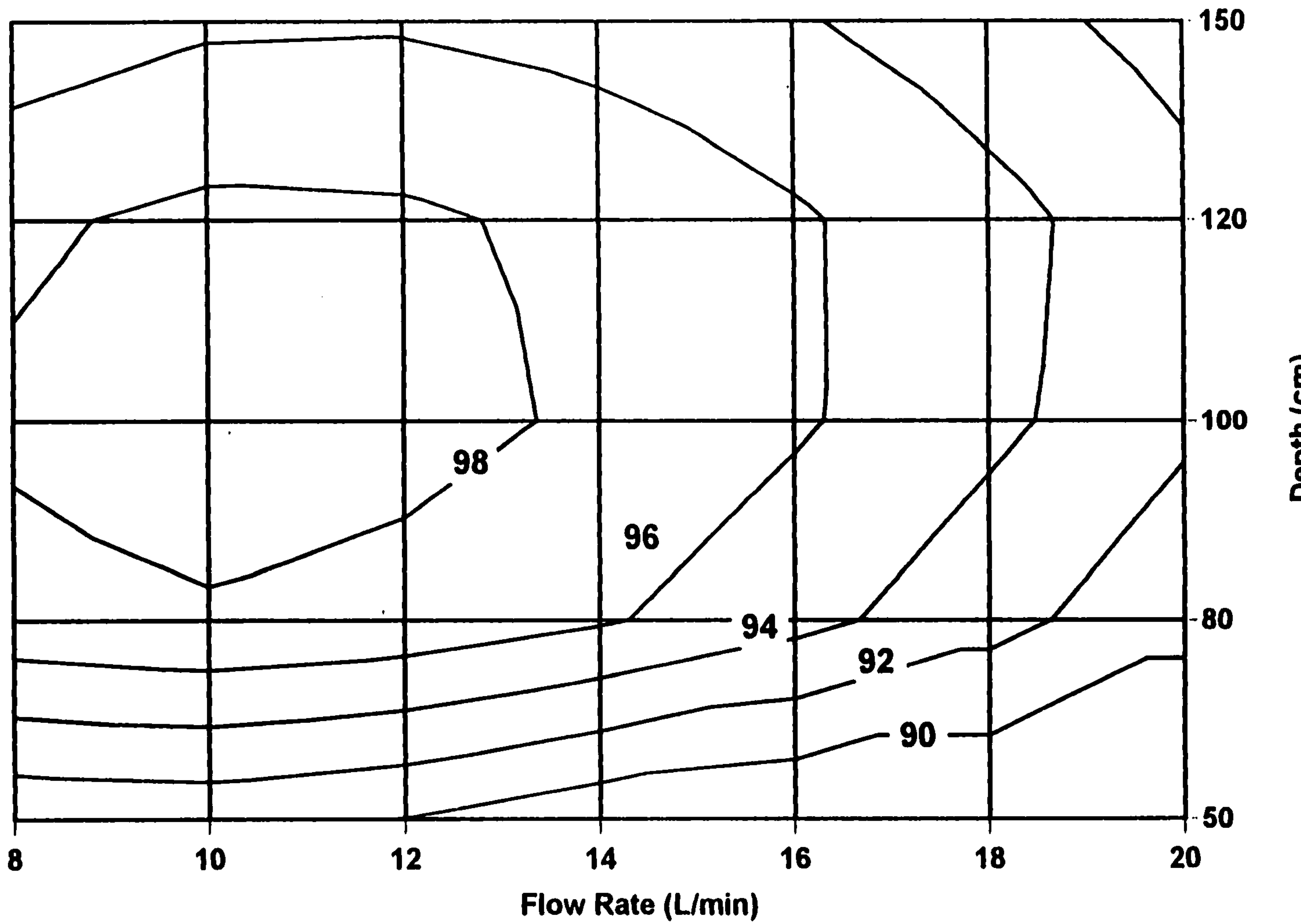

Fig. 5.26: Contours for Coliphages Showing Percent Removal at 0.3 mm Grain Size

coliform. But the general range for control variables can be selected for optimum removals of microorganisms. Sand bed depth should be in between 80-120cm ,whereas, the flow rate should be from 10 to 16 L/min (0.2-0.35 m/hr). A small decrease in bed depth decreases the removal efficiency significantly. It can also be concluded that sand grain size of 0.5 mm and 0.3 mm are not significantly affecting the removal of microorganisms.

6. CONCLUSIONS

This study is a detail statistical data analysis of slow sand filtration efficiency with respect to removal of microorganisms.

The slow sand filter data for various pollutants were available under different control variables. These control variables were filtration rate, sand bed depth and sand grain size. On the basis of statistical analysis following conclusions can be made.

1. The Lognormal distribution is found to be the best distribution for the fit of microorganism data.

2. The risk involved in violating the standards of total coliform is more than 85%, 95% and 97% for 1000, 200, 100MPN/100ml. Whereas for fecal coliform this risk is more than 75%, 90% and 94%.

3. These results suggest that slow sand filtration alone is not enough to meet the standards given by regulatory agencies and some extra treatment like chlorination, is required to use this water for beneficial uses.

4. Good fits to the data were obtained when the data of removal efficiency of microorganism indicators; total coliform, fecal coliform, standard plate counts and coliphages are plotted on Type III asymptotic extreme value distribution.

5. The characteristic parameters of the distribution helped to calculate the mean and standard deviation of pollutant removal efficiency under a given condition of control variables.

6. The mean values calculated from the distribution for different given conditions provide a regression model which would be able to predict the removal efficiency of the pollutants under known control variables.

7. In a comparison of regression model results with similar experiments conducted by other researchers, suggested that for total coliform the percentage error was less than 5% in 13 comparisons out of 18. In case of 10 comparisons of standard plate counts the percentage error was less than 5% in 5 comparisons.

8. The optimum response for all microorganisms (removal efficiency) can be achieved, when dealing with the control variables independently, at sand bed depth of 80-120 cm and filtration rate of 10-16 L/min (0.2-0.35 m/hr hydraulic loading) under the investigated range of parameters considered in this study.

7. ENGINEERING SIGNIFICANCE

The data generated during experimentation always have variation in the results. These variations of the results and deviation from the response can only be statistically analyzed. The uncontrolled variables like temperature, influent water quality and other environmental factors which are *noise-to- signal* or response present in all type of experimental procedures. These noise factors deviate the results from their true response. Statistical tools are very useful to get the meaningful results in the presence of noise factors.

In this research different statistical distributions were used to get the fit of removal efficiency data for microorganisms in slow sand filters. These statistical continuous distributions are very useful in fitting of any type of data. These distributions can also be used in fitting the data of flow variations to model the water quality in streams, the flow and waste load variations in the water and wastewater treatment plants and other industrial treatment units etc. The advantage of using these distributions are the characteristic parameters (mean, median, variance etc.) of the distribution. These parameters provide information about the shape of the curve and predict the results in advance. The estimated mean from a good fitted distribution with small data is very close to the true mean of results.

Regression analysis is a statistical tool to model the results of an unplanned experiment. Regression equations are very useful because they give the results in form of known independent variables. In any type of engineering experimentation these equations are required because most of the time the experiments cannot be designed in advance. These equations can predict the results of those conditions in which the experiment was actually not performed.

8. RECOMMENDATIONS

During this research, the experiments were conducted without any proper plan of design of experiments and many important set of readings under different levels of control variables were missing. To enhance the accuracy of the analysis the data corresponding to mid depths of 100-120 cm sand depth was needed to be generated, to see the effects on the removal efficiency and predicting the optimum condition of depth.

The suggested models are developed under three control variables namely; filtration rate, sand bed depth and sand grain size, but the effects of temperature and influent water quality were not considered. To develop more precise models these factors could be included in the regression equations.

The performance of the filter can be calculated by removal efficiency and head loss. This research focused on the removal efficiency of the slow sand filter only, but head loss development factor is not modeled. To develop a relationship between the control variables and head loss, the analysis as made in this research is required to be done.

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