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SECONDARY EFFLUENT TREATMENT BY SLOW SAND FILTERS: PERFORMANCE AND RISK ANALYSIS

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Abstract. The objective of this study is to examine the reuse of wastewater for beneficial purposes. To accomplish this objective, the efficiency of slow sand filters in removing total coliforms (TC) was studied using a probabilistic method. Three pilot scale slow sand filters were constructed at Alkhobar wastewater treatment plant, Dhahran, Saudi Arabia. The removal efficiency of filters was estimated under different operating control parameters, which included filtration rate (q), sand bed depth (d) and sand grain size (c). The Type III extreme value distribution best fitted the removal efficiency data. A multiple linear regression analysis was performed to develop a relationship for mean removal efficiency as a function of control parameters. The predicted mean response and experimental results of previous studies were compared to validate the empirical regression model. The control parameters and influent concentrations of total coliform were used in Monte Carlo (MC) simulations for calculating the reliability index (β). The reliability index and corresponding risk were calculated for lognormally distributed safety margins (SM). An effluent standard of 100 total coliform/100 mL was defined as capacity of the filter to ascertain the risks of exceedence, which was approximately less than 50 for 95% of the time. Pre and/or post disinfection would be necessary to meet the stipulated effluent standards for unrestricted agriculture use.

Keywords: agriculture reuse, Monte Carlo (MC) simulations, multiple linear regression, reliability index, safety margin, slow sand filters, tertiary treatment, Type III extreme value distribution

List of symbols

Γ	Gamma function
μ	Mean
θ	Scale factor for Type III distribution
σ	Standard deviation
$\varphi^{-1}\,[F_Y\,(Y)]$	Transformation factor (NORMSINV in Excel-7) = Z-score
BOD	Biochemical Oxygen Demand
C	Capacity (standard of 100 TC/100 mL)

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c	Sand grain size (mm)
COV	Coefficient of variation (σ/μ)
CDF	Cumulative distribution function
COD	Chemical Oxygen Demand
d	Depth of sand bed (cm)
E_i	Effluent concentration (TC/100 mL)
FC	Fecal Coliform
F	F-statistics
$F_Y\ (Y)$	Cumulative distribution function
GoF	Goodness of fit
I_i	Influent concentration (TC/100 mL)
L	Load (effluent concentration of TC/100 mL)
m	Shape factor for Type III distribution
MC	Monte Carlo simulation
MPN	Most Probable Number
n	Number of simulation
N	Total number of data points
P	Probability of exceedence
PDF	Probability Density Function
q	Flow rate (L min^{-1}), filtration rate (m hr^{-1})
R	Random number
β	Reliability index
s	Log normal scatter factor
SM	Safety Margin
TC	Total Coliform
TSS	Total Suspended Solids
x_i	Risk or reliability index
Y_o	Median value of removal efficiency (%)
Y_i or Y	Removal efficiency (%)
Y_m	Maximum value of removal efficiency (%)
Y_{mean}	Mean value of removal efficiency (%)

1. Introduction

Although slow sand filters are in use for water treatment from more than 150 yr, its application in wastewater treatment has recently gained popularity, especially in the context of wastewater reuse (Sadiq, 1997). The World Health Organization (WHO, 1989) guidelines on wastewater reuse in agriculture provide background and guidance to governments for making risk management decisions related to the protection of public health and preservation of environment.

The Kingdom of Saudi Arabia, an arid country, lacks perennial rivers. The national water demand in Saudi Arabia increased from 2.36 to 16.23×10^9 m^3 between 1980 and 1990 (Husain and Ahmed, 1997). Due to low rainfall (on an average less than 100 mm yr^{-1}) and the absence of rivers and lakes, the renewable surface and groundwater resources in Saudi Arabia are not enough to meet the growing demands of domestic, commercial, industrial, and agricultural sectors (Abu Rizaiza and Allam, 1989; Al-Ibrahim, 1990). Groundwater is the main source of water and therefore as a result of high rate of extraction, aquifers are showing significant decline in the water level. Since wastewater reuse can meet these demands to a certain extent, the policy is to utilize all treated municipal wastewater in the most beneficial manner with its main use in agricultural sector. In order to safeguard the public health and to protect the environment, regulations are imposed on the reuse of treated wastewater. One of the viable options to treat wastewater is the use of slow sand filters. The main objective of this article is to evaluate risk of total coliform exceedence in slow sand filter effluent under various operating conditions.

Health hazards are associated with the reuse of treated effluents due to presence of waterborne pathogens and chemicals in the reclaimed wastewater (Husain and Ahmed, 1997). The objective of slow sand filtration is to reduce the health risks associated with wastewater and reuse for irrigation and groundwater recharge.

Total coliforms (TC) and fecal coliforms (FC) are used in conjunction with specified requirements for treating wastewater, and in such cases it is assumed that the need for expensive and time consuming monitoring of treated wastewater for pathogenic organisms is eliminated. Bartone (1990) has suggested a guideline for restricted wastewater irrigation based on an effluent with less than one nematode egg/L and FC of 1000/100 mL. The World Health Organization (WHO, 1989) and United States Environmental Protection Agency (U.S. EPA, 1980) have also recommended these guidelines. Numerous technical and policy options for reducing and controlling the health risks associated with the wastewater reuse in agriculture were also evaluated by the UNDP/World Bank (Shuval *et al.*, 1986; Shuval, 1987).

In recognition of the importance of conserving water resources, Saudi Arabia had planned to recycle 730×10^6 m^3 wastewater by the end of year 2000. Ministry of Agriculture and Water (MAW) Saudi Arabia is responsible for planning and development of all water resources. It is a key organization for implementing agricultural and water-based policies. The MAW in cooperation with other governmental agencies has established guidelines defining the acceptable standards for wastewater treatment, disposal and reuse. The MAW has promulgated effluent standards of less than 10 mg L^{-1} for biochemical oxygen demand (BOD), total suspended solids (TSS) and NO_3-N concentrations for agriculture use. In the case of FC, a 7-day average of 2.2 most probable number (MPN) per 100 mL (with no sample more than 100 MPN/100 mL) for unrestricted irrigation is recommended. For restricted irrigation, the MAW recommended maximum FC concentration in any one sample should not exceed 200 MPN/100 mL and the last 7 days average should be less than 23 MPN/100 mL. Standards adopted by the MAW are based on the State of California Wastewater Reclamation Criteria (1978).

Meteorology and Environmental Protection Administration (MEPA) Saudi Arabia is responsible of environmental surveys and pollution assessment of environmental standards and regulations. The national wastewater discharge regulations are put forward by the MEPA (unpublished report). The MEPA water quality standards were promulgated in order to: minimize the volume of waste generated; reduce discharge of pollutants at source to minimum; ensure maximum assimilation of pollutants; protect the quality of ambient water bodies; and control the quality of wastewater before discharge. In the case of TC, a 7 day average of 2.2 most probable number (MPN) per 100 mL for unrestricted irrigation is recommended. MEPA set a maximum contaminant level (MCL) of 100 MPN/100 mL TC for unrestricted irrigation and 1000 MPN/100 mL for discharge into receiving water bodies.

TC includes all types of FC and other non-fecal lactose fermenting, gram-negative bacilli. As an indicator system, the TC group, thereby, contributes a factor of safety beyond that achievable with FC alone. The current study employed water quality reuse standards of 100 TC/100 mL for unrestricted irrigation in the evaluation of slow sand filter treatment efficiency.

2. Data Collection

Three pilot plant slow sand filters were built at Alkhobar wastewater treatment plant to study the reduction of total coliform population. The quality of secondary wastewater from the treatment plant was measured by taking three replicate grab samples of BOD, chemical oxygen demand (COD), TSS, nitrogen and phosphorous (N and P) and microbial indicators. The ranges and average values of the characteristics of the secondary effluent used as the influents for slow sand filter are reported in Table I. The total coliform concentration ranged from 3.1×10^3 to 1.2×10^7/100 mL.

Three slow sand filters each of 2 m in diameter were operated for approximately 15 months. Two filters were operated with coarse sand of 0.5 mm effective grain size and one filter with fine sand of 0.3 mm grain size (Farooq and Nakhla, 1996; Khan, 1996; Sadiq, 1997). The filters were operated to investigate the effectiveness of various control variables on the removal efficiency of the microbiological indicators. The filters were operated at flow rates of 8, 10, 16 and 20 L min^{-1} (0.15, 0.20, 0.30 and 0.40 m hr^{-1}) whereas the sand bed depth was varied from 150 to 80 cm and then to 50 cm. The effect of third control variable i.e. sand grain size

TABLE I
Characteristics of secondary effluent from Al-Khobar treatment plant

Parameter	Minimum	Maximum	Average
Temperature (C)	10	39	28
Turbidity (NTU)	0.2	0.95	0.7
BOD (mg L^{-1})	2.8	6.1	4.8
COD (mg L^{-1})	32	57.6	41
TSS (mg L^{-1})	8	88.4	14.7
TKN[a] (mg L^{-1})	0	6.2	3.2
Total-PO_4 (mg L^{-1})	0	1.15	0.56
Total Coliform (MPN/100 mL)	3.1 E+03	1.2 E+07	3.69 E+05
Fecal Coliform (MPN/100 mL)	0.0 E+00	9.4 E+05	1.53 E+05

[a] TKN: Total Kjeldahl nitrogen.

was studied at two levels – 0.3 mm (fine) and 0.5 mm (coarse). Two filters were filled with 0.5 mm and one filter with 0.3 mm sand grain size. The entire operation of the filter consisted of 14 sets of operating conditions, out of which 5 with fine sand and remaining 9 with coarse sand. The initial four conditions corresponded to operation at 0.5 mm, the next five with 0.3 mm, and the last five conditions were operated at 0.5 mm sand grain size. The program of operation was designed so that when one condition was over, the filter was adjusted to a new operating condition with respect to sand bed depth, filtration rate and media grain size. The data were collected under steady state condition upon the development of biological layer (Farooq and Nakhla, 1996; Sadiq, 1997). A summary of operational details is shown in Table II. The operation was suspended for some periods because of operational and maintenance problems such as pump failure, etc.

Filtration rate control is the key element in operation of filters. For treatment of surface water, generally a filtration rate of 0.1 to 0.2 m hr^{-1} is recommended but up to 0.6 m hr^{-1} is reported in the literature (Visscher, 1988). In this study control valves were used to maintain the flow rate from 0.15 to 0.40 m hr^{-1} and vigilant monitoring on a daily basis helped in maintaining the desired flow rates. The criteria used for terminating filter runs were break through of turbidity or attainment of head loss of 150–175 cm. The desired flow rates could not be maintained over these head losses.

3. Removal Efficiency Modeling

Several mathematical filtration models have been proposed during the last 30 yr. Most of these models were originally developed to describe aerosol removal by fibrous filter and later applied to aquasols (Sadiq, 1997). In filtration mechanisms,

TABLE II

Operating conditions of slow sand filters

Conditions	Grain size (c)	Filtration rate (q)		Sand bed depth (d)	Days of operation active/inactive
	(mm)	(L min^{-1})	(m hr^{-1})	(cm)	
1	0.5	8	0.15	150	177/32
2	0.5	10	0.20	150	35/1
3	0.5	10	0.20	80	99/2
4	0.5	10	0.20	50	76/2
5	0.3	16	0.30	150	191/39
6	0.3	20	0.40	150	21/1
7	0.3	20	0.40	80	99/3
8	0.3	20	0.40	50	79/3
9	0.3	10	0.20	50	18/0
10	0.5	16	0.30	150	191/55
11	0.5	20	0.40	150	60/1
12	0.5	20	0.40	80	60/2
13	0.5	20	0.40	50	79/6
14	0.5	16	0.30	50	18/0

macroscopic and microscopic theories are widely accepted. In the macroscopic approach, a first order kinetics in the removal of particulate is assumed, whereas the microscopic approach takes into account single collectors efficiencies. Filtration equations describing the deep bed filtration of aquasols were proposed by Yao *et al.* (1971). Similarly there are many other models available in the literature including Hinds (1983), Rubow and Liu (1986), Tien and Paytakes (1976) and Fuchs (1964). These models require data for characteristics of filter media, type of flow and liquid. Contrary to above listed models a statistical approach is employed in this research to model the removal efficiency as a function of operating control parameters.

3.1. Selection of the Distribution

Exponential, normal, lognormal, uniform, weibull and various types of extreme value distributions are commonly used distributions for data fitting. The removal efficiency is calculated by

$$Y_i = \left(\frac{I_i - E_i}{I_i}\right) \times 100 ,$$

TABLE III

Statistical distributions for removal efficiency (Raudkivi, 1979; Lewis, 1987)

Distribution	CDF $F_Y\ (Y_i)$	Linearized form
Normal	$\varphi\left[\frac{Y_i - \mu_Y}{\sigma_Y}\right]$	$Y_i = \mu_Y + \sigma_Y \varphi^{-1}[F_Y(Y_i)]$ μ_Y = Mean σ_Y = Standard deviation
Lognormal	$\varphi\left[\frac{1}{s}\mathrm{Ln}\left(\frac{Y_i}{Y_o}\right)\right]$	$\mathrm{Ln}\ (Y_i) = \mathrm{Ln}\ (Y_o) + s\varphi^{-1}[F_Y(Y_i)]$ $Y_o = \frac{\mu_Y^2}{\sqrt{\mu_Y^2 + \sigma_Y^2}}$ and $s = \mathrm{Ln}\left[\frac{\mu_Y^2 + \sigma_Y^2}{\mu_Y^2}\right]$ Y_o = Median s = Measure of scatter
Type III Extreme value	$\exp\left[-\left(\frac{Y_m - Y_i}{\theta}\right)^m\right]$	$\mathrm{Ln}\,\mathrm{Ln}\left(\frac{1}{F_Y(Y_i)}\right) m\mathrm{Ln}\,(Y_m - Y_i) - m\mathrm{Ln}(\theta)$ $\mu_Y Y_m - \theta\Gamma\left(1 + \frac{1}{m}\right)$ $\sigma^2 = \theta^2\left[\Gamma\left(1 + \frac{2}{m}\right) - \Gamma^2\left(1 + \frac{1}{m}\right)\right]$ Y_m = Maximum value m = Shape factor θ = Scale factor $\Gamma(Y)$ = Gamma function

$\varphi^{-1}\ [F_Y(Y)]$ = Z-Score and Y_i = Removal efficiency. (See definition of parameters in the list of symbols).

where Y_i, I_i and E_i are % removal efficiency, influent total coliform, and effluent total coliform concentrations, respectively. To estimate the characteristic parameters of the distribution, removal efficiency data were fitted to three candidate distributions: normal, lognormal and extreme value Type III distribution. The details of CDF (cumulative distribution function) and characteristic parameters (mean, median and standard deviation etc.) of the selected distributions are summarized in Table III.

The normal distribution is the most commonly used distribution when the random variable Y_i arises from the sum of a number of random effects. Lognormal distribution is suitable when Y_i is a product of random effects. The Type III distribution is a three parameter model and has a truncation (Y_m) on one side, which is 100% in our case. The m and θ are the two unknown parameters of this distribution. The m is the shape factor, which gives information about scatter of data and θ is

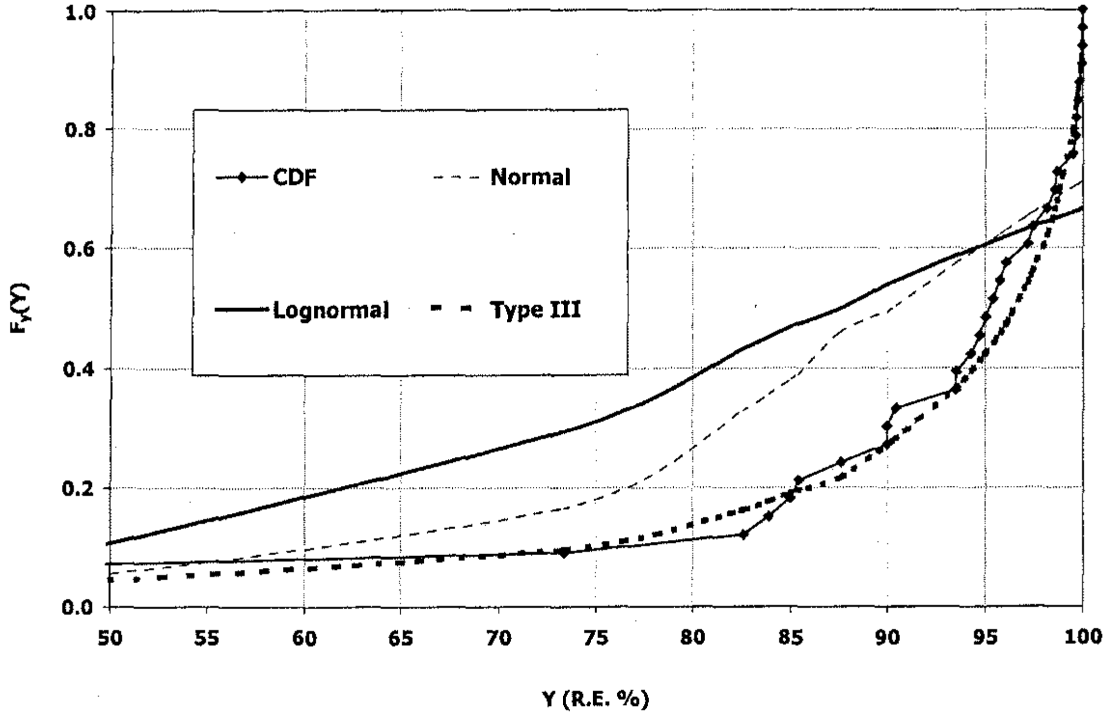

Figure 1. CDF of removal efficiency of total coliform, condition 1.

the scale factor. The expected value and variance of the distribution are given in Table III. The details of these distributions can be found elsewhere (Lewis, 1987).

For each condition, a set of data points were obtained (number ranges from 6 to 38) for total coliforms at the influent and the effluent end of filter. The removal efficiency of bacterial indicators through the slow sand filter was fitted to normal, lognormal and Type III maximum extreme value distributions. The Kolmogrov-Simrnov (K-S) test was performed to check the goodness of fit (GoF) for candidate distributions. The details of this statistics can be seen elsewhere (Sadiq, 1997; Benjamin, 1970). The empirical CDF of total coliform removal efficiency for condition #1 is plotted in Figure 1. The CDFs of all three distributions are also plotted on the same graph. The results of GoF test confirmed that Type III distribution characterized the removal efficiency data in the best manner. The summary of K-S test results is given in Table IV. The result shows that Type III distribution is the best candidate for removal efficiency data in 8 conditions out of 14, which is shown by **shaded boxes**. Even for remaining operating conditions the values were within 5% level of significance.

The selected distribution was fitted and regressed to the data. The method of least square was used to estimate the parameters of the Type III distribution. The estimated parameters of the distribution were used to calculate mean response, and to develop an empirical model as a function of operating conditions. The equation was linearized to plot the data on the Type III distribution (Table III). The characteristic parameters m and θ were calculated from the intercept and slope of

TABLE IV

Summary of K-S test for removal efficiency data

Conditions	Data points	K-S (%)	Normal	Lognormal	Type III[a]
1	33	0.234	0.406	0.287	**0.100**
2	10	0.410	0.136	0.131	0.158
3	14	0.349	0.353	0.267	0.335
4	17	0.318	0.144	0.147	0.159
5	38	0.221	0.255	0.158	**0.132**
6	6	0.521	0.212	0.210	0.213
7	14	0.349	0.125	0.126	0.126
8	17	0.318	0.242	0.254	0.257
9	9	0.412	0.230	0.331	**0.122**
10	38	0.221	0.274	0.302	**0.251**
11	14	0.349	0.299	0.307	**0.203**
12	6	0.521	0.161	0.158	**0.151**
13	17	0.318	0.199	0.191	**0.168**
14	9	0.432	0.223	0.219	**0.213**

[a] Bold figures showing Type III as the best fit.

straight-line equation by plotting Ln Ln $[1/F\ (Y)]$ on y-axis and Ln (Ym-Y) on x-axis. The probability positions were calculated by the mean rank formula (Weibull plotting position) as given by the following equation.

$$F_y(Y_i) = \frac{i}{(N+1)}\,, \tag{1}$$

where N is the total number of data points and i is the i^{th} observation. The fitted plot for condition #1 of total coliform removal efficiency is shown in Figure 2. The above procedure was repeated for other conditions and similar results were obtained and these are summarized in Table V. The m and θ values were calculated by comparing fitted equation with the straight-line equation. The statistics including mean (Y_{mean}), standard deviation (σ_Y) and coefficient of determination (R^2) are also reported in Table V.

As shown in Table V the extreme value is a skewed distribution and its shape depends on parameter m. The smaller values of m indicate a higher skewness and imply a higher variability in data. The mean removal value (Y_{mean}) of total coliform in condition 1 was 96.5% with a standard deviation of 10%. In all operational conditions the removal efficiencies of total coliform were more than 90% except for conditions 4, 8 and 13. The conditions 8 and 13 represented the extreme operational condition with respect to a high flow of 20 L min^{-1} (0.40 m hr^{-1}) and low bed

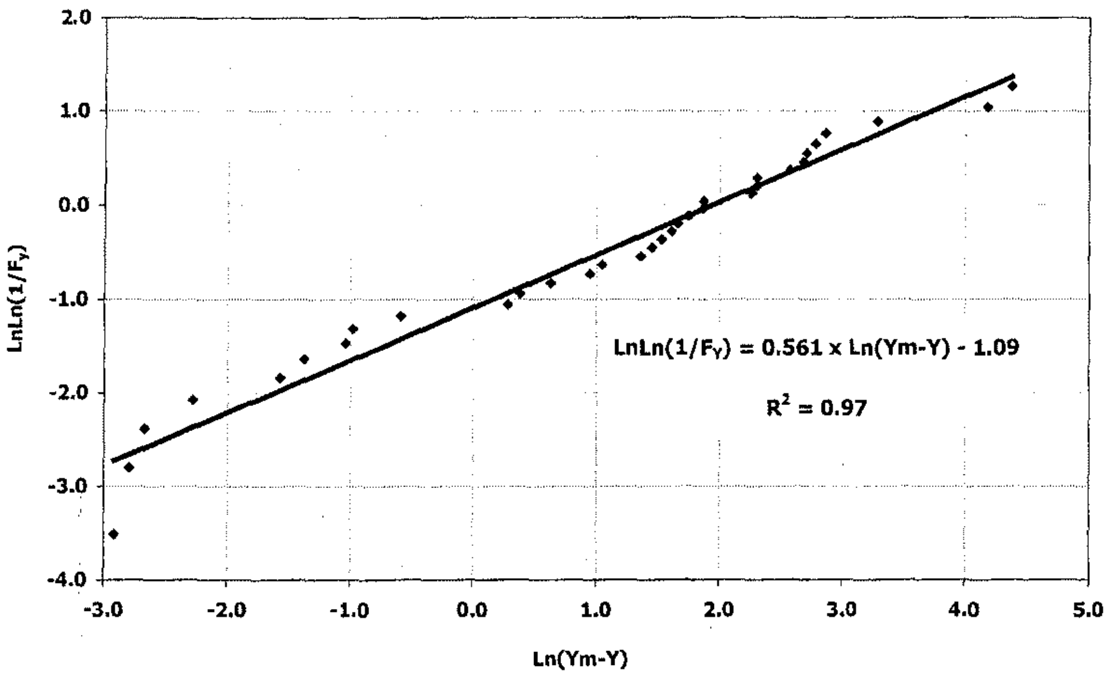

Figure 2. Fit of Type III maximum extreme value distribution to characterize the removal efficiency of total coliform, condition 1.

TABLE V

Removal efficiency data of total coliform at various operational conditions

Conditions	Data points	R^2	m	θ	Y_{mean}	σ_Y
1	33	0.97	0.56	7.00	96.48	10.60
2	10	0.89	2.06	2.96	97.38	1.33
3	14	0.99	4.44	2.72	97.52	0.63
4	17	0.89	4.93	17.51	83.94	3.73
5	38	0.93	0.90	5.49	94.40	5.84
6	6	0.92	1.11	2.49	97.61	2.16
7	14	0.94	2.11	6.31	94.41	2.79
8	17	0.80	4.19	23.00	79.10	5.62
9	9	0.92	4.84	12.32	88.71	2.66
10	38	0.82	1.30	5.44	94.98	3.90
11	14	0.95	1.24	5.93	94.47	4.49
12	6	0.97	2.82	10.00	91.09	3.43
13	17	0.94	5.73	22.44	79.24	4.20
14	9	0.88	6.30	1.15	98.93	0.20

TABLE VI

Coefficients of regression model

Predictor	Coefficient	Standard deviation	t-ratio	p
Constant	108.1	20.57	5.26	0.000
c	–85.9	34.46	–2.49	0.037
q	–2.58	0.8650	–2.98	0.018
d	0.537	0.2794	1.92	0.091
$d{\cdot}q{\cdot}c$	0.0585	0.02163	2.70	0.027
d^2	–0.0023	0.001357	–1.70	0.127

depth of 50 cm. In condition 4, although the flow rate was not high but the bed depth was the minimum. The data fitted well in all conditions and R^2 values were satisfactorily high (0.78–0.99).

3.2. Regression Model of Average Removal Efficiency

To predict the removal efficiency of total coliform through slow sand filters a mean response model as a function of control variables is required. A multiple linear regression model is developed to predict removal efficiency of total coliform using filtration rate (q), sand bed depth (d) and effective media grain size (c). The model was selected based on regression diagnostics. One of the criteria for selection of the best model was to check the significance of independent variables, which can be determined from individual p-values. The selection of a regression model is based on various statistical parameters such as mean absolute error (MAE), leverage, scattering and trend of residuals, R^2 and R^2_{adj}, overall p-value of model. Several regression models were tried to get statistically acceptable results before selecting the following final regression equation:

$$\mu_Y = 108 - 85.9(c) - 2.58(q) + 0.54(d) + 0.059(d{\cdot}q{\cdot}c) - 0.0023(d^2)\,, \quad (2)$$

where μ_Y is the mean response of the removal efficiency (Y_i). The diagnostics of regression model is shown in Figure 3. The normality of residuals can be observed from normality plot and histogram, which has the approximate shape of a normal distribution. The homoscedacity and trends of residuals were also studied to ensure the regression assumptions. The coefficients of independent variables and their significance levels are given in Table VI. The individual p-values are significant at approximately 90% or more for all variables. The range for which regression model can predict the mean removal efficiency varies from 0.15 to 0.4 m hr^{-1} (8 to 20 L min^{-1}) for filtration rate, 50 to 150 cm for sand bed depth and 0.3 to 0.5 mm for grain size.

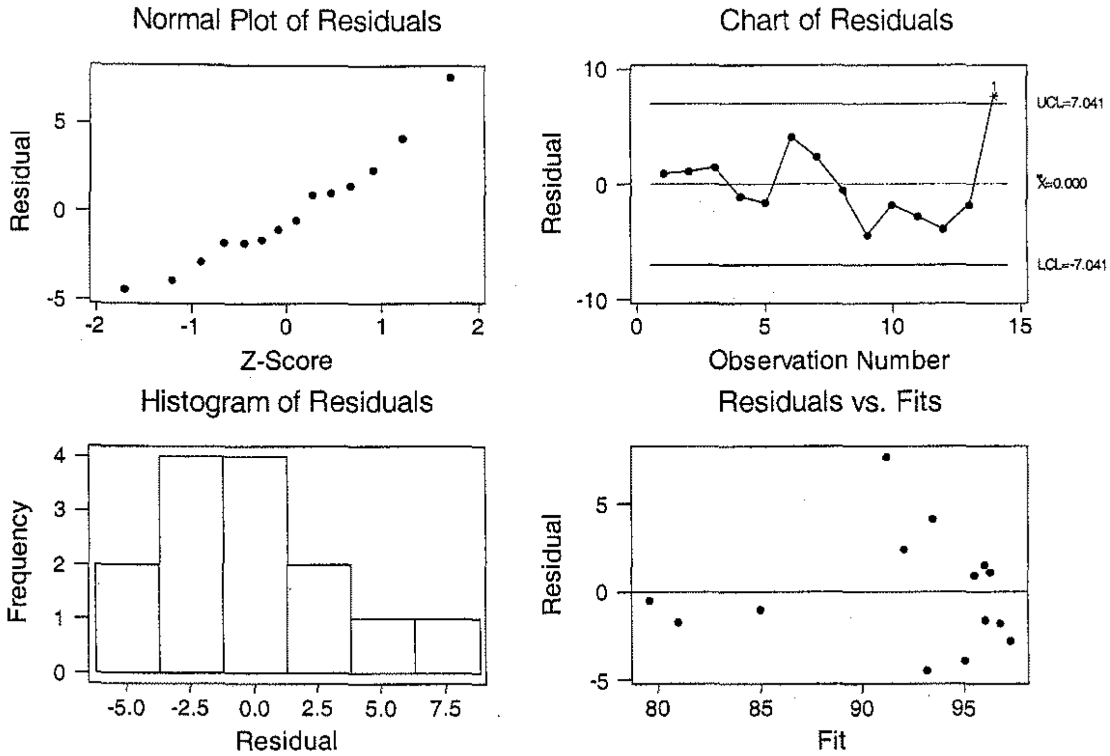

Figure 3. Regression analysis and model diagnostics of residuals.

The analysis of variance (ANOVA) of the selected model is given in Table VII. The coefficient of determination ($R^2 \approx 0.76$), implied that 76.40% of the variability of dependent variable (μ_Y) was explained by this model. The R^2_{adj} value is 61.7%, which is a more reliable parameter for multiple regression models. The advantage of the R^2_{adj} over R^2 is that, it does not increase automatically as new regressors are inserted in to the model (Montgomery, 1991). The standard error (4.17) of the estimate is the standard deviation of the residuals. The mean absolute error (MAE) of 2.54 is the average value of the residuals. The calculated F value is 5.18, which gave overall p-value of 0.02 giving a significance level of 98%. A comparison of predicted and measured values, and confidence and prediction interval envelopes are plotted in Figure 4.

3.3. Model validation

Three studies were selected from literature and values of filtration rate, sand bed depth and media grain size were used to predict the mean response from the model. As shown in Table VIII, a close agreement between experimental results and predicted values is observed. The filtration rate reported in (m hr^{-1}) was converted into (L min^{-1}) corresponding to 2 m diameter filter for using this regression model.

A regression model was used to determine the optimum range of operation for slow sand filters. The contours of removal efficiency at fixed level of sand grain size (c = 0.3 and 0.5 mm) were plotted and shown in Figures 5 and 6. To achieve re-

TABLE VII

Analysis of variances (ANOVA) for selected model

Source	DF	SS	MS	F	p	R^2 (%)	R^2_{adj} (%)	MAE	Standard error
Regression	5	451.8	90.37	5.18	0.020	76.4	61.7	2.54	4.17
Error	8	139.5	17.4						
Total	13	591.4							

DF: Degree of freedom; SS: sum of squares; MS: mean sum of squares; and F: F-test value.

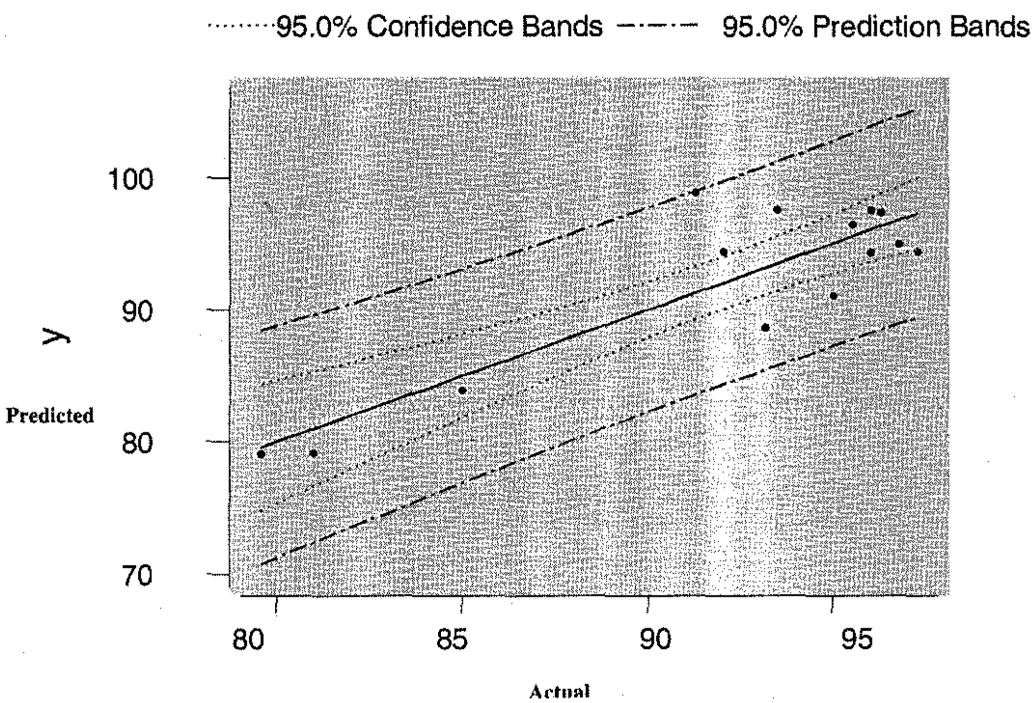

Figure 4. Comparison of fitted and measured values.

moval efficiency of 98% or more for 0.3 mm grain size, the depth (d) should range from 75 to 130 cm and filtration rate (q) from 0.22 to 0.35 m hr^{-1}. Similarly for 0.5 mm grain size, the range for filtration rate was from 0.19 to 0.36 m hr^{-1} to get the same removal efficiency. The optimum ranges of depths and filtration rates are shown in Figures 5 and 6. These ranges are important from optimal operation point of view. It can be observed from the ranges of optimum operational conditions of q and d that grain size does not affect significantly to the removal efficiency of slow sand filters. The model developed in this section will now be used for risk analysis.

TABLE VIII

Comparison of predicted and experimental results

Study	Details	Filtration rate (m hr^{-1})	q (L min^{-1})	d (cm)	c (mm)	$Y_{\text{predicted}}$	$Y_{\text{experimental}}$
Al-Yousaf (1990)	Pilot-scale	0.16	8.4	55	0.31	90.66	93.46
	diameter = 1 m	0.16	8.4	105	0.56	98.02	97.26
Bellamy *et al.* (1985)	Pilot-scale	0.12	6.3	48	0.29	92.45	92.00
	diameter = 0.3 m	0.12	6.3	97	0.62	90.99	96.50
Ellis (1987)	Pilot-scale	0.30	15.7	95	0.60	98.48	99.00
	diameter = 0.14 m	0.15	7.85	95	0.60	92.55	99.00

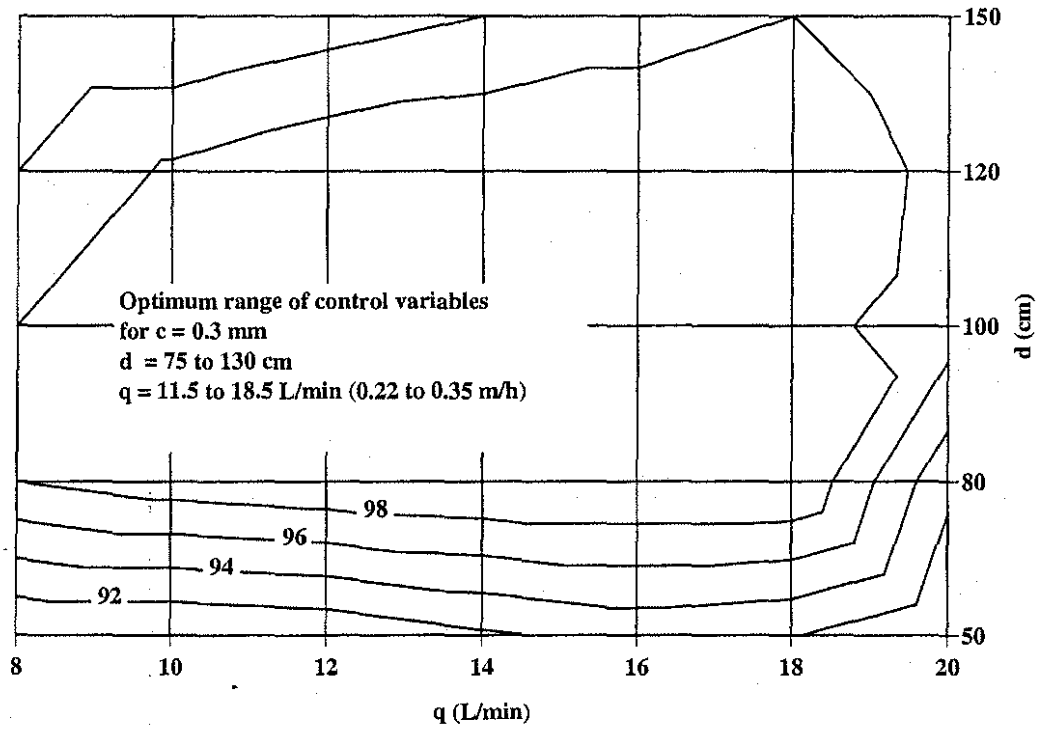

Figure 5. Contours of removal efficiency at 0.3 mm sand grain size.

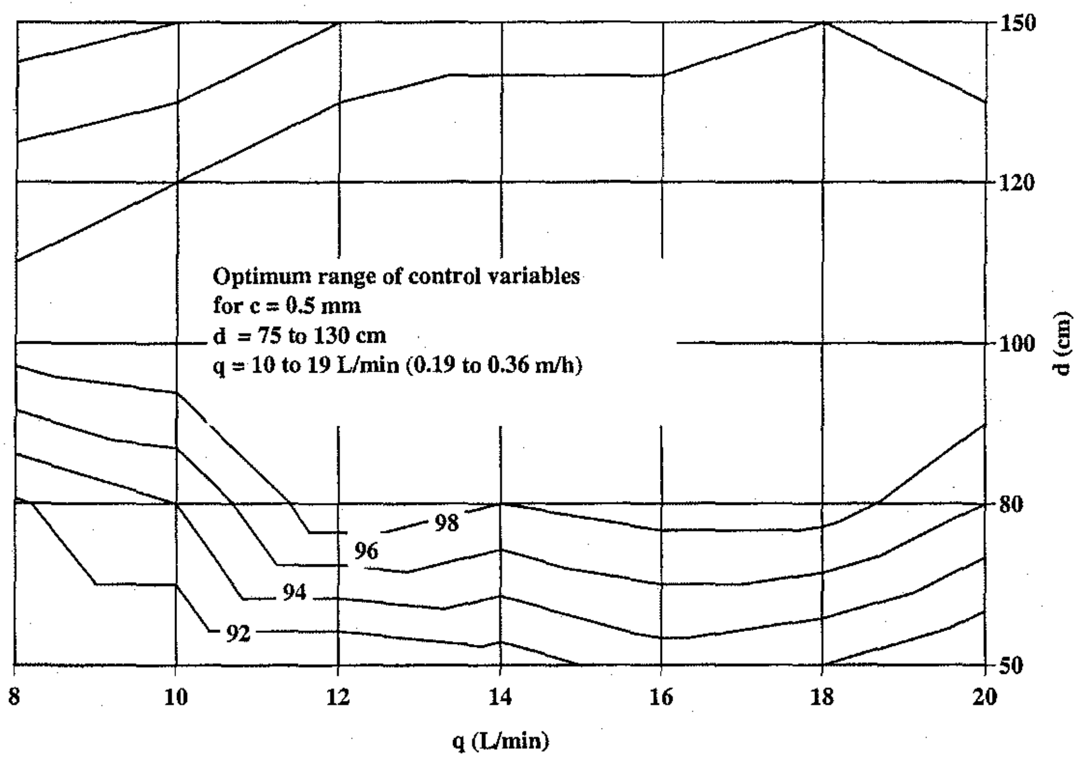

Figure 6. Contours of removal efficiency at 0.5 mm sand grain size.

TABLE IX

Assumed parameter values for normally distributed control variables

Parameter	Mean (μ)	COV (σ/μ)	Standard deviation (σ)
q (L min^{-1})	12	0.2	2.4
d (cm)	80	0.3	24
c (mm)	0.4	0.25	0.1

4. Risk Assessment

Probabilistic risk analysis is a useful tool for setting standards and guidelines in water and wastewater. In the probabilistic analysis the risk is treated as a random variable and its distribution defines the probability of the event that this random variable is below a certain value. If this value is a predefined limit then violation or exceedence of this value is risk and value less than this is acceptable. This study will determine the risk of exceeding reuse standards of 100 TC/100 mL for slow sand filtration treated effluent.

To generate the random values of input variables (q, d and c) normal distributions were assumed. Mean and coefficient of variations (COV) of q, d and c were assumed and given in Table IX. The means and COVs were assumed so that it would cover the ranges of operating parameters for which regression model was developed. The mean value of the filtration rate (q) was assumed 12 L min^{-1} (0.24 m hr^{-1}) with COV of 0.2. Similarly values for depth (mean = 80 cm and COV = 0.3) and grain size (mean = 0.4 mm and COV = 0.25) were assumed arbitrarily.

4.1. Reliability Index and Composite Risk Analysis

Composite risk analysis is a method of accounting for the risks resulting from various sources of uncertainty to produce an overall risk assessment for a particular engineering design. In composite risk analysis, the concepts of loading and capacity are central to the analysis. The loading (L) or demand placed on system, is the measure of impact of external events. In this research working of slow sand filters under various operating conditions is a loading to the system. In contrast to that capacity (C) or resistance is the measure of ability of the system to withstand the loading to meet the demand. The standards promulgated by different regulatory agencies could be the capacity in our case as discussed in the first section of this

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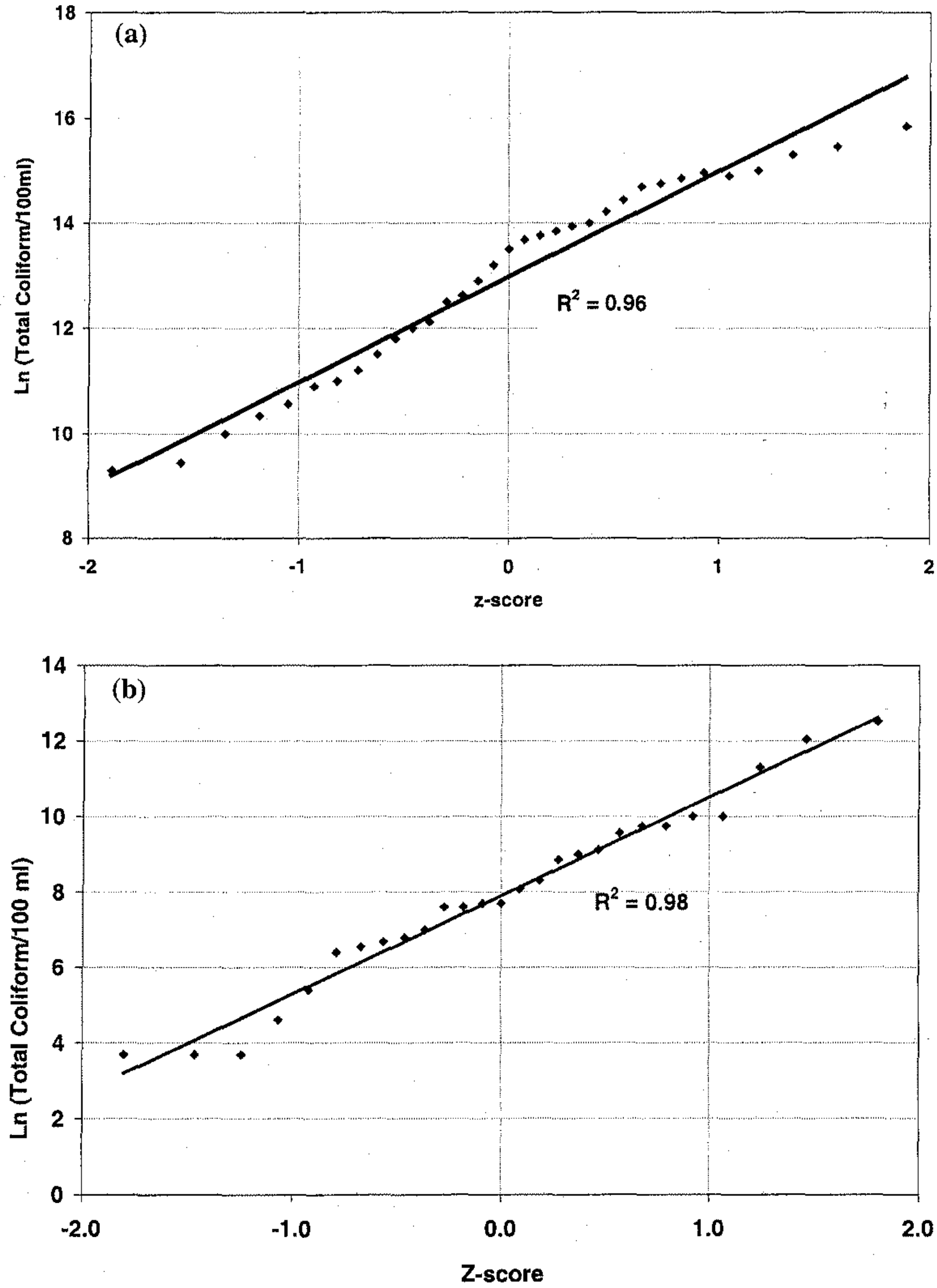

Figure 7. (a) Lognormal fit to influent total coliform concentration for condition 1. (b) Lognormal fit to effluent total coliform concentration for condition 1.

article. The effluent concentration of total coliform (E_i) can be written in form of influent concentration (I_i) and removal efficiency (Y_i) as

$$E_i = I_i \left(1 - \frac{Y_i}{100}\right) . \tag{3}$$

The effluent concentration of TC/100 mL in slow sand filter (E_i) is the loading (L with mean of μ_L), whereas standard value of 100 TC/100 mL is considered as the capacity of system. To use regression model (Equation (2)) mean value (μ_Y) of removal efficiency Y_i will be used in Equation (3). Due to larger variations in total coliform influent and effluent populations, lognormal distribution could be the best choice for data fitting. The influent (I_i) and effluent concentrations are fitted to lognormal distribution for condition 1 and results are given in Figures 7a and b, respectively. Data were fitted using mean rank formula as given in Equation (1). The R^2 values of 0.96 and 0.98 were obtained for influent and effluent concentration data, respectively. Selection of lognormal distribution for influent total coliform data was based on analysis reported in Sadiq (1997) and Saleem (1997). The minimum and maximum values (as given in Table II) were defined as lowest 1% and highest 99% to calculate the parameters of lognormal distribution for I_i, influent total coliform concentration. Therefore, Equation (3) becomes:

$$\mu_L = E_i = \exp\left(\mathrm{Ln}(Y_o) + s\varphi^{-1}\left[F_y(Y)\right]\right)\left[1 - \frac{\mu_Y}{100}\right] , \tag{4}$$

where $\varphi^{-1}[F_Y(Y)]$ is a z-score and defined by NORMSINV function in MS-Excel. The risk of failure is given by the probability that load exceeds capacity, i.e., when we are not able to treat water below 100 TC/100 mL. In mathematical form we can write

$$\mathrm{Risk} = P\left(\frac{C}{L} < 1\right) . \tag{5}$$

The risk depends on probability distribution of load (L) and capacity (C). Although there are many simpler approaches available for calculating risk (Lewis, 1987) but the most common approach is safety margin (SM) or performance function approach which is the difference between capacity and value calculated for design loading, i.e.,

$$\mathrm{SM} = C - L \qquad \text{or} \qquad \mathrm{SM} = C - E_i . \tag{6}$$

Therefore probability or risk of failure is

$$\mathrm{Risk} = P(C - E_i < 0) \qquad \text{or} \qquad \mathrm{Risk} = P(SM < 0) . \tag{7}$$

The mean and variance of SM are given by

$$\mu_{\mathrm{SM}} = \mu_C - \mu_L \tag{8}$$

and

$$\sigma_{\mathrm{SM}}^2 = \sigma_C^2 + \sigma_L^2 \,. \tag{9}$$

As capacity is a defined fixed value of μ_C = 100 TC/100 mL, so variance of capacity (σ_C^2) will be zero. Therefore, the variance of SM and load will be equal ($\sigma_{\mathrm{SM}}^2 = \sigma_L^2$). The effluent concentration (E_i) and μ_L are representing the same quantity and therefore μ_{SM} will be calculated using Equations (4) and (8).

The normal distribution is used widely to relate safety factors to reliability when small variations in dimensional tolerances are expected. Similarly when the uncertainty about the load or capacity or both is large, the lognormal distribution is useful (Lewis, 1987). For normally distributed safety margin the risk of failure is defined as

$$\mathrm{Risk} = F_x\left(-\frac{\mu_{\mathrm{SM}}}{\sigma_{\mathrm{SM}}}\right) . \tag{10}$$

where F_x is the standard normal distribution function. The term $\left(\frac{\mu_{\mathrm{SM}}}{\sigma_{\mathrm{SM}}}\right)$ is called reliability index (β) and it is the measure of safety of the system. The reliability index offers a comparative reliability evaluation rather than a risk evaluation. In terms of reliability index if SM is normally distributed,

$$\mathrm{Risk} = P(x_i < -\beta) \tag{11}$$

therefore,

$$\mathrm{Risk} = 1 - F_x(\beta) \,. \tag{12}$$

If the capacity and loading are lognormally distributed, the reliability index becomes

$$\beta = \frac{\ln\left(\frac{\mu_C}{\mu_L}\right)}{\sqrt{\mathrm{COV}_C^2 + \mathrm{COV}_L^2}} \tag{13}$$

As coefficient of variation for capacity (COV_C) is zero, so Equation (13) reduces to

$$\beta = \frac{\ln\left(\frac{\mu_C}{\mu_L}\right)}{\mathrm{COV}_L} \tag{14}$$

Putting β from Equation (14) into Equation (12), risk can be calculated. In this study lognormally distributed SM was assumed because influent and effluent concentration of total coliform follow lognormal distribution (Sadiq, 1997; Saleem, 1997).

$$\mathrm{Risk} = 1 - F_x = \left(\frac{\ln\left(\frac{\mu_C}{\mu_L}\right)}{\mathrm{COV}_L}\right) \tag{15}$$

TABLE X
Summary of calculated risks

Probability of exceedence	5%	50%	95%
Risk_L	0.29	0.48	0.49

4.2. Monte Carlo (MC) simulations

The variables including filtration rate (q), sand bed depth (d), sand grain size (c) and influent concentration (I_i) of total coliforms are taken as uncertain inputs. To define the risk in probabilistic terms Monte Carlo (MC) simulations were performed. MC is a widely used method for uncertainty measurements. The term MC is used when the simulation performed for replicating the real world involves random values of the parameters with known or assumed probability distributions. In MC simulations a set of random values is generated in accordance with predefined probability density function (PDF) of the parameter. For each simulation SM was calculated using the random values of the input parameters. Detailed description of MC for risk analysis can be found in U.S. EPA (1996). 10 000 simulations were performed and μ_L's were calculated using Equation (4). The variance was calculated from the following relationship.

$$\sigma_L^2 = n \times \text{Variance of}(\mu_L)\,, \tag{16}$$

where n is the number of simulations. The Equations (4) and (16) can be substituted in Equation (15) to calculate the risk of exceedence. In Figure 8, the risk of exceedence is plotted. Table X gives a summary of risk calculated at different probabilities. It can be observed that risk varies from 0.0 to approximately 0.50. The risk at 5% certainty level is 0.29 and median value (50%) of risk is approximately 0.48. At 95% confidence level the exceedence risk probability is approximately 0.50. Approximately 90% of data show risk exceedence probability level above 0.45.

The estimated higher risk values represented the non-compliance of the unrestricted agricultural reuse standards. In addition to slow sand filers as tertiary treatment device, post or pre chlorination of treated wastewater can be performed which would improve the wastewater quality and help in conforming agricultural reuse standards and other beneficial purposes.

5. Conclusions

A general methodology of performing risk analysis for slow sand filter treated wastewater is presented using total coliform as an indicator organism. Higher risks

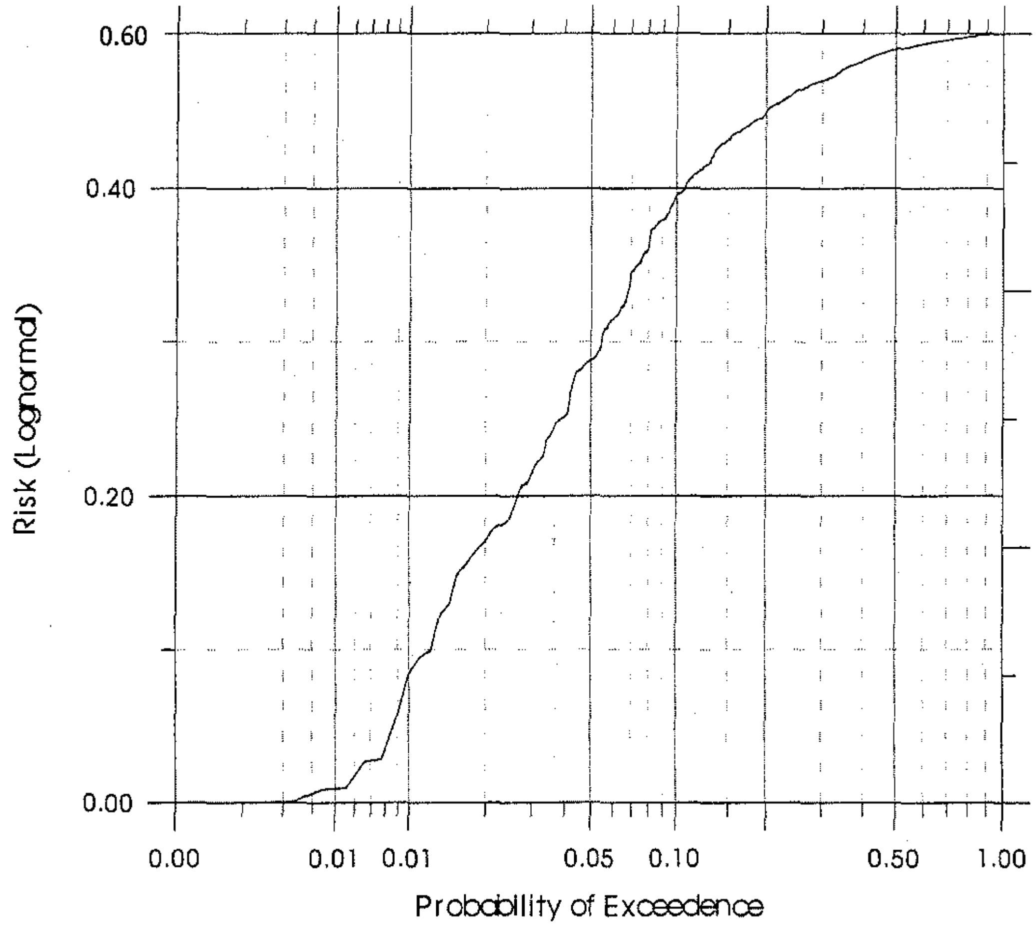

Figure 8. Risk calculated for lognormally distributed safety margin (SM).

of excedences from reuse standards of TC concentrations were obtained for slow sand filter tertiary treated wastewater. The specific conclusions of this study were:

1. Under steady state conditions, the removal efficiency of TC in slow sand filters can be chracterized by Type III extreme value distribution;
2. The average TC removal effciency through slow sand filter can be adequately expressed in terms of operational parameters such as flow rate, sand depth and grain size;
3. Slow sand filter average removal efficiency is not significantly affected by the sand grain size. To obtain better removal efficiency of TC in slow sand filters, the flow rates and sand bed depths ranged from 0.2 to 0.35 m hr^{-1} and 75 to 130 cm, respectively; and
4. The risk of exceeding reuse standard for unrestricted irrigation of 100 TC/100 mL was approximately 50%, at 95% confidence level.

This methodlogy developed in this article can be extended to other treatment options like disinfection, adsorption etc. The methodlogy is developed using TC as a microbial indicator but can also be applied to other regulated chemical and biological pollution indicators.

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