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REGRESSION MODELS ON DESIGN AND OPERATIONAL PARAMETERS OF SLOW SAND FILTERS

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ABSTRACT

The aim of this research was to obtain a regression model that relates the design and operational parameters and inflow water quality for slow sand filters. Therefore, three laboratory scale slow sand filters with sands of different effective diameters were operated at three different temperatures and at five flow rates. Stream water was used as inflow. Small quantities of settled sewage were added to the feed water. From the data produced, 72 regression models were developed relating inflow water quality and treatment rate to effluent quality for each of four quality parameters, three sand sizes and three temperatures. Attempts to create more complex models linking sand size, treatment rate, bed depth, temperature, inflow quality and filtrate quality were not possible due to the discontinuities in the data. Nine of these simple models can be readily employed in the design of slow sand filters. Effective removal of all four quality parameters was achieved with all flow rates at 25 ^oC and 15 ^oC but a definite reduction in the removal of indicator organisms was recorded with the higher flow rates at 5 ^oC. No significant variation in effluent quality with sand size was recorded. Maturation of the new filters was apparently complete within a week.

Key Words: Slow sand filters, Regression models, Sand bed properties, Temperature, Filtration rates

YAVAÞ KUM FÝLTRELERÝNÝN TASARIM VE ÝÞLETME PARAMETRELERÝ ÜZERÝNE REGRASYON MODELLERÝ

ÖZET

Bu çalýþmada yavaþ kum filtrelerinin dizayn ve iþletme parametreleri, giriþ suyu kalitesi ile çýkýþ suyu kalitesi arasýndaki baðýntýyý ifade eden bir regrasyon modeli geliþtirmek amaçlanmýþtýr. Gerekli verileri sistematik ve karþýlaþtýrýlabilir þartlar için elde etmek üzere laboratuvar ölçeðinde üç yavaþ kum filtresi yapýlmýþtýr. Filtreler iki yýlý aþkýn bir zaman sürekli olarak çalýþtýrýlmýþtýr. Her bir filtre deðiþik etkin dane çaplý kum yataðýna sahiptir. Filtreler üç deðiþik sabit sýcaklýkta ve herbir sýcaklýk için 0.1, 0.2, 0.3, 0.4 ve 0.5 m/h olmak üzere beþ ayrý filtrasyon hýzýnda çalýþtýrýlmýþtýr. Filtrelere beslenen dere suyuna az miktarlarda çökelmiþ atýksu karýþtýrýlmýþtýr. Çalýþma sýrasýnda üç ayrý kum yataðýna sahip filtrelerden elde edilen veriler kullanýlarak giriþ suyu kalitesi, arýtma hýzý ve çalýþma sýcaklýklarýnýn filtre çýkýþ suyu kalitesine etkilerini ifade etmek üzere incelenen dört kalite parametresi için 72 regrasyon modeli geliþtirilmiþtir. Kum etkin dane çapý, arýtma hýzý, yatak derinliði, sýcaklýk ve giriþ suyu kalitesinin filtre çýkýþ susyu kalitesine olan etkilerini ifade etmek üzere bir regrasyon modeli geliþtirilmek istenmiþse de verilerde görülen süreksizlik buna imkan vermemiþtir. Ancak geliþtirilen regrasyon modellerinden 9 tanesi yavaþ kum filtrelerinin tasarýmýnda kullanýlabilir. Ýncelenen kalite parametrelerinin hepsindede bütün sýcaklýk ve hýzlarda etkin bir iyileþme görülmüþtür ancak 5 ^oC deki yüksek arýtma hýzlarýnda indikatör organizma giderimi relatif olarak düþmüþtür. Etkin kum dane çapýnýn filtre çýkýþ suyu kalitesine önemli bir etkisinin olmadýðý gözlenmiþtir. Yeni baþlatýlan yavaþ kum filtrelerinin olgunlaþmasýnýn bir hafta içerisinde tamamlandýðý gözlenmiþtir.

Anahtar Kelimeler: Yavaþ kum filtreler, Regrasyon modelleri, Kum yataðý özellikleri, Sýcaklýk, Filtrasyon hýzý

1. INTRODUCTION

With the technique of slow sand filtration the principal design and operational variables can be listed as rate of treatment, sand grain size, sand bed depth, temperature, and together with the quality of inflow water these factors govern the quality of the filtrate produced and the length of run between two successive cleanings.

Investigations have been carried out to link two or, occasionally, three of these factors but no systematic work has been done to connect all four.

Conventionally a treatment rate of 0.1 m/h has been considered as being normal for slow sand filters although rates of flow for non pretreated waters of between 0.8 m/h and 0.21 m/h have frequently been reported (Van Dijk and Oomen, 1978). Ridley (1967) suggested rates of treatment from as little as 0.05 m/h to as high as 0.15 m/h although for the higher rates he considered that it would be necessary to pretreat the raw water. Investigations by the Metropolitan Water Board in London (Windle-Taylor,1969-70) and Ellis and Aydýn (1993) indicated that treatment rates of as high as 0.5 m/h were possible without a significant deterioration of filtrate quality. Rachwal and co-workers (1988), reviewing the operation of full-scale filters at London, suggested that an average rate of more than 0.3 m/h was quite feasible although only with relatively good quality feed water in which the Chlorophyll ‘a’ level was less than 5 mg/l and the particulate organic carbon less than 500 mg/l. Joshi et al, (1982) also indicated that rates of as great as 0.3 m/h are possible but, again, only with good quality feed water.

Recommendations for the effective size (ES) of the sand employed in slow sand filters vary between about 0.15 mm and 0.4 mm. Huisman and Wood (1974) and Thanh et al (1983) recommended as ES of between 0.15 mm and 0.35 mm. Cox (1969) advised an ES of between 0.2 mm and 0.4 mm while Ridley (1967) suggested between 0.25 mm and 0.35 mm and Toms and Bayley (1988) that of about 0.32 mm.

There is less agreement, concerning the depth of sand required. Cox (1969) suggested the appreciable minimum depth of 800 mm while Ridley (1967) advised 650 mm. Most London slow sand filters operate to a minimum depth of only 300 mm (Toms and Bayley, 1988). Certainly the limited minimum depth of 300 mm would appear to be sufficient for the removal of the majority of the turbidity as well as a high percentage of the coliform bacteria but it is doubtful whether the depth would be sufficient for the adequate removal of viruses (Ellis and Aydýn, 1993).

The regression models developed by Ellis and Aydýn (1995) concerned with the extension of biological activity and the penetration of solids into the sand, demonstrated that the most active part of the filter beds was the first 400 mm depth.

Williams (1987) and Kerkhoven (1979) operated slow sand filters at rates of 0.05 and 0.1 m/h, 0.2 m/h and 0.3 m/h respectively and reported no deterioration in filtrate quality with increasing flow rates although the lengths of run declined as the treatment rates increased. Bellamy and his co-workers (1985), using filters with an effective size of 0.28 mm at rates of 0.04, 0.12 and 0.4 m/h, also reported no deterioration in filtrate quality with increasing treatment rates. Rachwal and co-workers (1988) reported an inverse relationship between mean filtration rate and run length for full scale filters but found that the cumulative volume filtered per run was essentially the same for both high rate and conventional rate filters. Logsdon and Fox (1988), reporting on the operation of laboratory scale filters with effective size of 0.17 mm, 0.29 mm and 0.32 mm at rates of 0.12 m/h and 0.18 m/h, found no particular variation in filtrate quality either with effective size or rate of treatment.

Bellamy and co-workers (1985, 1985a) operated a number of laboratory scale slow sand filters in a systematic fashion to consider the influences of effective size, bed depth and temperature. Sand sizes of 0.13, 0.29 and 0.62 mm were employed at a treatment rate of 0.12 m/h and three temperatures of 2 ^{o}C, 5 ^{o}C and 17 ^{o}C. The control filter had a bed depth of 0.97 m while the other filter had the more limited depth of 0.48 m. As expected the efficiency of filtration reduced with bed depth and temperature.

Jack and Charles (1961)employed sand filters with effective sizes of 0.32 mm, 0.40 mm and 0.52 mm to remove algae from water and reported that removal efficiencies reduced with the increasing coarseness of the sand. Flow rates of 0.1 m/h and 0.2 m/h produced no discernible trend of varying removal efficiencies. Williams (1987), employed three fine sand filters (E.S. 0.26 mm, U.C. 1.9) and one coarse sand filter (E.S. 0.62, U.C. 1.6), and reported with the finer filter a 2.3 log removal of faecal coliforms at rates of 0.1 m/h and 0.05 m/h and a slightly lesser removal (2.0 log) with the coarser filter. Surprisingly, investigations at the higher flow rate of 0.2 m/h were abandoned as a result of too frequent blockages.

2. EXPERIMENTAL

During an extended investigation into the effects of design and operational variables on filter efficiency, three laboratory scale slow sand filters (Figure-1) were employed. Each filter was of 150 mm diameter with a constant sand bed depth of 1200 mm and a constant head of supernatant water of 1500 mm. Three different sand sizes were employed. Filter A contained a sand of ES 0.17 mm, filter B contained 0.35 mm ES sand and filter C a sand of 0.45 mm ES. Each filter had five filtrate sampling points at depths of 100 mm, 200 mm, 400 mm, 600 mm and 1200 mm below the sand surface. Each filter was constructed of two separate lengths of perspex connected by a flanged joint at the level of the sand surface to facilitate sand cleaning. A drainage valve was installed immediately above the top sand level for ease of removal of the supernatant water prior to cleaning and arrangements were included to allow the sand bed to be re-filled from the bottom. A constant depth of filter medium was maintained by replacing any sand removed during filter cleaning with sand of identical specifications.

The investigation reported here lasted for two years and following a necessary maturation period of 3 months was equally divided into three separate stages during each of which a different constant temperature was operated i.e. 5 ^{o}C, 15 ^{o}C and 25 ^{o}C. During each of the constant temperature periods, five

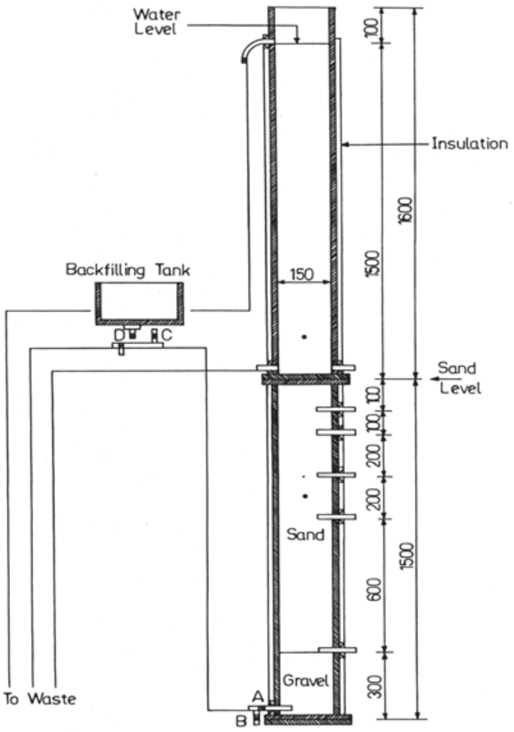

Figure 1 Experimental filters used in the research

different filtration rates of 0.1 m/h, 0.2 m/h, 0.3 m/h, 0.4 m/h and 0.5 m/h were employed. In order to be able to maintain the constant temperature it was necessary to insulate the filter columns with fiber glass jackets.

The raw water employed was abstracted from the stream which flows adjacent to the laboratories. On occasions it was necessary to add some settled sewage in order to maintain an adequate concentration of indicator organisms at about 4000 total coliforms/100 ml. The water was fed to the filters by means of peristaltic pumps with the rates being frequently checked at the filter outlets.

Spot samples of the feed to the filters and of the various filtrates were taken three times a week with no allowance being made for the time of flow between filter inlet and filter outlet. Feed and filtrate samples were analyzed for total coliform bacteria, faecal coliforms suspended solids, turbidity, pH, nitrate nitrogen, ammoniacal nitrogen and occasionally, total organic carbon (TOC). The total coliforms and fecal coliform organisms were determined by a membrane filtration technique (0.45 μm) with the total coliforms being developed on a BBL M-Endo broth at 37 ^{o}C for 24 hours and the fecal coliforms on a Difco mFc broth base at 44.5 ^{o}C for 24 hours. Turbidities were determined using a Hach Turbidimeter (model 16800).

Filter cleaning took place when an individual filter was no longer able to pass the water at the required rate. The feed was then stopped and the supernatant water quickly drained off. The residual water was then allowed to drain quickly below the level of the schmutzdecke at which point the upper section of the filter column was unbolted and removed and the sand surface carefully cleaned using a curved plastic scoop. A clear colour division was always discernible between the dirty sand and the clean and between 30 mm and 70 mm of sand had to be removed on each occasion. The level of sand was maintained at a constant height by the immediate addition of an amount of clean, previously used and washed sand, of identical specifications, equal to the quantity removed. The filter was then re-filled with water, initially from the bottom up, and immediately returned to operation.

3. RESULTS AND DISCUSSION

Full details of observations made on the influent water quality are given in Table-1. Total coliform counts varied between a maximum of 40 500 per 100 ml and 10 per 100 ml with a mean of 4605. The corresponding figures for the fecal coliforms were

Table 1 Analysis of the Influent Data

Parameter	Number of observations	Maximum Minimum Mean Median	Standard deviation	Correlation Coefficients			
				Total coliform	Fecal coliform	Suspended solids	Turbidity
Total coliform (CFU/100 ml)	190	40500 10 4605 2635	6087	1.00	0.79	0.28	0.35
Fecal coliform (CFU/100 ml)	190	12750 10 1143 582	1600	0.79	1.00	0.35	0.41
Turbidity (NTU)	190	37 0.7 6.1 3.5	6.9	0.28	0.33	1.00	0.91
Suspended solids (mg/l)	190	31.8 0.9 6.3 4.4	5.4	0.35	0.41	0.91	1.0

12 700, 10 and 1143. Turbidity levels ranged from 37 NTU to 0.7 NTU with a mean of 6.1 NTU, while with a mean of 6.3 mg/l suspended solids concentrations varied between a maximum of 31.8 mg/l and a minimum of 0.9 mg/l.

All the data collected for the three temperature ranges concerned with effluent quality at five sand bed depths, five flow rates and three different sand size were analyzed using the statistical computer package Minitab and regression models attempted where possible. The theoretical approach to the statistical analysis was based on the work of Anderson et al (1990).

In the approach employed plots of the data were first produced in order to be able to determine the trend of the results and then, following this, multiple regression analyses were carried out. Flow rate variables were used to permit different slopes for each flow rate and influent indicator variables were employed to allow different quality influents to produce different effects on the filtrate quality at each flow rate. The models obtained were checked for significance by employing the coefficient ofdetermination, the t-test and F-statistic. The possibility of reducing the full model to a simpler model, without changing its significance, was examined by leaving out one or more variables at a time and then comparing the simpler model with the original by means of the partial F-test. Examination of the residual was carried out by producing plots and histograms of the residuals. One of the principal aims of this investigation had been to establish a relationship between the variable sand size, sand bed depth, temperature, flow rate, influent quality and filtrate quality. It had been hoped to be possible to produce a single model including all the variables for each of the quality parameters considered. This would have meant that four models would have been obtained, each providing an estimate of the filtrate quality under a variety of conditions. Attempts were made to fit a single model containing all the design and operational variables to all the data obtained for each quality parameter. The model initially developed was then checked to see if the assumptions of regression analysis were satisfied. However, as a result of the further analysis it became evident that there was an unacceptable pattern in the residuals and hence the assumptions of regression analysis were violated. One of the assumptions of regression analysis is that the residuals are normally distributed (Anderson et al, 1990). With these multi-regressional models the pattern in the residuals indicated that the residuals was not normally distributed and hence violated this assumption. This was probably due to the fact that the relationship in the data did not have a linear pattern. To overcome this the usual procedure would be to apply one of the transformation techniques to the data in an endeavor to make the relationship linear. Transformations such as the logarithmic and squaerroot transformation were applied but these were not able to solve the problem associated with the non-normal distribution pattern in the residuals.

The principal reason for this unacceptable pattern in the residuals was the apparent step functions, or discontinuities, in the data. For example, the temperature effect was not very pronounced between the 25 ^{o}C period and the 15 ^{o}C period but it was much more noticeable between 15 ^{o}C and 5 ^{o}C.

In addition there was often no influent effect at the 1.2 m bed depth but a marked influent effect at the 100 mm bed depth. Such data which possess a discontinuity cannot be modeled by simple continuous functions. Therefore an attempt was made to develop a model for each quality parameter and for each temperature and bed depth. This process increased the number of models from the original 4 to (4 x 3 x 2) 24.

Table 2 List of the Regression Models Developed For 25 °C Period

list of the fecal coliform models

$$\sqrt{fc\,a10} = 1.47 + 0.13\sqrt{\inf}\;C012 + 0.22\sqrt{\inf}\;C005$$

$$\sqrt{fc\;effa} = 0.715$$

$$\sqrt{fc\,b10} = 2.46 + 0.13\sqrt{\inf}\;C003 + 0.32\sqrt{\inf}\;C045$$

$$\sqrt{fc\;effb} = 0.49\,C012 + 1.86\,C345$$

$$\sqrt{fc\,c10} = 1.42 + 0.06\sqrt{\inf}\;C002 + 0.21\sqrt{\inf}\;0.21\sqrt{\inf}\;C003 + 0.38\sqrt{\inf}\;C045$$

$$\sqrt{fc\;effc} = 0.10\,C001 + 0.56\,C234 + 1.03\,C005$$

list of the total coliform models

$$\sqrt{tc\,a10} = 2.86 + 0.03\sqrt{\inf}\;C002 + 0.12\sqrt{\inf}\;C034 + 0.20\sqrt{\inf}\;C005$$

$$\sqrt{tc\;effa} = 1.88$$

$$\sqrt{tc\,b10} = 3.94\,C001 + 8.13\,C2345 + 0.12\sqrt{\inf}\;C003 + 0.21\sqrt{\inf}\;C004 + 0.24\sqrt{\inf}\;005 - 0.18\,run\,b$$

$$\sqrt{tc\;effb} = 1.32\,C001 + 2.50\,C002 + 3.50\,C003 + 3.57\,C045 - 0.06\,run\,b$$

$$\sqrt{tc\,c10} = 4.97 + 0.04\sqrt{\inf}\;C002 + 0.19\sqrt{\inf}\;C034 + 0.39\sqrt{\inf}\;C005$$

$$\sqrt{tc\;effc} = 1.57 + 0.013\sqrt{\inf}\;C002 + 0.03\sqrt{\inf}\;C034 + 0.06\sqrt{\inf}\;C005 - 0.06\,run\,c$$

list of the suspended solid models

$$ss\,a10 = 0.80 \qquad ss\;effa = 0.48$$

$$ss\,b10 = 0.33\,C001 + 0.70\,C234 + 1.40\,C005 \qquad ss\;effb = 0.48$$

$$ss\,c10 = 0.39\,C001 + 0.56\,C023 + 1.36\,C045 \qquad ss\;effc = 0.37$$

list of the turbidity models

$$tur\,a10 = 0.38\,C1234 + 0.61\,C005 \qquad tur\;effa = 0.30$$

$$tur\,b10 = 0.41\,C123 + 0.78\,C045 \qquad tur\;effb = 0.30$$

$$tur\;effc = 0.43\,Cf + 0.28\,Cr$$

Cf: *First 20 observations*
Cr: *All other observations*
but can be assumed

$$tur\,c10 = 0.59\,C123 + 1.14\,C045 \qquad tur\;effc = 0.30$$

The models originally developed showed that the sand size effect was not significant. However, this result must be treated with considerable caution as the model, as has been demonstrated above, was known to be inadequate. It is possible that the sand size really had no effect. Alternatively it is possible that the effects of the parameters such as flow rate and influent quality are different for different sand sizes. In other words it is possible that the combination of sand size and flow rate combined, for example, produces an effect rather than merely sand size. Hence, in order to obtain more accurate models the regression analyses were carried out for each filter (sand size) to determine the effect of flow rate, the influent quality and the run lengths. Since three filters were employed, the number of models increased (24 x 3) to 72 (Tables 2 to 4). Each of these models was then checked for significance and also checked by examining the residuals to see if they fulfilled the assumptions of regression analyses. All of these models were satisfactory from this point of view.

The reduction of the number of models, however, for practical purposes from the initial 72 down to a smaller number is possible. Since the suspended solids and turbidity contents of the influent water are reduced to a satisfactory level even at the 100 mm depth, and certainly at the filtrate level, there is no need to use these models at all. This reduces the number of models from 72 to 36. Then, as the total coliform bacteria are more resistant to removal than are faecal coliform bacteria (Oliver and Newman, 1987), only the total coliform models need be employed and the number of models would be reduced from 36 to 18. Finally if the minimum sand bed depth is accepted as being 600 mm, there is no need for practical purposes to use the models created for the depth of 100 mm. This reduces the number of models to be employed from 18 down to 9.

Table 3 List of the Regression Models Developed for 15 ^{o}C Period

list of the fecal coliform models

$$\sqrt{fc\,a10} = 2.3 + 0.15\sqrt{\inf}\,C234 + 0.36\sqrt{\inf}\,C005$$
$$\sqrt{fc\ effa} = 0.1 + 0.02\sqrt{\inf}\,C004 + 0.09\sqrt{\inf}\,C005$$
$$\sqrt{fc\,b10} = 4.1 + 0.14\sqrt{\inf}\,C002 + 0.29\sqrt{\inf}\,C003 + 0.41\sqrt{\inf}\,C045$$
$$\sqrt{fc\ effb} = 0.26\,C012 + 1.74\,C345$$
$$\sqrt{fc\ c10} = 2.3 + 0.11\sqrt{\inf}\,C001 + 0.30\sqrt{\inf}\,C2345$$
$$\sqrt{fc\,effc} = 0.9\,C345 + 0.04\sqrt{\inf}\,C005$$

list of the turbidity models

$$\sqrt{tc\,a10} = 2.5 + 0.16\sqrt{\inf}\,C234 + 0.36\sqrt{\inf}\,C005$$
$$\sqrt{tc\ effa} = 0.6 + 0.03\sqrt{\inf}\,C004 + 0.08\sqrt{\inf}\,C005$$
$$\sqrt{tc\,b10} = 6.6 + 0.10\sqrt{\inf}\,C002 + 0.25\sqrt{\inf}\,C003 + 0.37\sqrt{\inf}\,C045$$
$$\sqrt{tc\ effb} = 0.8\,C012 + 2.5\,C034 + 5.5\,C005$$
$$\sqrt{tc\ c10} = 7 + 0.24\sqrt{\inf}\,C2345$$
$$\sqrt{tc\,effc} = 0.4\,C001 + 1.8\,C345 + 0.04\sqrt{\inf}\,C005$$

list of the total coliform models

$$tur\,a10 = 0.35$$
$$tur\ effa = 0.24$$
$$tur\ b10 = 0.46$$
$$tur\ effb = 0.24$$
$$tur\,c10 = 0.50$$
$$tur\ effc = 0.24$$

list of the suspended solid models

$$ss\,a10 = 0.55$$
$$ss\ effa = 0.34$$
$$ss\,b10 = 0.45\,C123 + 0.74\,C045$$
$$ss\,effb = 0.34$$
$$ss\ c10 = 0.63$$
$$ss\ effc = 0.34$$

These 9 total coliform filtrate models (Table-6) can then be used to estimate the filtrate content of a slow sand filter for various levels of coliform bacteria in the influent and for three different sand sizes and for three temperature levels of 25 ^{o}C, 15 ^{o}C and 5 ^{o}C. As a result of this reduction in the number to be employed, these models become a useful tool for assisting the designer to make a decision on sand size and filtration rates under various influent and climatic conditions.

3.1 Removal Of Indicator Bacteria

From the models developed it can be seen that the removal of faecal coliforms usually decreased with increasing filtration rates at both the 100 mm and 1.2 m sand bed depths although the decrease was more severe at the 100 mm level than at the 1.2 m level. All three filters performed adequately even under the most rigorous conditions of 5 ^{o}C and 0.5 m/h flow rate. No significant difference in the performance of the filters could be contributed to sand grain size. During the 5 ^{o}C stage filter A appears to have performed in a slightly poorer manner than the others but the difference was probably the result of the frequency of cleaning of this filter. When the models for the 100 mm sand level are examined it can be seen that all the filters achieved well at all flow rates during the 25 ^{o}C sage although it was obvious that at the higher flow rates (0.4, 0.5 m/h) substantially more bacteria were penetrating deeper into the sand. As the temperature decreased to 15 ^{o}C and then to 5 ^{o}C the penetration of the bacteria became even more noticeable even at the lowest flow rate employed.

The models developed for the total coliform bacteria indicated very similar removal rates and stresses developing with increasing flow rates and decreasing temperatures particularly at 100 mm depth as were found to have developed for the fecal coliforms. The indication was, as expected, that the region of the schmutzdecke was most highly effective for the removal of bacteria.

During the 25 ^{o}C stage the models produced indicate that about 88 % of the applied influent bacteria was removed by all three filters by the 100 mm sand level although this declined (Table-2) in the direction filter A to filter B to filter C. Then, by the 200 mm, 400 mm, 600 mm and 1200 mm depths additional removals of approximately 4.3 %, 4.5 %, 1.9 % and 0.7 % were achieved. With a temperature of 15 ^{o}C the removal of fecal coliforms by the 100 mm level had reduced to less than 85 % with a further, approximately, 13 % being removed by the 200 mm level. On reducing the temperature to only 5 ^{o}C thefirst 100 mm of sand was only able to remove about 55 % of the influent fecal coliform count with an additional 20 % being removed by the 200 mm level and a further 17 % by the 400 mm level. Overall there was little, if any, reduction in the removal of the fecal coliforms as the temperature decreased from 25 ^{o}C to 15 ^{o}C but a significant reduction of about 3 % was predicted when the temperature was lowered to 5 °C. It was however noticeable that the penetration of the bacteria into the sand bed increased appreciably as the temperature was reduced. For the removal of total coliform bacteria a pattern, very similar to that found for the removal of fecal coliform bacteria, was obtained.

Table 4 List of the Regression Models Developed for 5 °C Period

list of the fecal coliform models

$$\sqrt{fc\,a10} = 4.4 + 0.34\sqrt{\inf}\,C023 + 0.66\sqrt{\inf}\,C045$$

$$\sqrt{fc\ effa} = 0.9 + 0.10\sqrt{\inf}\ C023 + 0.17\sqrt{\inf}\ C045$$

$$\sqrt{fc\,b10} = 13.4\,C001 + 3.9\,C2345 + 0.08\sqrt{\inf}\,C004 + 0.22\sqrt{\inf}\,C005$$

$$\sqrt{fc\ effb} = 1.5 + 0.08\sqrt{\inf}\ C004 + 0.22\sqrt{\inf}\ C005$$

$$\sqrt{fc\ c10} = 7.0\ C001 + 0.34\sqrt{\inf}\ C002 + 0.75\sqrt{\inf}\ C345$$

$$\sqrt{fc\ effc} = 0.8\ C012 + 0.17\sqrt{\inf}\ C345$$

list of the total coliform models

$$\sqrt{tc\ a10} = 9 + 0.33\sqrt{\inf}\ C023 + 0.54\sqrt{\inf}\ C045$$

$$\sqrt{tc\ effa} = 2.5 + 0.07\sqrt{\inf}\ C023 + 0.13\sqrt{\inf}\ C045$$

$$\sqrt{tc\,b10} = 30\,C001 + 6.7\,C2345 + 0.41\sqrt{\inf}\,C023 + 0.64\sqrt{\inf}\,C045$$

$$\sqrt{tc\ effb} = 3.1 + 0.06\sqrt{\inf}\ C004 + 0.17\sqrt{\inf}\ C005$$

$$\sqrt{tc\ c10} = 16.7\ C001 + 0.31\sqrt{\inf}\ C002 + 0.71\sqrt{\inf}\ C345$$

$$\sqrt{tc\ effc} = 2.6 + 0.12\sqrt{\inf}\ C345$$

list of the suspended solid models

$$ss\,a10 = 0.56 + 0.22\inf - 0.34\,run\,a$$

$$ss\,effa = 0.49 + 0.08\inf - 0.02\,run\,a$$

$$ss\,b10 = 0.9 + 0.17\inf - 0.02\,run\,b$$

$$ss\,effb = 0.4 + 0.09\inf - 0.01\,run\,b$$

$$ss\,c10 = 0.9 + 0.18\inf\ C2345 - 0.02\,run\,c$$

$$ss\,effc = 0.44 + 0.66\inf - 0.01\,run\,c$$

list of the turbidity models

$$tur\ a10 = 0.24\,C2345 + 0.15\inf\ C023 + 0.24\inf\ C045$$

$$tur\ effa = 0.2 + 0.02\inf$$

$$tur\ b10 = 0.48 + 0.28\inf - 0.01\,run\,b$$

$$tur\ effb = 0.20 + 0.02\inf$$

$$tur\ c10 = 0.15 + 0.11\inf\ C012 + 0.40\inf\ C345$$

$$tur\ effc = 0.2 + 0.02\inf$$

3.2 Suspended Solids Removal

The suspended solids content of the filtrates from both the 100 mm and 1.2 m levels was found to be independent of the influent quality during the 15 °C and 25 °C stages as well as being independent of the flow rates. Although the models produced were different for each of the filters the estimated suspended solids content of either filtrate, for an influent content of 10 mg/l was always less than 1.0 mg/l except for the 5 °C stage. The large majority of the suspended solids was always removed within the 100 mm level and probably nearly entirely at the schmutzdecke.

3.3 Turbidity Removal

From the models produced it can be seen that the turbidity in the filtrate from the 1.2 m sand depth was largely independent of the influent water quality and of flow rates and sand grain size. Although the different models give different estimates of the turbidity obtained at the 1.2 m level for individual filters, these differences are not of importance from an engineering point of view as they are all less than 0.4 NTU.

The models produced also indicated that for the filtrate from the 100 mm sand level the residual turbidity was independent of the influent quality for all results during the 25 °C and 5 °C stages although not necessarily for the 5 °C stage.

All the models again show different values for different flow rates and different filter beds but at 15 °C and 25 °C these were not significant from an engineering point of view as all were less than 1 NTU. This was not necessarily so for the 5 °C stage.

3.4 Maturation Period

Regression models prepared from the data produced during the maturation period (Table-5) demonstrated that there was no significant improvement of the filtrate quality in terms of total and fecal coliform bacteria and of suspended solid content with increasing number of days. The turbidity models did, however, reveal some definite improvement in the filtrate quality with time but this was hardly significant as the turbidity levels in the filtrates were at acceptable levels even at the beginning of the run.

Traditionally it has been held to be necessary to operate newly constructed slow sand filters for a prolonged maturation period. This period has been considered as being as long as six weeks, during which the filtered water would either be wasted or passed on to another filter. The results of this work show that the need for maturation has been much over-exaggerated. The filtrates from all three filters were of an acceptable quality with regards to turbidity levels and suspended solids contents from the day following start-up and by the sixth day after start-up 99.9 % of both fecal coliform bacteria and of total coliform bacteria were being removed. The indications from this is that probably little more than a week is necessary as a maturation period for a new slow sand filter.

Table 5 List of the Regression Models Developed for Maturation Period

list of the fecal coliform models

$$\sqrt{fc\,a10} = 15.6 - 0.42\,temp - 0.10\,totrun + 0.003\sqrt{\inf}\,totru$$

$$\sqrt{fc\,effa} = 1.18$$

$$\sqrt{fc\,b10} = 1.18 + 0.12\sqrt{\inf}$$

$$\sqrt{fc\ \ effb} = 1.40$$

$$\sqrt{fc\,c10} = 0.40 + 0.25\sqrt{\inf}$$

$$\sqrt{fc\,effc} = 2.63 + 0.03\sqrt{\inf} - 0.04\,totrun$$

list of the total coliform models

$$\sqrt{tc\,a10} = 23.9 + 0.08\sqrt{\inf} - 0.99\,temp$$

$$\sqrt{tc\,effa} = 2.67$$

$$\sqrt{tc\,b10} = 10.7 + 0.09\sqrt{\inf} - 0.38\,temp$$

$$\sqrt{tc\,effb} = 2.67$$

$$\sqrt{tc\,c10} = 27.5 + 0.20\sqrt{\inf} - temp$$

$$\sqrt{tc\,effc} = 3.65$$

list of the suspended solid models

$$ss\,a10 = 0.56$$

$$ss\,effa = 0.55$$

$$ss\,b10 = 0.65$$

$$ss\,effb = 0.60$$

$$ss\,c10 = 0.53$$

$$ss\,effc = 0.52$$

list of the turbidity models

$$tur\,a10 = 0.91 - 0.007\,totru$$

$$tur\,effa = 0.80 - 0.006\,totru$$

$$tur\,b10 = 0.83 + 0.05\inf - 0.007\,totrun$$

$$tur\,effb = 0.83 - 0.006\,totru$$

$$tur\,c10 = 1.18 - 0.009\,totru$$

4. PRACTICAL SIGNIFICANCE OF RESULTS

No significant effect of sand size on the quality of the filtrate was established. In practice locally available sand is frequently employed in the construction of slow sand filters in order to reduce the overall cost. Since the effect of sand size is not significant (within a certain size range) for the production of an adequate quality of filtrate there is no need to endeavor to obtain a finer sand than that which is, perhaps immediately available. Therefore a coarser sand than is often suggested could be employed as the filter medium in order to increase the run lengths and reduce the operational costs.

Increasing flow rates and decreasing temperatures had the effect of causing bacteria to penetrate deeper into the sand bed although about 95 % of the fecal coliform and about 99 % of total coliform organisms were always removed within the first 600 mm of the bed. However, both the fecal and total coliform removal through the lower 600 mm sand was only about 0.5 % of the initial count. The removal in this part of the filters were not significant from an engineering point of view.

Filtration rates are particularly important when slow sand filters are built to serve relatively large populations. In these circumstances the selection of higher filtration rates with coarser sand sizes could be considered. The point estimate of the models developed as a result of this investigation demonstrated that the fecal coliform count is reduced from 1000/100 ml to about 1/100 ml at 0.1 m/h with all three filters even when operating at the least favorable temperature of 5 ^{o}C. However, under the same temperature conditions when the flow rate was increased to 0.5 m/h the filters were only able to reduce fecal coliform count from 1000/100 ml to about 30/100 ml. This represented a reduction in the removal percentages from 99.9 % to only 97 %. The point estimate of total coliform models developed in this investigation also demonstrated that the total coliform count was reduced from 5000/100 ml to about 2/100 ml at 0.1 m/h during the 25 ^{o}C period. At the same temperature, when the flow rate was increased to 0.5 m/h, the total coliform count was only reduced from 5000/100 ml to 30/100 ml. Under the most rigorous conditions i.e. those of 5 ^{o}C period and 0.5 m/h the total coliform count was reduced again from 5000/100 ml to about 165/100 ml. This represented a reduction in the percentage removal from 99.96 % to 96.7 %. This level of reduction could, however, still be considered to be adequate if the filtration process was to be followed by an effective and continually reliable disinfection process. For the places where the water demand is higher in the summer but lower in the winter filters could be operated at higher than conventional rates, even up to 0.4 or 0.5 m/h, at temperatures of above 15 ^{o}C without markedly reducing the safety.

The models developed in this investigation can be used to estimate the filtrate quality of a slow sand filter under various conditions and hence the models are useful tools to help the designer to decide on the sand size and filtration rate under varying influent and climatic conditions.

5. CONCLUSION

Table 6 List of the 9 Total Coliform Models for Practical Purposes

25 ^{o}C period

$$\sqrt{tc\ effa} = 1.88$$

$$\sqrt{tc\ effb} = 1.32\ C001 + 2.50\ C002 + 3.50\ C003 + 3.57\ C045 - 0.06\ run\ b$$

$$\sqrt{tc\ effc} = 1.57 + 0.013\sqrt{\inf}\ C002 + 0.03\sqrt{\inf}\ C034 + 0.06\sqrt{\inf}\ C005 - 0.06\ run\ c$$

15 ^{o}C period

$$\sqrt{tc\ effa} = 0.6 + 0.03\sqrt{\inf}\ C004 + 0.08\sqrt{\inf}\ C005$$

$$\sqrt{tc\ effb} = 0.8\ C012 + 2.5\ C034 + 5.5\ C005$$

$$\sqrt{tc\ effc} = 0.4\ C001 + 1.8\ C345 + 0.04\sqrt{\inf}\ C005$$

5 ^{o}C period

$$\sqrt{tc\ effa} = 2.5 + 0.07\sqrt{\inf}\ C023 + 0.13\sqrt{\inf}\ C045$$

$$\sqrt{tc\ effb} = 3.1 + 0.06\sqrt{\inf}\ C004 + 0.17\sqrt{\inf}\ C005$$

$$\sqrt{tc\ effc} = 2.6 + 0.12\sqrt{\inf}\ C345$$

1- It was not possible to establish a single relationship between the variables of sand size, sand depth, temperature, influent quality and filtrate quality because of pronounced discontinuities evident with some of the data particularly temperature and sand depth.

2- 72 regression models were produced to relate four filtrate quality parameters (faecal coliforms, total coliforms, suspended solids, turbidity) to the operational and design parameters of sand size, sand depth, flow rate, temperature and influent quality.

3- For practical purposes these 72 models could be reduced to 9. These 9 models can be used to predict the count of total coliforms in the filtrate from 600 mm deep sand filters of three different sand sizes at three different temperatures (5 ^{o}C, 15 ^{o}C, 20 ^{o}C) at various flow rates and influent qualities.

4- Effective removal of turbidity, suspended solids, faecal coliform organisms and total coliform organisms was achieved at flow rates of 0.1 m/h to 0.5 m/h at temperatures of 25 ^{o}C, 15 ^{o}C and 5 ^{o}C. 5- No significant variation in effluent quality was discernible with sand sizes between E.S. 0.17 mm, E.S. 0.35 mm and E.S. 0.45 mm but the run lengths of the finest filter, particularly at the higher flow rates employed, were too short for practical purposes.

6- Little effect of the temperature change between 25 ^{o}C and 15 ^{o}C was noticeable but at the lowest temperature employed (5 ^{o}C) there was a definite reduction in the efficiency of removal of indicator organisms of fecal pollution especially at the highest flow rate (0.5 m/h).

7- No evidence of any necessity to extend the maturation period for a new slow sand filter beyond one week was discovered.

6. SYMBOLS

fc	the count of fecal coliform organisms (per 100 ml)
tc	the count of total coliform organisms (per 100 ml)
ss	suspended solids content (mg/l)
tur	turbidity value (NTU)
a10	sample taken 100 mm below, filter a
b10	sample taken 100 mm below, filter b
c10	sample taken 100 mm below, filter c
effa	filtrate sample from filter a
effb	filtrate sample from filter b
effc	filtrate sample from filter c
run a	number of days the filter a in operation since last cleaning.
run b	number of days the filter b in operation since last cleaning.
run c	number of days the filter c in operation since last cleaning.
totrun	number of days the filter in operation since the beginning.
inf	influent content of the relative parameter.
C001	indicator variable. This variable takes the value of 1 for 0.1 m/h flow rate but is zero at

all other flow rates.

C023 indicator variable. This variable takes the value of 1 for the flow rates of 0.2 and 0.3 m/h but is zero at all other flow rates.

C045 indicator variable. This variable takes the value of 1 for the flow rates of 0.4 and 0.5 m/h but is zero at all other flow rates.

C2345 indicator variable. This variable takes the value of 1 for the flow rates of 0.2, 0.3, 0.4 and 0.5 m/h but is zero for 0.1 m/h

7. REFERENCES

Anderson, D.R., et al., 1989. "Statistics for Business and Economics", West Publishing Co., Saint Paul.

Bellamy, W.D., et al., 1985. "Slow Sand Filtration", Journal of American Water Works Association, 77 (12), 62-66.

Bellamy, W.D., et al., 1985a. "Removing Giardia Cysts with Slow Sand Filtration", Journal of American Water Works Association, 77(2), 52-60.

Cox, C.R., 1969. "Operation and Control of Water Treatment Processes", World Health Organization, Geneva.

Ellis, K.V. and Aydýn, M.E., 1995. "Penetration of Solids and Biological Activity Into Slow Sand Filters", Water Research, 29(5), 1333-1341.

Ellis, K.V. and Aydýn, M.E., 1993. "A Study of Three Slow Sand Filters at Various Flow Rates With Constant Temperature", Journal of Water SRT-Aqua, 42(2), 88-96.

Huisman, L. and Wood, W.E., 1974. "Slow Sand Filtration", World Health Organization, Geneva.

Jack, A.B. and Charles, R.O., 1961. "Slow Sand Filtration of Algal Suspensions", Journal of American Water Works Association, 53(12), 1493-2502.

Joshi, N.S. et al, 1982. "Water Quality Changes During Slow Sand Filtration", Indian Journal of Environmental Health, 24, 261-276.

Kerkhoven, P., 1979. "Research and Development on Slow Sand Filtration", World Water, 2, 19-25.

Logsdon, G. and Fox, K., 1988. "Slow Sand Filtration in the United States", Slow Sand Filtration-Recent Developments in Water Treatment Technology (Editor:N.J.D. Graham), Ellis Horwood, New York.

Rachwal, A.J. et al, 1988. "Advanced Techniques for Upgrading Large Scale Slow Sand Filters", Slow Sand Filtration-Recent Developments in Water Treatment Technology (Editor:N.J.D. Graham), Ellis Horwood, New York.

Ridley, J.E., 1967. "Experience in the Use of Slow Sand Filtration, Double Sand Filtration and icrostraining", Proc. Soc. Water Treat. Exam., 16, 170-184.