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A STUDY OF BACTERIA REDUCTION BY SLOW SAND FILTRATION

by

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SYNOPSIS

Slow sand filtration (SSF) is a well known water treatment process which generally reduces water quality indicator bacteria by more than 99%. However, post-chlorination is usually recommended to guarantee complete disinfection of drinking water. A two year study was carried out by the National Institute for Water Research (NIWR) to directly compare different SSF process variables, in order to determine whether SSF could consistently reduce viable indicator bacteria to levels which meet drinking water standards. A pilot plant was constructed for the study, and the filter influent was highly bacteriologically polluted river water (average 1 000 faecal coliforms/100 ml). An arrangement was designed for drawing representative water samples from various depths in the pilot plant filters. The results of the study indicate that virtually all indicator bacteria reduction occurred in the top 20 cm of the filter bed, and that the different process variables which were compared had little effect on the bacteriological quality of the filtered water. There was also a wide scatter of individual test results, even under constant operating conditions. Therefore, chlorination of drinking water after SSF must continue to be recommended if the raw water is highly bacteriologically polluted.

OPSOMMING

Stadige sandfiltrasie (SSF) is 'n baie bekende waterbehandelingsproses wat gewoonlik waterkwaliteit-indikatorbaterieë met meer as 99% verminder. Chlorinering nà filtrasie word egter aanbeveel om volledige disinfeksie van drinkwater te verseker. 'n Studie wat oor twee jaar gestrek het, is deur die Nasionale Instituut vir Waternavorsing (NIWN) gedoen om verskillende SSF prosesveranderlikes direk te vergelyk, om sodoende vas te stel of SSF indikatorbakterieë konsekwent kan verminder na lewensvatbare vlakke wat drinkinwaterstandaarde bevredig. 'n Loodsaanleg is vir die studie opgerig. Die invloei van die filter was rivierwater wat bakteriologies hoogs besoedel was (gemiddeld 1 000 fekale koliforme/100 ml). 'n Opstelling is ontwerp om verteenwoordigende monsters op verskillende dieptes in die loodsskaalfilters te neem. Die resultate van die studie dui daarop dat feitlik alle verwyderde indikatorbakterieë in die boonste 20 cm van die filterbed verwyder word en dat die verskillende prosesveranderlikes wat vergelyk is, 'n baie klein invloed op die bakteriologiese kwaliteit van die filtraat het. Daar was ook 'n wye verspreiding van individuele toetsresultate - selfs onder konstante bedryfstoestande. Dus moet daar voortgegaan word om chlorinering van drinkwater nà SSF aan te beveel as die rou water bakteriologies hoogs besoedel is.

KEYWORDS

Bacteriological quality, drinking water, faecal coliforms, slow sand filters

INTRODUCTION

Slow sand filtration (SSF) is a well known water treatment process which combines both clarification and a significant reduction of pathogenic microorganisms. It is used, in particular, for small water treatment plants where the raw water has a reasonably low turbidity (<10 NTU), because it does not need skilled treatment plant operators or mechanical equipment. However, post-chlorination is generally recommended in order to guarantee a properly disinfected water.

This paper presents the results of a study which compares the reduction of viable water quality indicator microorganisms by SSF operating under different process design variables. The study was carried out by the National Institute for Water Research over a two year period from October 1983, with the objective of determining whether certain SSF process variables significantly affect the bacteriological quality of the filtered water.

LITERATURE REVIEW

The theory of biological filtration in SSF is discussed by Huisman and Wood (1974), and this includes a section on the bacteriological purification mechanisms. It is evident that a SSF is a complex biological and biochemical system which is basically hostile to enteric bacteria. In particular, the highly biologically active slime layer on the surface of the filter bed, called the schmutzdecke, screens out suspended solids and breaks down the degradable organic matter and bacteria thus retained to simpler substances. These processes cause the dramatic reduction (>99%) of faecal coliforms and other indicator bacteria in filtered water, which is a well known characteristic of SSF.

A comprehensive literature review of previous SSF studies has been compiled by Ellis (1985). This includes a section on the removal of bacteria and other organisms. The studies quoted indicate, with few exceptions, that at least 90% of *E. coli* are removed by SSF, with generally more than 99% reduction. These studies were carried out in various parts of the world with significantly different climatic conditions, raw waters and SSF process variables (i.e. flow rate, sand, etc). As SSF is basically a 'natural' process, these variations in the studies mean that the results may not be relevant to conditions in southern Africa. Also, the studies are generally observations of existing filters, and do not directly compare variations of individual process variables.

Three studies which do compare variations of individual SSF process variables are by Bellamy *et al*(1985), NEERI (1977) and Williams (1984). The work by Bellamy *et al* was a laboratory study using a bank of six 0,3 m diameter filters. The study by NEERI used a bank of three 1,67 m diameter filters. The results of these studies are referred to in the discussion section of this paper. The paper by Williams was a preliminary report on the study discussed in this paper.

SLOW SAND FILTER PILOT PLANT

In this study the raw water was pumped from the Apies River, which flows through Pretoria. The river has a constant base flow of clear water (<5 NTU turbidity), but increases to a very high flow of turbid water after thunderstorms, due to stormwater runoff from the streets. This occurs during the rainy season (October to April). However, the river has a consistently high bacteriological count, which made it suitable for this study. A typical chemical analysis of the base flow is given in Table 1.

TABLE 1: Typical chemical analysis of Apies river water (base flow)

Property	Unit	Typical analysis
pH		8,7
Colour	mg/1 Pt	40
Total dissolved solids	mg/1	350
Calcium (Ca)	mg/1	50
Magnesium (Mg)	mg/1	26
Total hardness ($CaCO_3$)	mg/1	232
Alkalinity ($CaCo_3$)	mg/1	174
Chloride (Cl)	mg/1	47
Sulphates (SO_4)	mg/1	44
Nitrates (N)	mg/1	1,7
Phosphates (P)	mg/1	0,2

Four filters were used, each 1,5 m diameter. These filters could be operated in parallel or in series. Sampling points were installed at 5 cm and 20 cm depths in each of the four filters, with additional sampling points at 10, 35 and 50 cm depths in filter no. 1. Samples could also be taken of the effluent from each of the filters (75 cm filter depth). The filter design and sampling arrangement are shown in Figures 1 and 2.

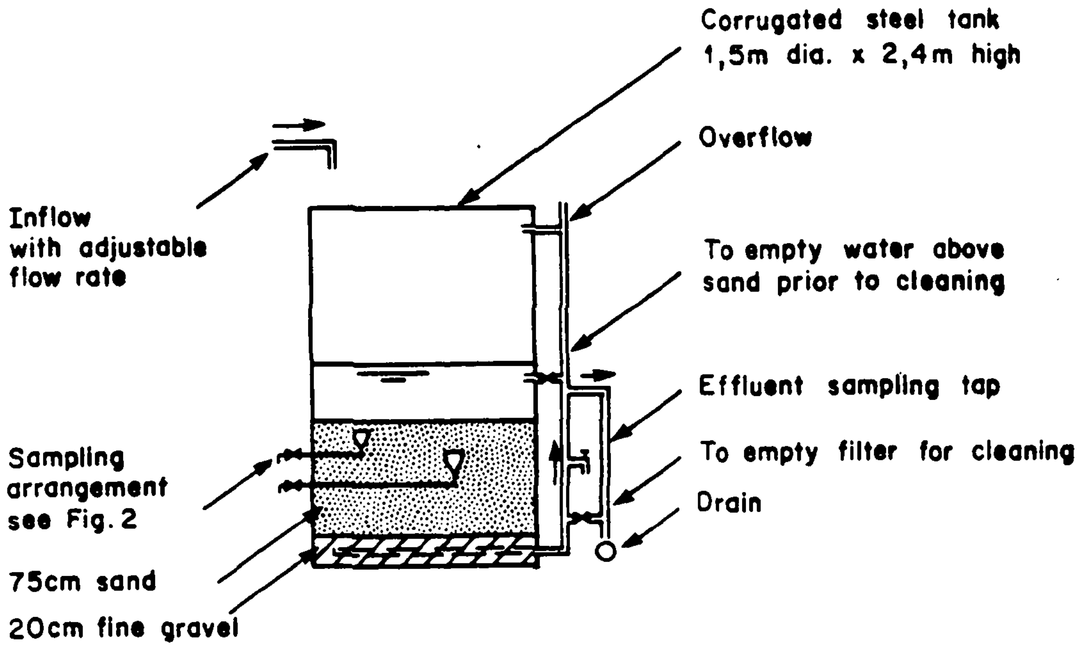
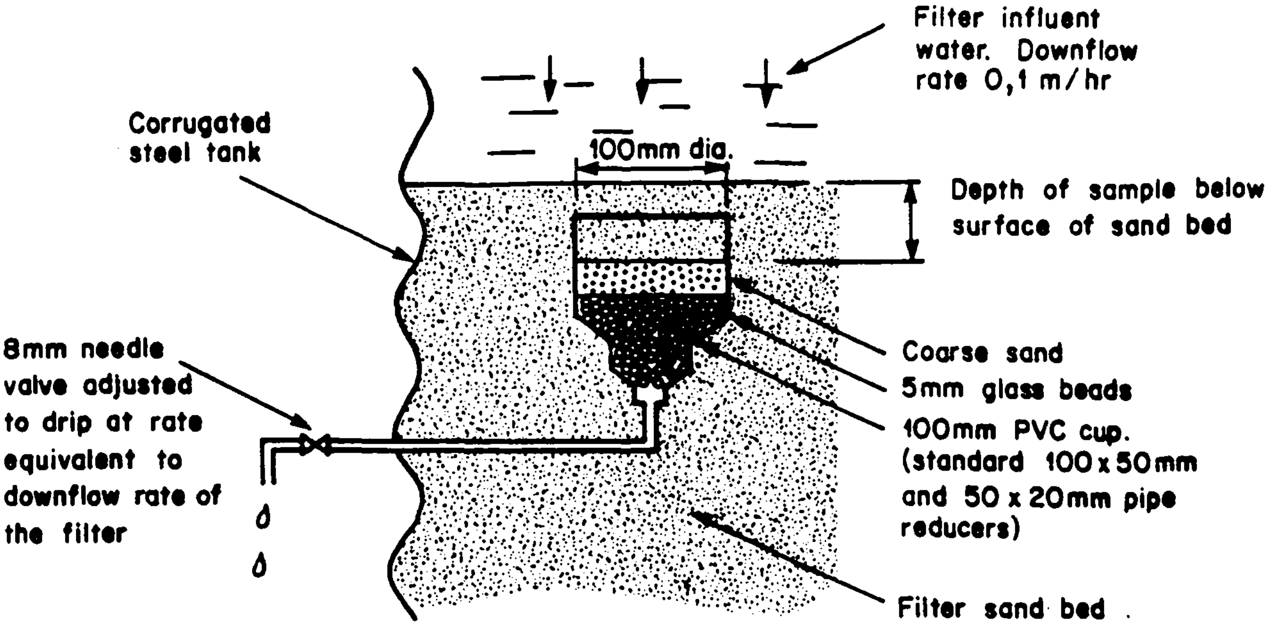
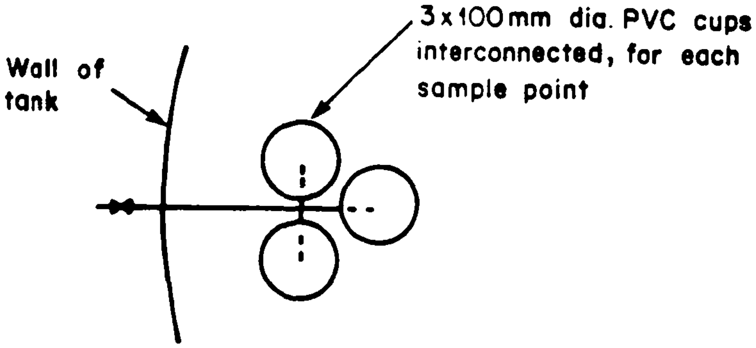


FIGURE 1: Pilot plant slow sand filter

The sampling arrangement was designed to be representative of the water at the particular depth in the filter. Therefore, the needle valve was adjusted to drip continuously at a rate equivalent to the downflow rate through the filter (i.e. at 40 ml/min for a filter operating at 0,1 m/h). This system worked satisfactorily, although the drip rate of the valves had to be checked daily, and was only accurate to within 20%. The total surface area of all the sampling cups in filter 1 was 6,7% of the surface area of the filter, and the corresponding figure for each of filters 2, 3 and 4 was 2,7%. It was assumed that this would not significantly affect the operation of the filters.



CROSS-SECTION



PLAN VIEW

FIGURE 2: Arrangement to sample water at depths in the filter bed

OPERATION, SAMPLING AND ANALYSIS PROGRAMME

Filter 1 was operated as a control filter at a continuous flow rate of 0,1 m/h, unshaded, with fine sand. Filters 2 and 3 were filled with sand having the same grading as filter 1, whereas filter 4 was filled with a coarser sand. All filters were operated concurrently, which enabled comparisons to be made under the same climatic and raw water conditions. The comparison for each process variable was for a period of at least two months.

The following comparisons of process variables were made:

1. Fine versus coarse sand
2. Uncovered versus covered filter
3. Standard versus slower downflow rate
4. Continuous versus intermittent filter operation
5. Summer versus winter water temperature (these studies, obviously, could not be carried out concurrently).
6. Double filtration with aeration between filters versus double filtration without aeration.

Water samples were taken twice weekly (once weekly for filter 4) of the filter influent and effluent and at depths within the filters, and were analysed for faecal coliform bacteria count (FCC). In addition, samples of the filter influent and effluent were analysed once weekly for total coliform bacteria count (TCC) and standard plate count (SPC). All analyses were carried out in accordance with Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 1985).

In addition, the following short-term studies were carried out:

1. Fluorescent microscope examination of filter influent and effluent samples to estimate the reduction in total bacteria in the water.
2. Filtration of SSF influent through sterile glass-fibre filter paper to determine the reduction in microorganisms by removing suspended matter from the water, without any biological action.

RESULTS

Bacteriological analyses

Generally, previous SSF studies have quoted the microorganism results in terms of per cent reduction. However, in order to highlight the comparisons in this study, the bacteria reduction figures have been calculated directly as logarithmic differences between the bacteria count for the filter influent and the count for the particular sample point in question (i.e. 90% is one log reduction, 99% is two log reduction, etc).

For each comparison the mean average and standard deviation of the bacteriological results of the comparison filter have been calculated and compared with the control filter, during a period of almost concurrent operation. These figures indicate trends, although they are not statistically valid because of uncontrolled variables (such as the river water quality and the weather) and the relatively few results for each comparison. Nevertheless, the trends are useful in indicating whether there are significant differences in results between SSF process variables. The results are presented in Tables 2 and 3 and Figure 3.

TABLE 2: Filter influent - bacteriological counts expressed as logarithms(b)

Bacteria(a)	n	$\bar{y}$	average count $(10^{\bar{y}})$	s
FCC per 100 ml	172	3,0	1 000	0,6
TCC per 100 ml	96	3,9	8 000	0,5
SPC per ml	96	3,6	4 000	0,5

TABLE 3: Logarithmic differences between SSF influent and effluent(b)

Comparison	FCC			TCC			SPC		
	n	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s
Coarse sand(d)	68	2,1	0,6	68	2,3	0,6	68	1,6	0,6
Control(c)	122	2,5	0,7	65	2,7	0,8	65	1,8	0,7
Covered filter(e)	45	2,3	0,6	26	2,4	0,7	26	1,9	0,8
Control(c)	45	2,7	0,7	23	2,8	0,7	23	1,8	0,9
Slower filtration rate(f)	38	2,6	0,7	17	3,0	0,9	17	1,8	0,6
Control(c)	32	2,6	0,7	16	3,1	1,0	16	2,0	0,5
Intermittent filtration(g)	25	2,7	0,6	12	3,0	0,8	12	1,8	0,7
Control(c)	24	2,8	0,6	13	3,3	1,0	13	2,0	0,5
Summer(h)	46	2,8	0,7	25	3,1	0,9	25	1,6	0,8
Winter	41	2,2	0,7	23	2,5	0,6	23	1,9	0,6
Double filtration(i)									
• without aeration(j)	16	2,7	0,7	16	3,0	0,8	16	1,6	0,4
• with aeration(k)	21	2,8	0,8	13	3,1	0,9	13	1,7	0,4
Control(c)	21	2,2	0,7	13	2,4	0,7	13	1,7	0,4

Notes referring to Tables 2 and 3

(a) FCC = faecal coliform count (per 100 ml)
TCC = total coliform count (per 100 ml)
SPC = standard plate count (per ml)

(b) n = number of samples
$\bar{y}$ = mean average of the logarithms of the bacteria counts of the filter influent
$\bar{x}$ = mean average of the logarithmic differences between the bacterial counts of the filter influent and effluent. In cases where the effluent had a bacteria count of less than one, this was recorded as one (i.e. $\log 1 = 0$)
s = standard deviation of $\bar{y}$ or $\bar{x}$.

(c) The control filter was filter 1, which was uncovered and operated at 0,1 m/h continuous flow rate with 75 cm depth of fine sand (effective size 0,26 mm, uniformity coefficient 1,9)

(d) Coarse sand: effective size 0,62 mm, uniformity coefficient 1,6

(e) The covered filter excluded light

(f) Slower filtration rate was 0,05 m/h . (A faster filtration rate of 0,2 m/h was tried on several occasions, but the filter blocked within two to three weeks and therefore it was not possible to get a sufficient number of results.)

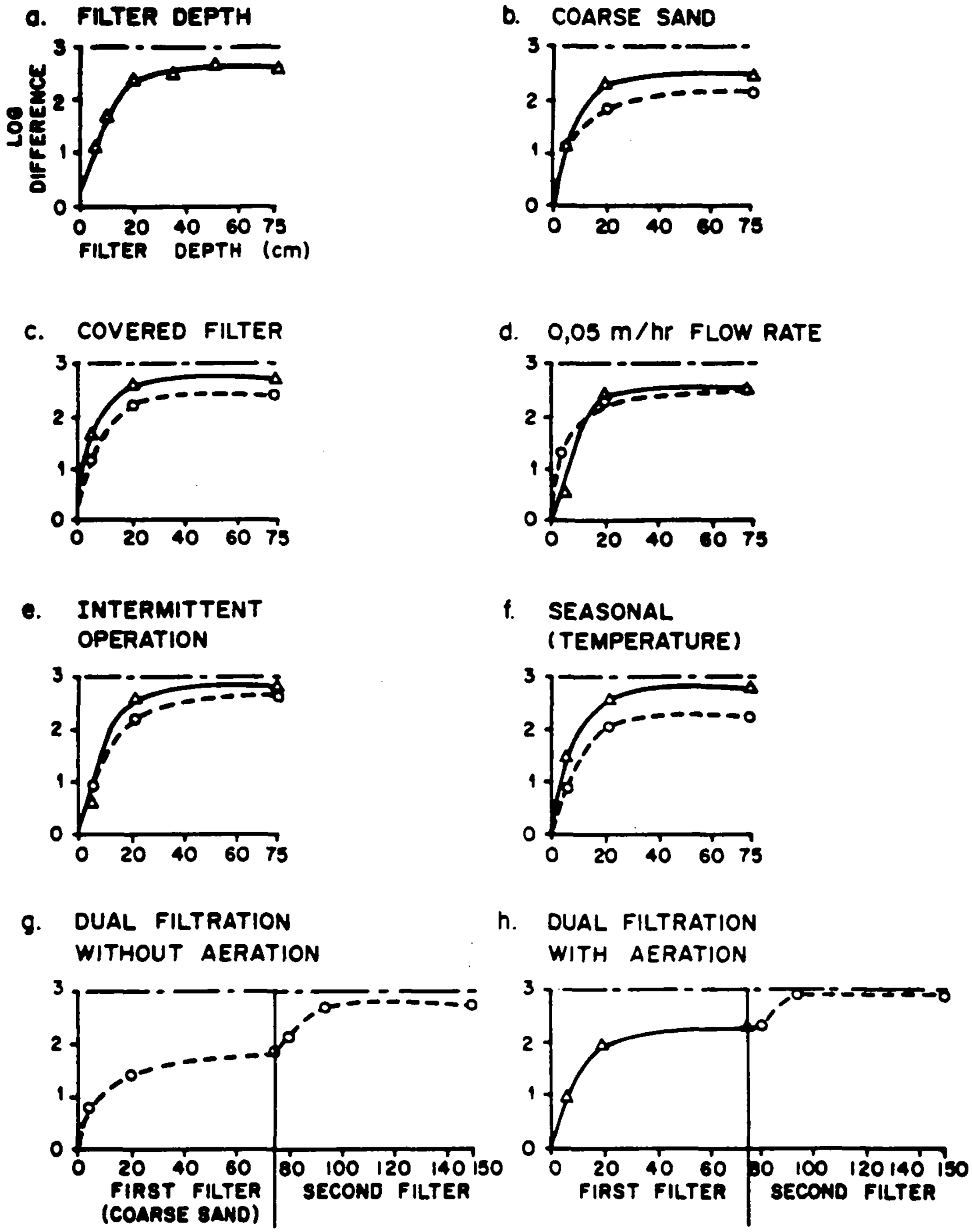
(g) Intermittent filtration was 4,5 days operating and 2,5 days not operating per week. Samples were taken approximately 12 hours after starting the filter and just before stopping it

(h) Summer months were December to March, when the filter influent water temperature was 18 to 32 °C. Winter months were May to August, when the water temperature was 8 to 20 °C. Diurnal variations were 8 to 12 °C. Results quoted are from the control filter

(i) In double filtration the effluent from one filter was introduced as the influent to the next filter

(j) The first filter in this system was filter 4, which contained coarse sand. The second filter contained fine sand. The dissolved oxygen level of the river water (influent to the first filter) was saturated, at about 8 mg/l . The dissolved oxygen in the effluent from this filter varied, but was generally less than 2 mg/l

(k) Both filters in this system contained fine sand. The effluent from the first filter was aerated to increase its dissolved oxygen level to about 5 mg/l before introduction to the second filter



LEGEND: 1. Average log FCC/100 ml — - — - —

2. Average log difference of FCC between filter influent and at filter depth

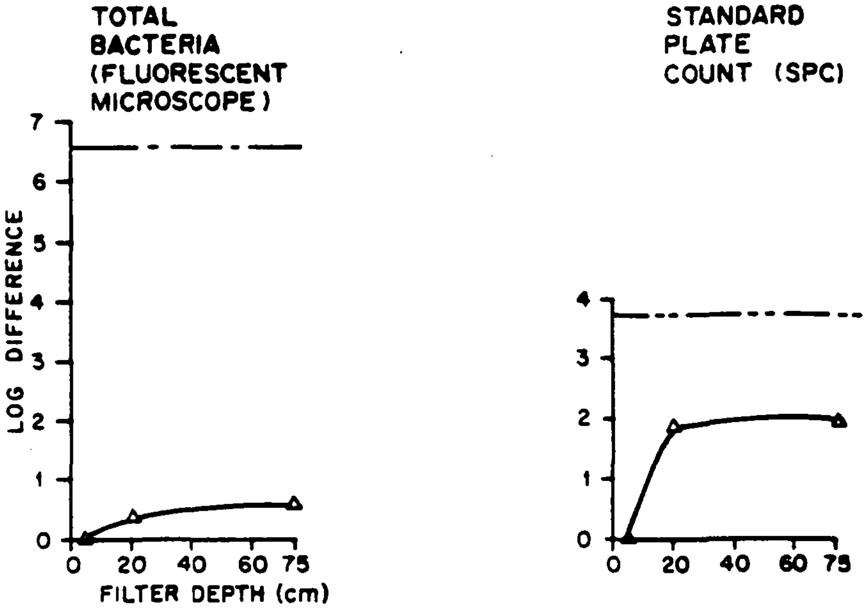
(a) Control filter △———△

(b) Comparison filter ○- - - - -○

FIGURE 3: Comparison of faecal coliform count results of SSF operating under different process variables

Total bacteria - fluorescent microscope studies

The results of the fluorescent microscope studies are presented in Figure 4. In these studies, the total number of samples (n) was 7.



LEGEND:
1. Average log total bacteria count/ml — - — - — - —
2. Average log standard plate count/ml — - - — - - —
3. Average log difference between filter influent and at filter depth △———△

FIGURE 4: Comparison of total bacteria (fluorescent microscope) and standard plate count results

Filtration of SSF influent through filter paper

Samples of the SSF influent water were filtered through sterile glass-fibre filter paper (Millipore type AP prefilter). Initially the water was passed through a single filter paper, but subsequently the experiments were carried out by filtering the water twice. The purpose of these experiments was to determine the effect of removing suspended matter from the water, without any biological action. The results of the study are summarized in Table 4.

TABLE 4: Comparison of logarithmic differences between SSF influent and after filtering through filter paper

Comparison	FCC			TCC			SPC		
	n	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s
Single filtered	22	0,8	0,3	12	0,9	0,4	11	0,9	0,4
Double filtered	14	2,9	0,5	7	2,8	0,6	6	1,6	0,4

Note: For definitions of terms in this table, see notes (a) and (b) accompanying Tables 2 and 3.

The turbidity of the filter influent water during the period of this study was low (0,8 to 2,0 NTU) and it was only reduced slightly through the filter paper. The non-filterable residue (suspended solids) of four samples of influent water analysed during this period was in the range 0,8 to 3,0 mg/l, of which an average 50% was volatile at 550 °C.

DISCUSSION

Depth in filter bed - faecal coliforms

Figure 3(a) illustrates that in the control filter there was an average of one log (90%) reduction of FCC at 5 cm depth in the filter and another 1,3 log reduction at 20 cm depth, giving a total average reduction of 2,3 log (99,5%). There was negligible additional reduction between 20 and 75 cm depth. However, the standard deviation of 0,7 indicates that there was a wide scatter of results. Therefore, in practice, 2 log reduction of FCC cannot be guaranteed in any individual sample.

Figures 3(b) to (f) indicate that a similar pattern of FCC reduction with filter depth was obtained with filters operating under different process variables to the control filter.

Figures 3(g) and (h) indicate that additional FCC reduction can be obtained by filtering the water through a second SSF although, from Table 2, it can be seen that there is still a wide scatter of individual results. There was no significant difference in results whether the water was aerated or not between the filters.

Different SSF process variables

Figures 3(b) to (f) indicate that varying the process variables of SSF did not have a significant effect on the faecal coliform reduction. Although there are some trends, these cannot be considered statistically significant because of the wide scatter of individual results, as indicated by the large standard deviation in all cases (see Table 2). Nevertheless, the trends are worth comparing with the results obtained by other researchers.

Coarse sand: The average FCC, TCC and SPC reductions for coarse sand were slightly less than for fine sand. This is in line with the results obtained by Bellamy *et al* (1985) which were 1,8 and 1,4 log reductions of TCC for fine and coarse sand respectively (sand gradings similar to this study). NEERI (1977) also found find sand to give a slightly better result than coarse builders grade sand. This possible disadvantage of coarse sand should be weighed against the longer filter runs obtained with coarse sand (Williams, 1984).

Covered filter: The uncovered (control) filter gave slightly better results than the covered filter (except for SPC). NEERI (1977) found that there was no significant difference between shaded (i.e. direct sunlight excluded) and uncovered filters.

Slower filtration rate: There was virtually no difference in bacteriological quality of the effluent for filters operating at 0,1 and 0,05 m/h . NEERI (1977) used flow rates of 0,1, 0,2 and 0,3 m/h and found that there was not a significant difference in *E. coli* reductions.

Intermittent filter operation: There was very little difference in results between the filter operating continuously (control) and the one operating intermittently (4,5 days/week on and 2,5 days/week off). Also, the individual results did not indicate any significant difference between the samples taken soon after start-up of the filter each week and those taken immediately before shut-down. The filter bed remained covered with water at all times. NEERI (1977) found no deterioration in water quality with a filter operating 10 h/day on and 14 h/day off.

Seasonal (temperature): The average results were slightly better during the summer months than during the winter months (except for SPC). Bellamy *et al* (1986) used temperatures of 17 °C and 5 °C and obtained results of 1,5 log and 0.9 log reductions respectively. Huisman and Wood (1974) state that 'The efficiency of slow sand filtration may also be seriously reduced by low temperature, owing to the influence of temperature both on the speed at which chemical reactions take place and on the rate of metabolism of bacteria and other microorganisms.' This applies particularly at temperatures below 7 °C, which is lower than that encountered in this study.

Comparison of FCC, TCC and SPC

The South African Bureau of Standards' specification for Water for Domestic Supplies (SABS 1984) gives the following bacteriological limits for water:

TABLE 5: Bacteriological limits - SABS 241-1984

Property	Recommended allowable limit	Maximum allowable limit
Faecal coliform bacteria count per 100 ml (FCC)	Nil	Nil
Total coliform bacteria count per 100 ml (TCC)	Nil	5
Standard plate count per ml (SPC)	100	not specified

Table 2 indicates that the filter influent had consistently high bacteriological counts. Table 3 indicates that in no case was the average reduction in bacteria counts sufficient to consistently meet the SABS standard, although this did occur for individual samples on occasions. The different process variables made no significant difference to the reduction of FCC, TCC or SPC. It can be expected that slow sand filtration of water which is not so highly bacteriologically polluted would bring the average water quality much closer to the SABS standard. However, because of the wide scatter of individual results, some samples would inevitably not meet the standard.

From Table 3, the TCC reduction was consistently slightly greater than the FCC reduction by 0,1 to 0,3 log. This could be explained by the fact that the TCC count of the filter influent was an average of eight times greater than the FCC. The FCC of individual samples was frequently reduced to one or nil/100 ml, which is the maximum reduction that could be recorded, whereas the TCC were rarely reduced to this level.

The SPC reduction was consistently less than the FCC reduction by 0,3 to 1,2 log, and in fact the average SPC reduction did not exceed 2,0 log for any of the comparisons in Table 3. This indicates that SSF are more effective in reducing specific types of bacteria (i.e. coliforms) than the variety of types represented by the SPC. Table 2 indicates that the SPC count was 50 times greater than the TCC (per ml) and 400 times greater than the FCC.

The standard deviations of average results given in Tables 2 and 3 all indicate a wide scatter of results. This study was not sufficiently controlled to be able to determine the reasons for this scatter. However, the study represented operating conditions of slow sand filters, and therefore it appears that this scatter of results cannot be avoided in practice.

Total bacteria - fluorescent microscope studies

Figure 4 indicates that the average total number of bacteria per ml (as counted from the fluorescent microscope examination) in the SSF influent was approximately 600 times greater than the SPC. It also indicates that the average reduction in total bacteria through the filter is only 0,6 log (75%) compared with 1,9 log (98%) reduction of SPC. The study did not indicate whether the bacteria in the filter effluent was the same type as in the influent, or whether microbiological and biochemical processes had caused a change of bacteria type within the filter bed.

Filtration of SSF influent through filter paper

Table 4 indicates that filtration through a single glass-fibre filter paper reduced the FCC, TCC and SPC by almost one log. This is equivalent to the reduction achieved in the top 5 cm of SSF.

Filtering the water through a second filter paper reduced the FCC and TCC by approximately another 2 log for the FCC and TCC, giving a total reduction of almost 3 log. The total reduction for the SPC was 1,6 log. These figures are approximately equivalent to the results obtained from the SSF (Table 3). The reduction in total suspended solids by filtration through a single filter paper was 0,8 to 3 mg/l .

These results indicate that the primary bacteria removal processes in SSF are screening and adsorption of suspended particles and bacteria in the schmutzdecke and sand bed. Microbiological and biochemical processes can then take place on the organic matter and bacteria retained in the filter.

CONCLUSIONS

The main conclusions which can be drawn from this study are:

1. Virtually all faecal coliform reduction in SSF has occurred by 20 cm depth in the filter.

2. Operating SSF with different process variables did not have a significant effect on the reduction of potable water indicator bacteria (i.e. FCC, TCC and SPC).

3. SSF did not consistently reduce the water quality indicator microorganisms in the highly bacteriologically polluted influent water to the allowable SABS microbiological limits for potable water. Therefore, chlorination after SSF should continue to be recommended for these conditions.

4. The total bacteria count in the river water and the SSF effluent, as counted by the fluorescent microscope examinations, was far greater than that indicated by the standard plate count (SPC), and there was less reduction of total bacteria than SPC through the SSF.

5. Filtration of low turbidity river water through two glass-fibre filter papers was as effective in reducing indicator bacteria as SSF.

ACKNOWLEDGEMENTS

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