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SLOW SAND FILTRATION AS A TECHNIQUE FOR THE TERTIARY TREATMENT OF MUNICIPAL SEWAGES

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Abstract—The investigation was designed to demonstrate the viability, or otherwise, of slow sand filtration as a means of tertiary treatment for secondary effluents derived from conventional aerobic, biological treatment processes operating with municipal wastewaters. Secondary effluents derived from both an activated-sludge plant and from a percolating filtration plant were employed.

The basic slow sand filtration unit used consisted of a 140 mm i.d. perspex cylinder, 2.65 m in height containing a 950 mm depth of fine sand. Treatment rates were either 3.5 or 7.0 m d^{-1} and the sand used was of an effective size initially of 0.3 mm and then later of 0.6 mm.

This investigation has demonstrated that a laboratory-scale slow sand filtration unit is capable of consistently removing at least 90% of the suspended solids, more than 65% of the remaining BOD and over 95% of the coliform organisms from the settled effluent from an operational percolating filter plant. The length of operational run averaged 20 days at 3.5 m d^{-1} and 13 days at 7.0 m d^{-1}. Slightly inferior results were achieved when using the settled effluent from an operational activated sludge unit.

Further investigation employing a horizontal-flow gravel pre-filter demonstrated that at flows of 2 m h^{-1} with a contact time of 33 min up to 82% of the suspended solids in the secondary effluent could be removed prior even to slow sand filtration.

Key words—tertiary treatment, slow sand filters, percolating filters, activated-sludge, secondary effluent, coliform bacteria, BOD$_5$ removal, gravel filtration

INTRODUCTION

Tertiary treatment (frequently referred to as effluent polishing) can mean different things on opposite sides of the Atlantic, but in Britain, tertiary treatment is usually held to refer to those processes which primarily reduce the suspended solids content of a secondary effluent and, by doing so, also reduce the level of the BOD. This is not a comprehensive definition as some processes may be held to reduce the BOD, to some extent, by biological activity and one specific process (nitrifying filtration) employs biological activity not to remove material from the water but merely to change its form.

Generally the techniques of tertiary wastewater treatment can be listed as: microstrainers, grass plots, lagoons, sand filtration (slow filtration, rapid gravity filtration, upward flow filtration), upward flow clarifiers, and nitrifying filters.

Of these, microstrainers and rapid gravity filtration go right back to the inception of tertiary sewage treatment at the East Hyde treatment works, Luton, in the early 1950s. They are still effective and still popular. Grass plots and lagoons are also widely employed and have definite advantages for specific situations. Upward-flow clarifiers are widely employed, with varying success, usually on the effluents from small and remote works. Nitrifying filters operate merely to reduce the ammonia content in an otherwise acceptable effluent. Upward-flow, deep-bed filtration is a popular and effective form of polishing process. Slow sand filtration is rarely employed and this represents an enigma to those aware of its effectiveness in the potable water industry.

SLOW SAND FILTERS

Slow sand filters were the first of the modern treatment techniques devised for the purification of potable water. In the potable water industry slow sand filtration is still extensively employed and slow sand filters are known for their ability to produce consistently a high class filtrate with the minimum of control. They are also noted for being able to reduce the bacterial count in water by up to 99.9%.

Published results of the operation of slow filters in the wastewater industry, however, (Truesdale *et al.*, 1964; HMSO, 1963; Black, 1967; Pullen, 1976; Kershaw, 1976) suggest only a moderate removal of suspended solids through the filter of 60–65% with a limited 35–55% BOD removal. Similarly, reports of the percentage removal of coli-aerogenes bacteria are far less at 38–62% (Truesdale *et al.*, 1964) than might be expected by comparison with the operation of potable water slow filters.

Because of this paradox between the known abilities of slow sand filters in the potable water industry and their apparent lack of success with the wastewater industry it was decided to run a series of investigations in an attempt to discover the true capabilities of slow sand filtration as an effluent polishing technique. To this end two laboratory-scale slow sand filters were operated over a prolonged period treating the settled effluents from initially a percolating filtration plant and then from an activated-sludge unit. The results obtained were quite revealing.

EXPERIMENTAL

This reported investigation into the slow sand filtration of secondary sewage works effluent was carried out in four stages at the Loughborough and at the Wanlip Wastewater Recovery Works of the Soar Division, Severn Trent Water Authority. A subsequent, limited, investigation into the pre-filtration of secondary effluents prior to slow sand filtration was also carried out at the Loughborough works.

Apparatus

The principal apparatus employed in these investigations consisted of a 140 mm i.d. vertical perspex tube 2.62 m in height with a flanged joint 1.07 m from the bottom. The lower section contained a 120 mm depth of graded gravel held 20 mm clear of the bottom by a coarse plastic screen. On top of the gravel was placed the 0.9 m depth bed of sand. The depth of the sand bed was so arranged that its top surface was at a level with the flanged joint in the filter tube. A few millimeters below the top sand surface an annular incision was made into the wall of the perspex tube in an attempt to reduce the effect of water short-circuiting down the filter walls.

Piezometer tubes were set, at various levels, into the filter wall in order to allow the head-loss through the system to be gauged. An overflow weir was attached to the top of the filter column. At the bottom of the column a T-joint connection was inserted, through which the filtered water was withdrawn and through which water was added to refill the column after cleaning. Outside the filter column the filtered-water tube was led in an inverted U-tube to a position just above the top sand level, both to prevent the development of negative head and to prevent the sand from accidentally drying out. In this manner the U-tube fulfilled the same function as the effluent weir in a conventional slow sand filter.

For the additional stage of the investigation a horizontal flow pebble filter was used with overall dimensions of 2.2 m long, 0.35 m high and 0.15 m wide. The interior was divided into five separate pockets. First, there was a small pocket 0.15 m in length containing coarse 14–20 mm rounded gravel and then the main gravel pocket 1.5 m long containing smaller 5.0–6.3 mm rounded gravel. Then following the main mass of gravel there were three further consecutive pockets of 0.1, 0.1 and 0.15 m length containing 6.3–10 mm gravel, 10–14 mm gravel and 14–20 mm gravel. Each pocket was divided from the next by a coarse plastic screen set into vertical slides. The effluent was removed from the equipment by a perforated pipe set across the bottom of the filter box at the end of the final gravel pocket.

Analyses

The methods of analysis employed during this investigation were those recommended in *The Analysis of Raw, Potable and Waste Waters* (HMSO, 1972) with the exception of the coliform determination which was carried out according to the multiple-tube technique for presumptive coliform organisms in *The Bacteriological Examination of Water Supplies* (HMSO, 1977). The nitrate determinations were by the 2,4-Xylenol method.

First stage investigation

The principal objective of the first stage investigation was to compare efficiencies of two different grades of sand, one set in each of the two filters employed. In one was a 0.95 m depth of 0.3 mm effective size (UC 2.0)* sand while the second filter contained a similar 0.95 m depth of a coarser 0.6 mm effective size (UC 1.2) sand.

The filters were located at the Loughborough Wastewater Recovery Works. Settled, secondary effluent from the work's percolating filter plant was withdrawn continuously from the channel by means of a 340 W Stuart Turner pump and fed to a header tank (capacity 384 l. to the overflow). As a result of the height of the header tank above the effluent channel there was only a slow overflow from this tank. In order to maintain all the solids present in suspension this tank was slowly and continuously stirred at the rate of about 60 rpm using a 33.5 × 5 mm stirrer. From this tank the secondary effluent flowed along screw-clip controlled plastic tubes to the two filters at the rates required. Both the header tank and the filters were fitted with overflow devices to allow constant, maximum heads to be maintained at all times.

During this first stage both the filters were operated at the rate of 3.5 m d^{-1} ($m^3\,m^{-2}\,d^{-1}$) and were cleaned when, with the maximum hydrostatic head over the filter sand, it was no longer possible to maintain the desired filtration rate. Cleaning was accomplished by decanting the water above the sand bed to within about 100 mm of the sand surface and then draining down the remainder through the sand bed. The top 25 mm or so of the sand was then carefully removed with a spatula and replaced from a reserve stock of identical sand. The sand bed was then filled initially with fresh water from the bottom until the water level was about 200 mm above the sand, and then from the top in the normal manner.

This stage of the investigation continued for 4 months although samples were not taken for analysis until the end of the first month in order to allow the filters to mature. In all, samples were taken for analysis on 12 occasions. Details of the analytical results, removal efficiencies and run lengths are shown in Table 1.

During all the investigations spot samples only were taken for analysis. The large capacity of the stirred feed-tank protected the sand filters against any sudden variation in quality of the secondary effluent applied and ensured that the feed to the filters and, more particularly, the filtrate from them could only vary extremely slowly. There was therefore little advantage to be gained by employing a periodic sampling device as the filtrate sampled at any time could be realistically assumed to have emanated from a secondary effluent feed nearly identical in quality to that sampled at the same time as the filtrates.

Second stage

Having established that a good quality filtrate could be obtained using a 0.6 mm effective size slow sand filter it was necessary to determine whether or not this relatively coarse-sand filter could be operated at a higher rate of flow. For the second stage of the investigation two identical 0.6 mm effective size, sand filters were employed but with one operating at 3.5 m d^{-1} (37.4 ml min^{-1}) and the other at 7.0 m d^{-1} (74.8 ml min^{-1}). During the second stage the two filters were again positioned at the Loughborough treatment works.

The filter which had been operated as the coarse medium filter during the first stage of the investigation was now continued in operation at the original rate of 3.5 m d^{-1} and was now referred to as the slower filter. Consequently it did not require an extended period of maturation to bring it to

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*UC = Uniformity coefficient.

Table 1

	Mean inflow quality	% Removal	Maximum	Minimum
1st Stage		Fine filter (3.5 m d^{-1})		
BOD_5	22	69	82	53
Suspended solids	24	88	97	71
COD	106	54	79	12
Coliforms	1,366,000	97	98	78
Nitrate (as N)	18			
Average length of filter run 7.1 days (max. 11, min. 7)				
		Coarse filter (3.5 m d^{-1})		
BOD_5	22	76	87	65
Suspended solids	24	88	98	74
COD	106	47	79	11
Coliforms	1,366,000	97	99	75
Average length of filter run 19.7 days (max. 36, min. 14)				
2nd Stage		Faster filter (7.0 m d^{-1})		
BOD_5	16	65	80	45
Suspended solids	16	92	97	91
COD	110	37	53	28
Coliforms	442,000	96	99.9	88
Nitrate (as N)	18	22	53	18
Average length of run 12.8 days (max. 15, min. 11)				
		Slower filter (3.5 m d^{-1})		
BOD_5	16	76	88	31
Suspended solids	16	93	98	91
COD	110	50	68	33
Coliforms	442,000	99	99.9	90
Nitrate (as N)	18	41	66	8.3
Average run length 20 days (max. 23, min. 14)				
3rd Stage		Faster filter (7.0 m d^{-1})		
BOD_5	18	69	73	44
Suspended solids	16	58	89	38
COD	110	34	46	12
Coliforms	548,000	91	96	53
Nitrate (as N)	2.4	42	74	—
Average length of filter run 13.4 days (max. 20, min. 8)				
		Slower filter (3.5 m d^{-1})		
BOD_5	18	67	77	54
Suspended solids	16	65	86	52
COD	110	29	76	5
Coliforms	548,000	91	97	63
Nitrate (as N)	2.4	39	75	—
Average length of filter run 25.6 days (max. 33, min. 17)				
4th Stage				
BOD_5	18	79	93	68
Suspended solids	16	71	90	53
COD	67	61	73	33
Coliforms	388,000	99	99.5	74
Nitrate (as N)	4.3	42	88	1.4
Average length of filter run 24 days (max. 35, min. 13)				

Analytical results are given in terms of mg l^{-1} with the exception of the coliform count which is stated in terms of a number per 100 ml samples.

full efficiency. The other filter which had contained the finer medium for the first stage investigation had been emptied and refilled with the same coarser medium as the first filter and operated during the second stage at the faster rate of 7.0 m d^{-1}. This was referred to as the faster filter and as it had been refilled with clean sand it had to undergo a period of maturation before full efficiency could be expected.

This second-stage of the investigation ran for 3 months during which samples were taken for analysis on 20 occasions. Details of the mean analytical results together with percentage removals and run lengths are given in Table 1.

Third stage

By the end of the second stage an appreciable amount of information had been gathered concerned with the slow sand filtration of the effluent from a percolating filter unit. The results of operation obtained indicated a high degree of both BOD and of suspended solids removal. It was now decided to continue the investigation by operating the filters with the effluent from an activated-sludge plant in order to discover whether this would entail any appreciable differences in the efficiencies of the filters. The activated-sludge plant selected was that at the Wanlip works. Wanlip was selected not only because it was convenient but also because the effluent obtained is consistently of a high quality with regard to the BOD and suspended solids content. As there was some interest during this stage of the investigation in the potential of slow sand filters to nitrify ammonia the effluent used was taken after the secondary settlement but before the tertiary nitrifying filter stage.

In this third stage two similar filters—both containing 0.6 mm effective size sand—were again operated. The "fast" filter operated at a rate of 7.0 m d^{-1} (74.8 ml min^{-1}) and the "slow" filter operated at 3.5 m d^{-1} (37.4 ml min^{-1}). This comparison of slow sand filter operation at different rates for the filtration of a good-class activated-sludge effluent continued for three-and-a-half months during which samples were taken for analysis on 16 occasions. Details of the analytical results and of filter performances are shown in Table 1.

Fourth stage

Throughout the third stage of the investigation, and indeed throughout all the stages, little or no further nitrification of the effluent was recorded as it passed through the sand filters. This was contrary to what had been expected but was, at this stage, thought to be due to the low levels of dissolved-oxygen existing in the effluent in the water reservoir. Largely in an attempt to discover whether or not nitrification could be induced through tertiary treatment slow sand filters it was decided, as stage 4, to continue the operation of the slower filter (3.5 m d^{-1}) but with an air-diffuser installed halfway down the effluent reservoir. The immediate effect of this was to increase the dissolved-oxygen level above the sand from approx. 1.5 to 8.0 mg l^{-1}. This stage was operated for more than 4 months during which 11 samples were taken for analysis (Table 1). The temperature of the system was consistently between 12 and 15°C.

Additional stage

In the potable water industry the use of slow sand filters has been limited traditionally by the turbidity of the feed water. Normal suggested limits vary from 10 to 50 TU (Cox, 1969; Huisman and Wood, 1974; Thanh and Hettiaratchi, 1982; Paramasivan *et al.*, 1981). Recently a great deal of investigation has been carried out (Thanh and Ouano, 1977; University of Dar es Salaam, 1980, 1982; Wegelin, 1983; Trueb, 1982; Symons and Pardoe, 1984; IRCWD, 1984; Boller, 1982) into possible methods of reducing initial high turbidities prior to slow sand filtration. One of the most successful methods employed to reduce turbidity has been the horizontal-flow pebble filter and it was considered that the successful application of this principle prior to a tertiary treatment slow filter might appreciably extend the period of the filter runs and consequently greatly reduce the cost of filter operations. To this end the additional stage of the practical research was dedicated to an investigation of the potential of such a pre-filter to reduce significantly the suspended solids content of the secondary effluent.

Table 2

Additional stage		Horizontal flow pebble filter			
	Nominal retention period (min)	Mean secondary effluent quality			
Flow rate ($m h^{-1}$)		BOD_5	Suspended solids	COD	Turbidity (NTU)
1.2	60	10	9.4	50	
2.4	30	22	14	45	
2.0	36		18		13
4.0	18		14.6		10
		Mean % removals			
Flow rate	Nominal retention	BOD_5	Suspended solids	COD	Turbidity
1.2	60	78	75	17	
2.4	30	79	74	22	
2.0	36		75		48
4.0	18		60		30
Coliform removal					
99.5 from 200,000/100 ml (one sample only) at 1.2 $m h^{-1}$					
86 from 170,000/100 ml (one sample only) at 4.0 $m h^{-1}$					

Analytical results are given in $mg l^{-1}$ with the exceptions of the coliform count which is given as a number per 100 ml sample and of the turbidity which is recorded as nephelometric turbidity units.

The horizontal-flow gravel filter employed (described above) was operated using the settled effluent from a percolating filter plant at rates of up to 4 $m h^{-1}$. The unit was not operational continuously but merely started-up about 24 h before samples were taken. Eleven runs were made and 11 sets of samples removed for analysis, the results of which, together with removal efficiencies, are shown in Table 2.

DISCUSSION

Two conclusions were immediately apparent from the results of the first stage investigation. The improvement in effluent quality was consistently far superior to the results published in the literature and the quality of the filtrate from the finer filter (effective size 0.3 mm) was not substantially better than that from the coarser filter (ES 0.6 mm).

The 88% removal of suspended solids, 76% removal of BOD_5 and 97% removal of coliform organisms were all remarkably superior to the 35–45% removal of BOD_5 and 60% removal of suspended solids suggested in published results (Truesdale *et al.*, 1964; HMSO, 1963; Black, 1967) of slow sand filter operation. The only marked difference between the results of the operation of the finer filter and that of the coarser filter was in the run length which for the latter was, on average, more than twice the period of the former. This suggested that rate of treatment might be a more important parameter than sand grain size (within limits) and hence there was little difficulty in the decision to proceed with the investigation employing only the coarser of the two sands in both slow filters and doubling the flow rate in one.

Two additional factors may have influenced the ability of the slow sand filters to remove secondary solids from the effluents. The one was the disintegrating action of the impeller in the small pump used to lift the effluents to the header tank. The other was the possible flocculating action of the stirring mechanisms in the header tank. The stirrer was essential to maintain all the suspended solids in suspension. These two factors might have been expected largely to neutralize one another. No observations were made on the possible action of the delivery pump although it was considered that the limited contact between impeller and suspended solids would minimise any disintegrating action. As to the potential flocculating actions of the stirrer mechanism, it is possible to be more definite. Initially when the unit was first set up the pump delivered directly to the sand filters with overflow systems available to take off the excess secondary effluent. This arrangement was soon abandoned as it made collection of representative input samples difficult. However, no difference was noticed in the efficiency of sand filters whether being fed directly with secondary effluent or via a stirred header tank.

As a result of doubling the rate of filtration in one filter the mean rates of BOD_5, suspended solids and COD removal dropped to 65, 92 and 37% as compared with the 76, 93 and 50% in the reference filter which operated at the original slower rate of 3.5 $m d^{-1}$. Rather strangely, however, the removal of total coliforms improved from 96% in the slower filter to 99% in the faster filter. The length of filter run, as expected, was appreciably less for the faster filter with a mean of 12.8 days as compared with the 20 days for the slower filter. This was a decrease of only 36% resulting from a 100% increase in filtration rate.

The change from filtering the effluent from a percolating filtration plant to filtering that from an activated-sludge unit (stage 3) brought about an appreciable but not spectacular reduction in the overall efficiency of filter operation. Although the mean percentage removal of BOD_5 increased slightly at the faster rate (7.0 $m d^{-1}$), the mean percentage removals of suspended solids, COD and coliforms together with the BOD_5 from the slower filter all decreased appreciably. The percentage removal of nitrate was generally high and comparable with the percentage removal from the faster filter in stage 2, but the amounts of nitrate to be reduced were far less (Table 1).

Certainly the removal of suspended solids from activated-sludge effluent by slow sand filtration was far less than from a percolating filter effluent. This reduction in the percentage of suspended solids removed might possibly be the result of the two very differently sized fractions of activated-sludge solids discovered by Tchobanoglous and Eliassen (1970). The larger fraction (80–90 μm) would be readily trapped within the filter while the smaller-sized fraction (3–5 μm) might pass through. West *et al.* (1979) in their work for the Thames Water Authority discovered similar peaks in the particle size distribution in an activated-sludge effluent but at 25–30 and 6–7.5 μm. Unfortunately for this theory they also reported a similar particle size distribution for the effluent from a percolating filtration plant. More investigation is obviously required as to the particle sizes passing into and out of the slow filters.

Filtrate samples were also taken, during the first and second stages, from sample points immediately below the surface sand of the slow filters (Table 3). Comparing the quality of these samples with those of the samples taken at the filter bottom it was obvious that, generally, all the removable solids had been taken out at the surface layer but that the removal of biodegradable organic material continued to a substantial extent down the whole depth of the filter. The removal of the coliforms organisms also was achieved principally in the surface layer but this removal also continued, sometimes substantially, through the whole sand bed. In addition, approx. 50% of the

Table 3. Results from top and bottom sample points

Stage 1—Fine filter

	Mean inflow quality	Top sample point			Bottom sample point		
		% Removal	Maximum	Minimum	% Removal	Maximum	Minimum
BOD_5	22	66	78	50	69	82	53
Suspended solids	24	88	95	79	88	97	71
COD	106	40	54	8	54	79	12
Coliform	1,366,000	88	96	85	97	99.7	78
Nitrate							

Stage 1—Coarse filter

	Mean inflow quality	Top sample point			Bottom sample point		
		% Removal	Maximum	Minimum	% Removal	Maximum	Minimum
BOD_5	22	67	78	61	76	87	65
Suspended solids	24	88	94	83	88	98	74
COD	106	36	52	31	47	79	11
Coliform	1,366,000	95	98	93	97	99	75
Nitrate							

Stage 2—Slower filter

	Mean inflow quality	Top sample point			Bottom sample point		
		% Removal	Maximum	Minimum	% Removal	Maximum	Minimum
BOD_5	16	71	78	41	76	88	31
Suspended solids	16	90	97	85	93	98	91
COD	110	40	50	23	50	68	33
Coliform	442,000	94	99.9	88	99	99.9	90
Nitrate	18	23	30	7.5	41	66	83

Stage 2—Faster filter

	Mean inflow quality	Top sample point			Bottom sample point		
		% Removal	Maximum	Minimum	% Removal	Maximum	Minimum
BOD_5	16	42	78	19	65	80	45
Suspended solids	16	80	90	73	92	97	90
COD	110	32	45	14	37	53	28
Coliform	442,000	91	99.9	83	96	99.9	88
Nitrate	18	11	51	7.4	22	53	18

denitrification achieved was accounted for in the surface layer and the remainder through the total depth of the sand. Only in the faster filter of the second stage was there any appreciable improvement in the removal of suspended solids after the surface layer and this was reflected in the ~30%, increase in BOD_5 removal.

Overwhelmingly then most of the purification occurred at or about the surface sand layer in the mixture of humus, sand, algae, protozoa and metazoa which in a potable water filter would be referred to as the filter-skin schmutzdecke. Whether or not this should still be referred to as the filter-skin in a wastewater filter is questionable as the material skimmed-off during cleaning was most unlike the schmutzdecke of potable water treatment in that it possessed the consistency of black mud and the colour of digested sludge.

Further consideration, however, of the quality of the samples (Table 3) taken revealed more definitely that the purification achieved was not purely the result of a straining action at the surface. During the first stage operation the ratio of BOD_5 removed to that of suspended solids removed through the whole depth of the filter was 0.72 for the finer filter and 0.79 for the coarser filter. This ratio increased slightly through the second stage to 0.8 (faster filter) and 0.85 (slower filter). For the results of microstraining, however, in which the mechanism is purely mechanical straining, the ratio of BOD_5 removed to suspended solids removed over a 6-yr period at the Basingstoke (Axtell, 1976) wastewater treatment plant was within the range of 0.6–0.43 with a mean of only 0.45. Similarly, the results published for the Harpenden works for a 4-month period in 1962 (Truesdale *et al.*, 1964) give a ratio, for the operation of the microstrainers, of 0.5. These figures compare favourably with the ratio of BOD_5 to suspended solids suggested by Mara (1976) of 0.54. The higher ratios of BOD_5 removed to suspended solids removed obtained from the operations of a slow sand filter to those obtained from the operations of microstrainers must be the result of appreciable biological activity within the sand bed.

Interestingly the ratios of BOD_5 removed to suspended solids removed increased substantially during the filtration of an activated-sludge effluent in stage 3 and stage 4 to 1.17 (slower filter), 1.24 and 1.25. The higher ratios reveal that a greater proportion of the purification achieved was as the result of biological activity—this biological activity being appreciably greater than even that observed during the filtration of the effluent from a percolating filter plant in stage 1 and stage 2. This possibly indicates a greater availability of a readily biodegradable organic material in the effluent from the activated-sludge unit than in the percolating-filter effluent.

Prior to the commencement of the investigation it had been expected that continuing nitrification would be a feature of the slow sand filtration process. This was not to be and, in fact, it was the process of denitrification which was amongst the most prominent features. During the second stage the faster filter ($7.0\ \mathrm{m\,d^{-1}}$) removed on average 22% of the applied nitrate (mean value in secondary effluent $18\ \mathrm{mg\,l^{-1}}$) while the slower filter ($3.5\ \mathrm{m\,d^{-1}}$) managed to remove 41% of the nitrate. The nitrate content of the activated-sludge effluent applied during the third stage was much lower than that of the percolating filter effluent investigated earlier with an average value of only $2.4\ \mathrm{mg\,l^{-1}}$, of which the faster filter removed 42% and the slower filter 38%. It had been thought that this denitrification was the result of the low-dissolved-oxygen content of the secondary effluents (about $1.5\ \mathrm{mg\,l^{-1}}$) so in the fourth stage this was artificially increased to about $8.0\ \mathrm{mg\,l^{-1}}$ by positioning an air-diffuser half-way down the column of secondary effluent above the sand. This too was unsuccessful in inducing additional nitrification and, in fact, denitrification continued at an unreduced rate (42% removal from a mean input of $4.3\ \mathrm{mg\,l^{-1}}$). This effect must be indicative of the intensity of biological activity on and within the sand.

The proven ability of slow sand filters to remove coliform organisms during the treatment of potable waters suggested that worthwhile results might also be achieved with a slow filtration of secondary wastewater effluents. This proved to be so. A remarkably consistent percentage removal of more than 90 was achieved throughout all four stages of the investigation despite a varying count in the secondary effluent input. During stage 1 both the coarse and fine filters ($3.5\ \mathrm{m\,d^{-1}}$) removed, on average, 97% of the total coliforms from a mean inlet count of 1,366,000/100 ml. This percentage only dropped slightly during the second stage to 96% with the faster filter but increased slightly to 99% with the slower filter. In stage 3 (activated-sludge effluent) the removal percentages for both slower and faster filters was 91% from a mean input count of 548,000/100 ml, but this rose to 99% in the fourth stage (filtration rate $3.5\ \mathrm{m\,d^{-1}}$) from a mean count of 388,000/100 ml. It was possibly the improved aerobic conditions during stage 4 that were responsible for the increase from a 91% removal to that of 99%. This could be consistent with the findings by the National Environmental Engineering Research Institute (NEERI) (Paramasivam *et al.*, 1980) in India that high percentage coliform removals occur only under aerobic conditions.

The additional stage to the investigation was included in an attempt to discover a technique which would, by removing a certain proportion of suspended solids from the secondary effluent prior to the slow sand filters, increase the run length of the filters and, as a result, make them in practice more economically viable. The Banks pebble-bed clarifier (Banks, 1964, 1965) had already demonstrated the ability of packed gravel to reduce both the content of suspended solids (40–60% removal) and that of the remaining biodegradable organic material (20–40% removal of BOD_5) from settled secondary effluents (Truesdale and Birkbeck, 1967, HMSO, 1973) but the results achieved from this horizontal-flow gravel were appreciably superior and the unit was demonstrated as being an effective tertiary treatment process in its own right.

Most interest was with the removal of suspended solids but measurements were also made of the BOD_5, COD and occasionally the turbidity and the total coliform count. Seventy-five percent of the suspended solids were removed from a secondary effluent concentration of $9.4\ mg\ l^{-1}$ at a flow rate of $1.2\ m\ h^{-1}$ (60 min nominal retention time), 75% also from an inflow content of $18\ mg\ l^{-1}$ at $2.8\ m\ h^{-1}$ (36 min retention) and 74% from $14\ mg\ l^{-1}$ at $2.4\ m\ h^{-1}$ (30 min retention). These percentage removals of suspended solids dropped only to 60 when the flow rate was increased to $4.0\ m\ h^{-1}$ (18 min retention). These are fairly remarkable results to be achieved from such a simple device. BOD_5 removals, when recorded, were also high at 78 and 79% at 1.2 and $2.4\ m\ h^{-1}$, but the COD removals were, as would be expected, relatively low. Coliform removals were again remarkably high—99.5% at $1.2\ m\ h^{-1}$ and 86% even with the flow rate increased to $4.0\ m\ h^{-1}$—but turbidity removals were only moderate. Overall it was demonstrated that an horizontal-flow gravel filter could be either an effective device for reducing the mass of suspended material reaching the slow filters and hence for extending the filter runs or that the horizontal-flow filter could act very adequately on its own as an efficient effluent polishing system.

Cleaning a horizontal-flow gravel filter might present problems. Experience in the potable water industry suggests that this can only be achieved by periodically removing all the gravel bed, washing it and replacing but that the "run" between such cleanings would be considerable as a result of the high storage capacity for the deposited solids within the gravel-bed. Recent work carried out in Switzerland (IRCWD News, 1984) had indicated that most solids are removed by gravity settling and that they form loose agglomerates on top of the individual gravel pieces. Periodic draining of the bed creates a downward movement of this accumulated material, removes much of the sediment and goes a long way to restoring the full removal capacity of the bed.

CONCLUSIONS

The conclusions of this series of investigations can be summarised as follows:

(1) BOD_5 removal through a laboratory scale slow sand filter operating at a rate of $3.5\ m\ d^{-1}$ was generally 70–75% when treating a settled percolating filter effluent and 65–70% with a settled activated-sludge effluent. At the higher rate of $7.0\ m\ d^{-1}$ the percentage BOD removal fell somewhat with the percolating filter effluent but, if anything, improved slightly with the activated-sludge effluent.

(2) When filtering percolating filter effluent at the normal rate ($3.5\ m\ d^{-1}$) the slow sand filters removed about 88–93% of the suspended solids.

(3) Suspended solids removal fell to 60–65% when settled activated-sludge effluent was filtered.

(4) The slow sand filters were most effective at reducing the coliform count in the secondary effluent. The lowest mean percentage reductions were achieved with the activated-sludge effluent at approx. 91% but using percolating filter effluent these rose to 96% and occasionally to over 99%.

(5) No nitrification was observed during the filtration processes, even when the dissolved oxygen content of the secondary effluent was artificially enhanced, but up to 40% denitrification was a constant feature of the normal slow sand filtration operations.

(6) Slow sand filtration using a sand of effective size 0.3 mm gave no advantages over slow filtration using an effective size sand of 0.6 mm. Although the degree of purification achieved was similar with both filters the over-frequent blocking of the finer sand filter (every 7.1 days as opposed to 19.7 days) would make it unacceptable for full-scale operation.

(7) Appreciable biological purification through the slow sand filters was indicated by the relatively high BOD_5 to suspended solids removal ratios, by the continuing denitrification recorded and by the appreciable drop in COD values between the top sample point (immediately under the sand surface) and the filtrate.

(8) No dramatic decrease in filtrate quality was recorded when the filtration rate was doubled from 3.5 to $7.0\ m\ d^{-1}$ but the length of the filter run dropped to nearly half.

(9) In brief, slow sand filtration of settled secondary effluents using 0.6 mm effective sand size was shown to be most effective at a filtration rate of $3.5\ m\ d^{-1}$ although the efficiencies decreased appreciably when settled activated-sludge effluent was employed in place of percolating filter effluent.

(10) In addition, it was demonstrated that a 2 m long horizontal-flow gravel pre-filter containing principally 5.0–6.3 mm gravel could reduce the suspended solids content of a percolating filter effluent by between 60 and 80% at flow rates varying from 4.0 to $1.2\ m\ h^{-1}$ (nominal retention periods of 18–60 min).

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