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PERFORMANCE OF FABRIC PROTECTED SLOW SAND FILTERS TREATING POOR QUALITY RIVER WATER

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SUMMARY

In developing countries it is often necessary to employ the process of chemical coagulation to treat raw waters containing soluble colour-causing humic substances. Typically such a process leads to appreciable suspended solids concentrations passing on to the subsequent filtration stage. Experience in Tanzania has shown that slow sand filters (SSF) can be seriously overloaded by such a solids 'carry-over', leading to uneconomic filter run times and poor filtrate water quality.

The object of the study reported here has been the investigation of a method of protecting slow sand filter beds by laying non-woven, synthetic fabric layers on the surface of the sand. A pilot-scale water treatment process, incorporating chemical coagulation and slow sand filtration, has been constructed and tested on the premises of the North Surrey Water Company water treatment station, at Egham, Middlesex, with the River Thames as the source water.

During the period of experimentation three slow sand filter units have been operated in parallel in order to compare directly different fabric configurations. In summary, the results have shown that the application of a 25 mm layer of a particular fabric can dramatically extend filter run times, irrespective of seasonal changes in raw water quality. However, one of the two types of fabric tested allowed some penetration of contamination into the sand bed. Subsequent tests with a dual-fabric arrangement of 40 mm depth gave an increased filter run time approximately 4.5 times that of a conventional SSF, with the exclusion of any contamination in the underlying sand.

The authors conclude that the use of such fabrics in developing, and developed, countries can dramatically improve the performance of

overloaded SSF and simplify the filter cleaning procedure. Further work is required to investigate whether conventional sand depths can be substantially reduced as a consequence of the inclusion of the fabric layer, thus leading to significant savings in capital costs.

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DR N J D GRAHAM

T S A MBWETTE

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LIST OF ABBREVIATIONS

SSF	slow sand filter/filtration
NWF	non-woven synthetic fabric(s)
PVC	poly-vinyl chloride
PAC	poly-aluminium chloride
PCA I	population counting accessory I
TOC	total organic carbon

1. INTRODUCTION

Slow sand filtration is an important process of water treatment that can produce water of a very high quality provided the process is operated properly and adequate pretreatment is carried out. Slow sand filtration is particularly appropriate to rural community water supplies, both in developed and developing countries, since the operation and maintenance requirements are less demanding than alternative processes in terms of process technology and operator skill.

In general if slow sand filters are operated at conventional flow rates, i.e. between 0.1 and 0.2 m/h, they can achieve a one-log reduction in turbidity and between a one and two-log reduction in faecal coliforms concentrations. Thus, to achieve a water quality approaching WHO standards the influent turbidity and faecal coliform concentrations should not exceed 10 NTU and 100 organisms/100 ml. Slow sand filters are not an effective process for removing soluble colour of an organic nature and typical removal efficiencies are in the range 20-30%. Thus, to produce a water quality within WHO limits the influent colour concentration should not significantly exceed a level of 15 hazen units.

In the UK most slow sand filtration processes are adequately protected by conventional pretreatment such as rapid sand filtration and/or long-term raw water storage. Consequently the performance of the filtration process is good and the required quality of filtered water can be maintained. However, a very high proportion of the direct operational costs for slow sand filters (over 70% estimated by the Thames Water Authority) are associated with filter cleaning and resanding. It is clear therefore that any modification of the process that can reduce the average frequency of filter cleaning and resanding will reduce operating costs significantly.

In developing countries the importance of slow sand filtration is becoming increasingly realized, particularly for small-scale, rural water supplies. The difficulties in ensuring an adequate chemical disinfection of water supplies places emphasis on the inclusion and proper operation of slow sand filtration because of its capacity to remove micro-organisms. The application of an appropriate degree of raw water pretreatment in advance of slow sand filtration is fundamental to the satisfactory performance of the filter and low-cost pretreatment technologies, such as gravel-bed roughing filters, are currently receiving some interest.

In many developing countries surface water quality in rural areas can contain appreciable levels of colour in addition to particulate and bacterial contamination. A relatively recent survey of surface water quality in Tanzania (12) has found considerable levels of colour and turbidity in streams and rivers.

The typical form of surface water treatment in Tanzania for these streams and rivers includes chemical coagulation/flocculation with aluminium sulphate, followed by plain sedimentation and slow sand filtration. It is common for the performance of the flocculation and sedimentation unit processes to be unsatisfactory leading to suspended solids overloading of the slow sand filtration process; this is particularly so if the raw water quality fluctuates appreciably during the rainy season.

It is well-known that the process of purifying contaminated influent waters by slow sand filters is principally localised in the top 2 to 3 cm of the sand bed. The rationale of applying a non-woven fabric layer on the top surface of the sand filter is to concentrate the major part of the purification process within the fabric layer instead of within the top layers of the sand. The speculated benefits arising from this are two-fold:

i) the simplification of the filter cleaning by the removal and washing of the fabric alone;

ii) the extension of filter run times by a lower rate of pressure head loss development within the fabric. Associated with this is the ability of the fabric to protect the sand layer for short duration peaks in influent suspended solids concentrations.

1.1 Objectives

The aim of the research study was to quantify and optimise the performance benefits of protecting slow sand filters with a non-woven synthetic fabric layer when treating coagulated raw river water. In particular the work was designed to simulate the problems of inadequate pretreatment which results in substantial floc carry-over on to the slow sand filters, as well as to examine the optimal specification for the fabric layer.

The research was based on pilot-plant experiments undertaken at the Egham Water treatment Works in the North Surrey Water Company. The pilot-plant was assembled and commissioned during the first six months of the project and operated continuously over nine months to include seasonal changes in the raw water - the River Thames; the quality of the river varies considerably during each year.

The primary objectives of the research were:

i) To assemble and commission a pilot-plant water treatment process to treat approximately 1 m^3/h of raw river water consisting of an abstraction pump, header tank and screen, flow control and coagulant dosing, baffle-tank flocculation, sedimentation tank with variable floor area, and three slow sand filter units.

ii) To operate the plant with one filter unit as a reference and the other two with different types of fabric protection in order to compare treatment performances in terms of filter run times and effluent water quality.

iii) To assess the ability of selected fabrics to prevent solids penetration into the sand layer of the filter.

iv) To make an assessment of the effectiveness of removing retained coagulant floc in the fabrics by simple manual washing methods.

2. *PILOT PLANT DESIGN AND INSTALLATION*

2.1 Design

The design of the pilot plant was carried out by the authors in April 1987 with the SSF units designed to be operated at a nominal filtration rate of 0.15 m/h with provision for operation at a maximum rate of 0.30 m/h in order to increase flexibility. Three rectangular SSF units each with length, width and depth (internal dimensions) of 1.8 m, 1.2 m and 1.6 m, respectively were designed (Plate 1). Each unit was provided with a 200 mm thick underdrainage system comprising of perforated PVC pipes surrounded by a layer of pea gravel and a 600 mm depth of sand bed. A supernatant water depth of 750 mm and freeboard height of 5 cm were allowed for. Figure 1 shows a typical cross section through the SSF units installed at the pilot plant. Six manometer tubes for filter resistance measurements were located at 50 mm above sand (No.1), at the top level of sand (No.2) and then successively at 50 (No.3), 200 (No.4), 500 (No.5) and 700 mm (No.6) below the top level of sand, respectively.

On the basis of the maximum total quantity of water required to feed the three SSF (i.e. at 0.3 m/h) which was 46.7 m^3/d, the operational surface loading rate of each of the two clarifiers (see Figure 2a) with a diameter of 1.0 metre and manufactured as described in reference (1) was evaluated to be at least 1.24 m/h. Since it was necessary to ensure continuous supply of treated water, the clarifiers were designed to be operated either in series or separately. The clarifiers were fed by an overhead PVC mixing tank in which raw water was mixed thoroughly with poly-aluminium chloride (PAC) down-stream of a 60° vee-notch weir. The mixing tank and the weir were designed in accordance with the BS:3680:1981, Part 4A (2).

2.2 Installation and Time Schedule

The manufacturing, initial rehabilitation and installation of the SSF units were done between May and July 1987. Preliminary experiments carried out in August/September 1987 (3) led to changes in the raw water supply system and chemical dosing facilities. At the end of November 1987 the clarifiers were commissioned with the new raw water feeding system. After completion of rehabilitation and insulation of the pilot plant pipe system with an 105 mm thick fibre glass loft insulation (Supawrap, Pilkington Insulation Ltd., UK), the SSF units were commissioned on the 30 December 1987. The conduct of the experiments was divided into three main phases. *Phase* 1 *covered* the period between 30 December 1987 and 8 March 1988 while phase 2

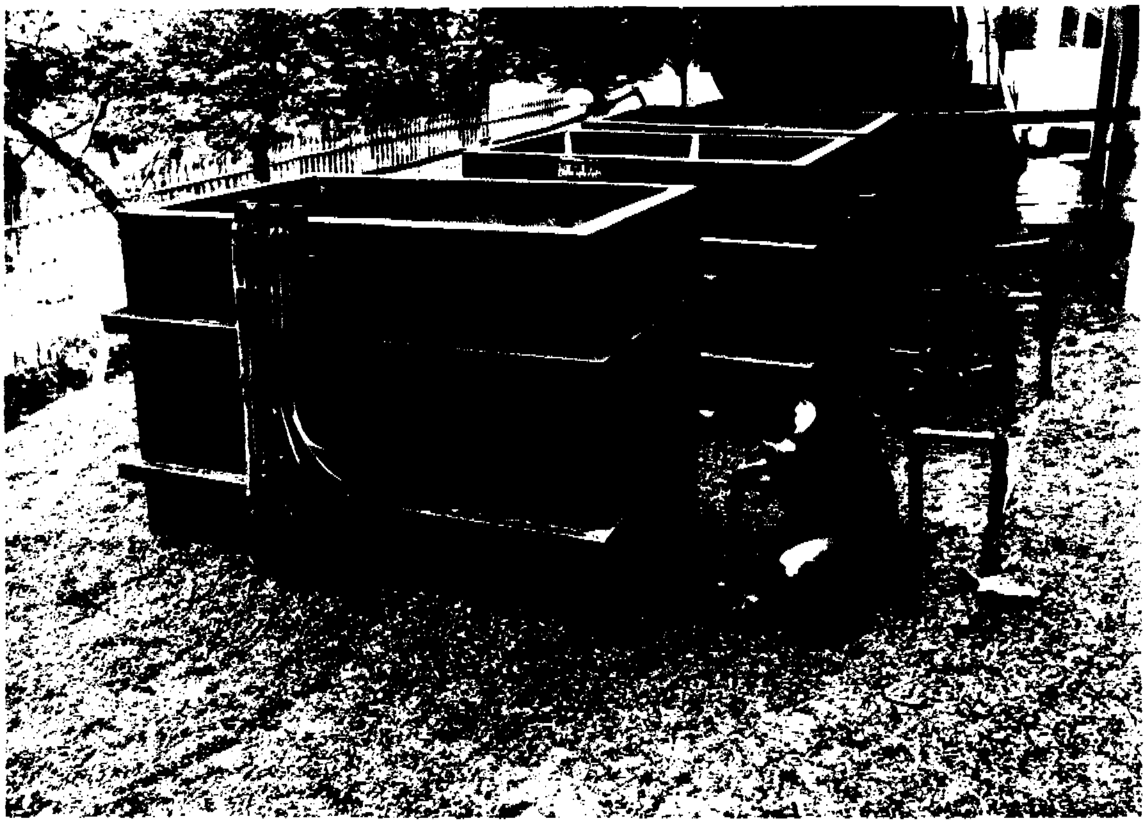

Plate. 1 A Side View of the Slow Sand Filter Units at Egham Pilot Plant .

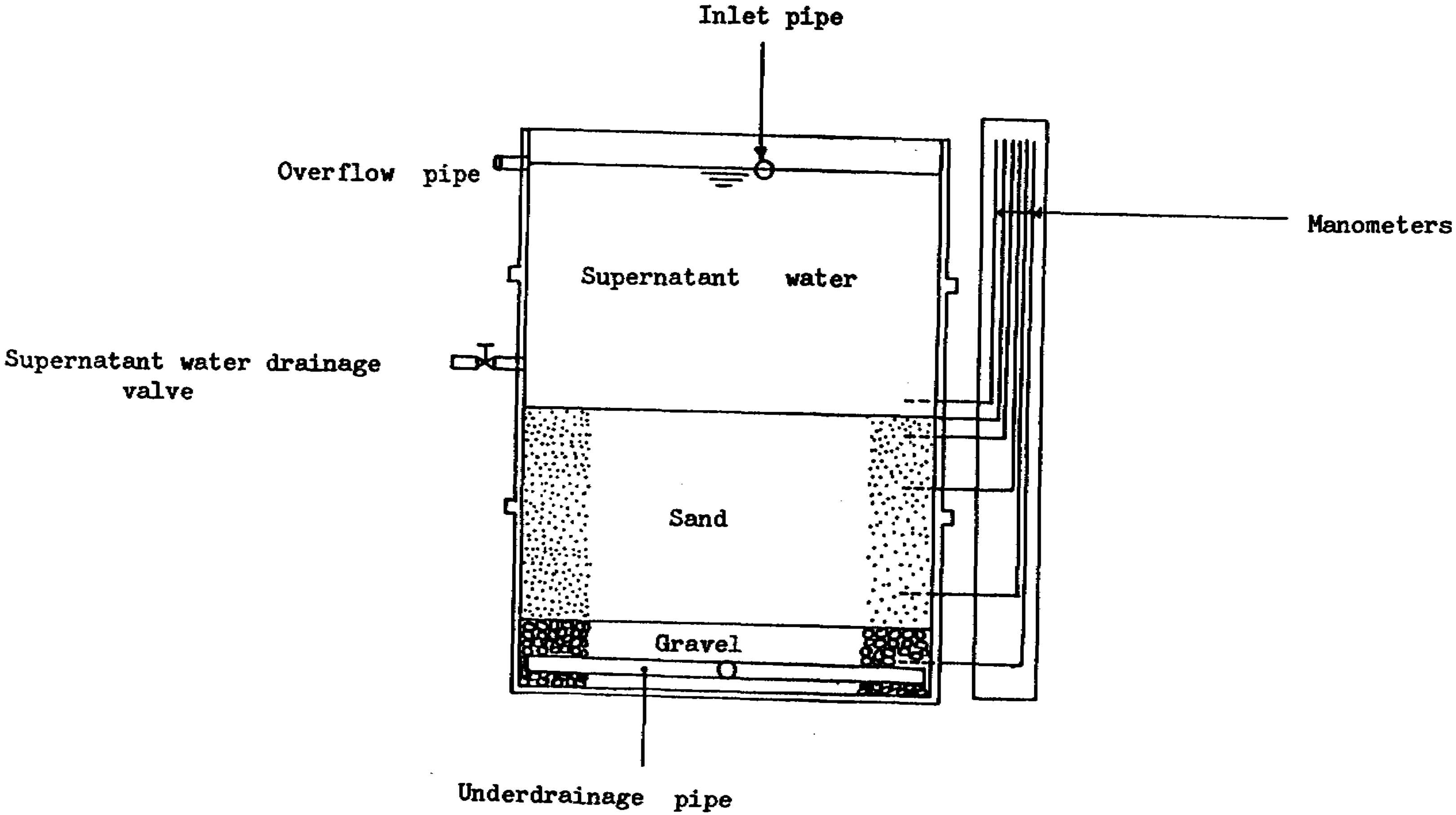

Fig.1 Typical cross section of a SSF unit.

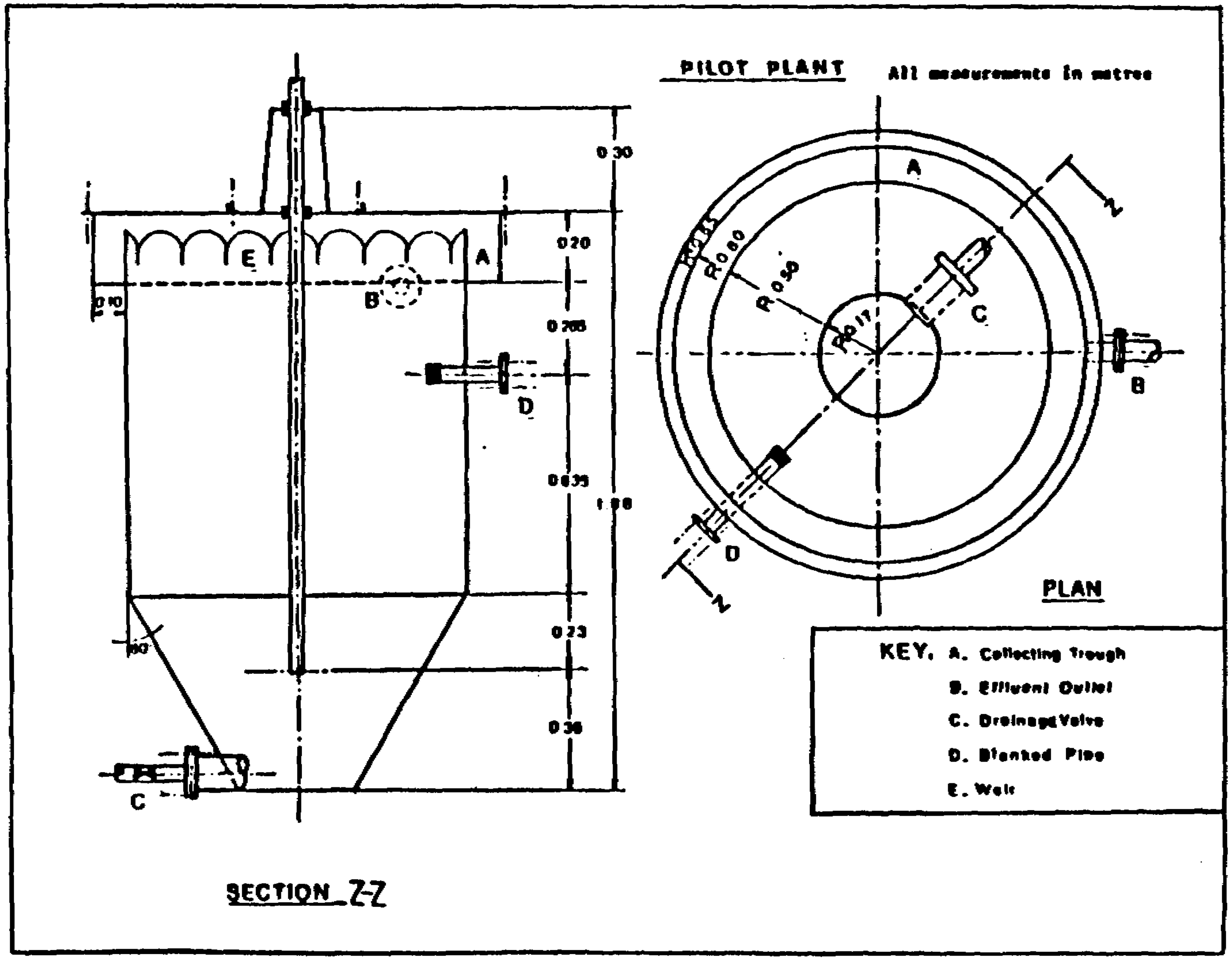

Fig. 2a Plan and Cross Section of the Clarifier (after Hunter, 1986)

covered the period from 8 March 1988 until 7 May 1988. Phase 3 extended from 18 May 1988 until 8 August 1988.

2.3 Pilot Plant Flow Sheet

The pilot plant layout is shown in Figure 2 while the schematic hydraulic profile is shown in Figure 3. At the start of the process an MF/VO-502 W/Ks vortex impeller submersible pump (Hodson Croydon Ltd) abstracted raw water from the River Thames, at the main works intake and delivered it into the PVC chemical mixing tank (located on the roof of the chemical house) via a 40 mm diameter pipe (Plate 2). In the mixing tank, poly-aluminium chloride (PAC) (Laporte Ind Ltd UK) was added downstream of the 60° vee-notch weir in correct proportion in order to coagulate impurities (colour and turbidity) in the raw water. The PAC storage container kept next to the mixing tank was provided with a model BD 6931 (BDH, UK), 300 W electro-thermal red rod immersion heater (connected to an MC-225 power regulator) to keep the PAC solution (10% strength weight/weight as Al_2O_3) within a specified temperature range i.e. 10-20°C. PAC was dosed into the mixing tank with the help of a model 60-128 WAB peristaltic tube-pump (Glen Creston, Middlesex) connected to a dosing beaker and one re-circulation line.

From the mixing tank, coagulated water flowed through a 3.0 m long 40 mm diameter vertical pipe in which further intense mixing took place. Then it was led into two upflow sludge blanket clarifiers operated under uniform conditions ensuring carry-over of flocs into the subsequent unit operation by adjustment of the top blanket level at a very high location relative to water extraction level. The combined clarifiers effluent was then led into three SSF units

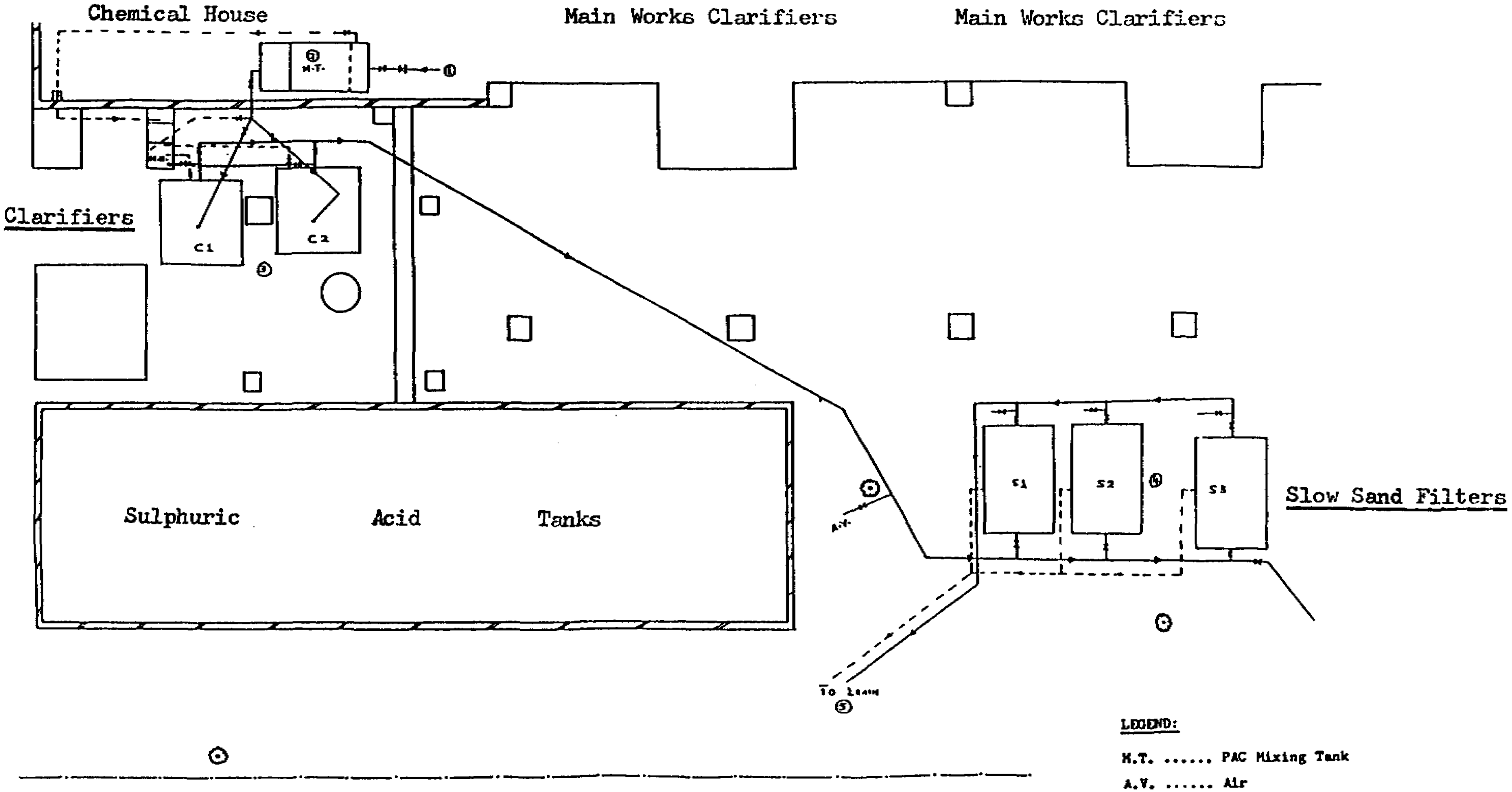

Fig.2 Egham Pilot Plant Layout Plan.

LEGEND:

M.T.	PAC Mixing Tank
A.V.	Air
M.H.	Man Hole
S	Slow Sand Filter
C	Clarifier
—⋈—	Gate Valve
—▷|—	Non- Return Valve
·—·—·	Fence
⊙	Tree

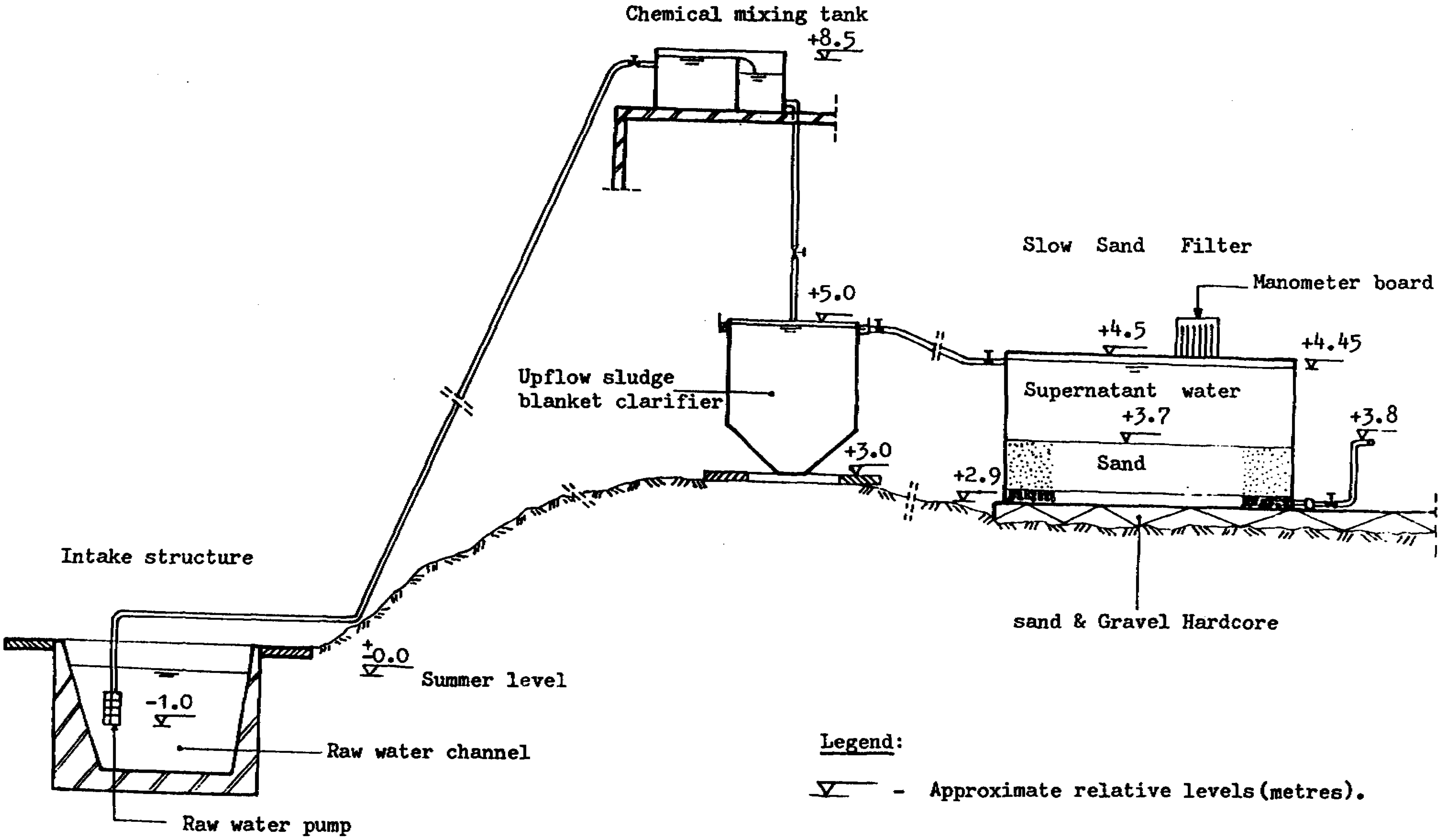

Fig.3 Schematic hydraulic profile of Egham pilot plant.

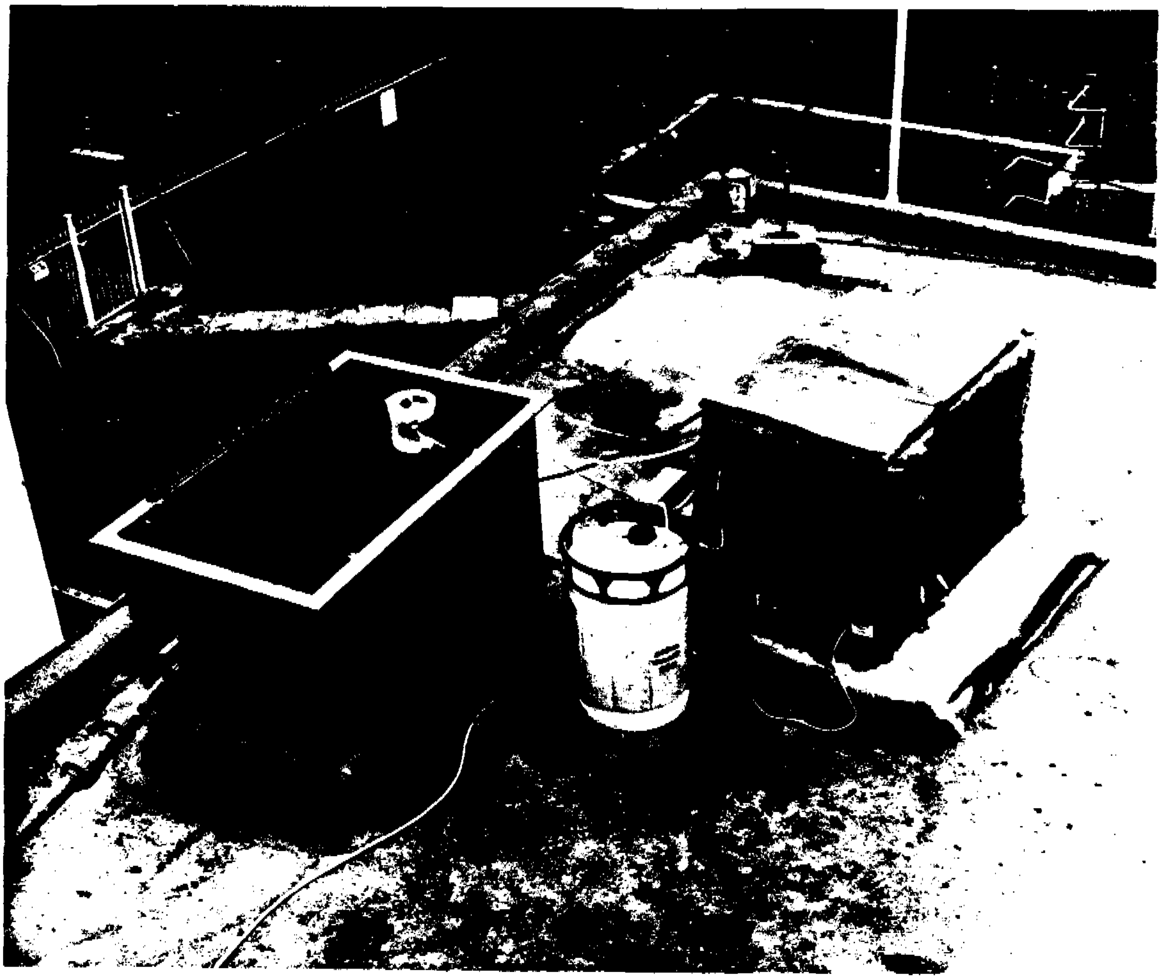

Plate. 2 The Chemical Mixing Tank and PAC Container at Egham Pilot Plant .

provided with varying media composition in order to compare the hydraulic and treatment performance. The walls of SSF boxes manufactured by Instalrite plastics Ltd were composed of an inner PVC lining covered with a reinforced glass fibre layer strengthened by two metal girders over the height. The SSF filtrates were then combined and led to the drain. Note that the two clarifiers were referred to as C1 and C2 while the filters were denoted by S1, S2 and S3.

2.4 River Water Quality

Table 1 gives the physico-chemical and bacteriological quality of River Thames at the Egham main works intake during the period 1984-1987 as analysed by the North Surrey Water Company Water Quality Laboratory (4-6). Clearly, it can be seen that although the mean turbidity and colour values are low, the periodic fluctuations are quite pronounced with the ratios of maximum: mean of 8.5 and 3.5, respectively. As regards the bacteriological quality, the maximum recorded values show that the river can be highly polluted. Since no mean values were reported, it is not possible to evaluate the overall mean counts in this case. Chlorophyll-a analysis of river water showed peak values during spring and summer. However, during 1986 there was one late peak in autumn (September/October). Between 1984-1987, the chlorophyll-a peaks ranged from 130 to 350 µg/l with minimum values of less than 10 µg/l. From 1986 to August 1988, the raw water TOC (mg/l as C) ranged from 2.66 to 5.07 while the mean value was 4.01.

TABLE 1 : Water Quality of River Thames at Egham Intake 1984-1987 (4-6)

PARAMETER	RECORDED RANGE		MEAN
	MAXIMUM	MINIMUM	
Turbidity (JTU)	97	1.8	11.4
pH	8.9	7.4	8.0
Conductivity µs/cm	700	520	624
Nitrates mg/l as N	15.7	4.3	8.4
Nitrites mg/l as N	0.226	0.010	0.067
Ammonia mg/l as N	1.02	<0.01	0.15
Colour (Hazen Units)	46	3	13
Chlorides mg/l as Cl	59	29	40.5
Sulphates mg/l as SO_4	72.2	48.2	61.4
Permanganate Oxidizability mg/l as O_2	9.7	1.0	3.3
Dissolved Oxygen Saturation rate (%)	129	62	97.5
Phosphorus mg/l as P	2.14	0.32	1.04
Dissolved Iron µg/l as Fe	677	10	70
Manganese µg/l as Mn	46	<5	9.5
Coliform Bacteria (No./100 ml)	310,000	800	-
E.Coli Bacteria (No./100 ml)	20,000	<25	-

2.5 Filter Media

The sand used as SSF bed was brought from Ashford Common Water Treatment Works. Its mean grading is shown in Figure 4 with an effective diameter (d_{10}) of 0.30 mm and a uniformity coefficient (d_{60}/d_{10}) of 2.1. On the basis of experience gained elsewhere (7), only fabrics lab. No.28 and No.32 were used during this study. The characteristics of these fabrics are given in Table 2. Scanning electron micrographs of the two fabrics are shown in Plates 3-6. Fabric No.28 is a needle-felted fabric constructed around carrier threads which can be seen in Plates 3 and 4. Fabric No.32 is a resin spray-bonded fabric containing an acrylate polyvinyldine chloride binder. The manner in which these filter media were used is explained in the next section.

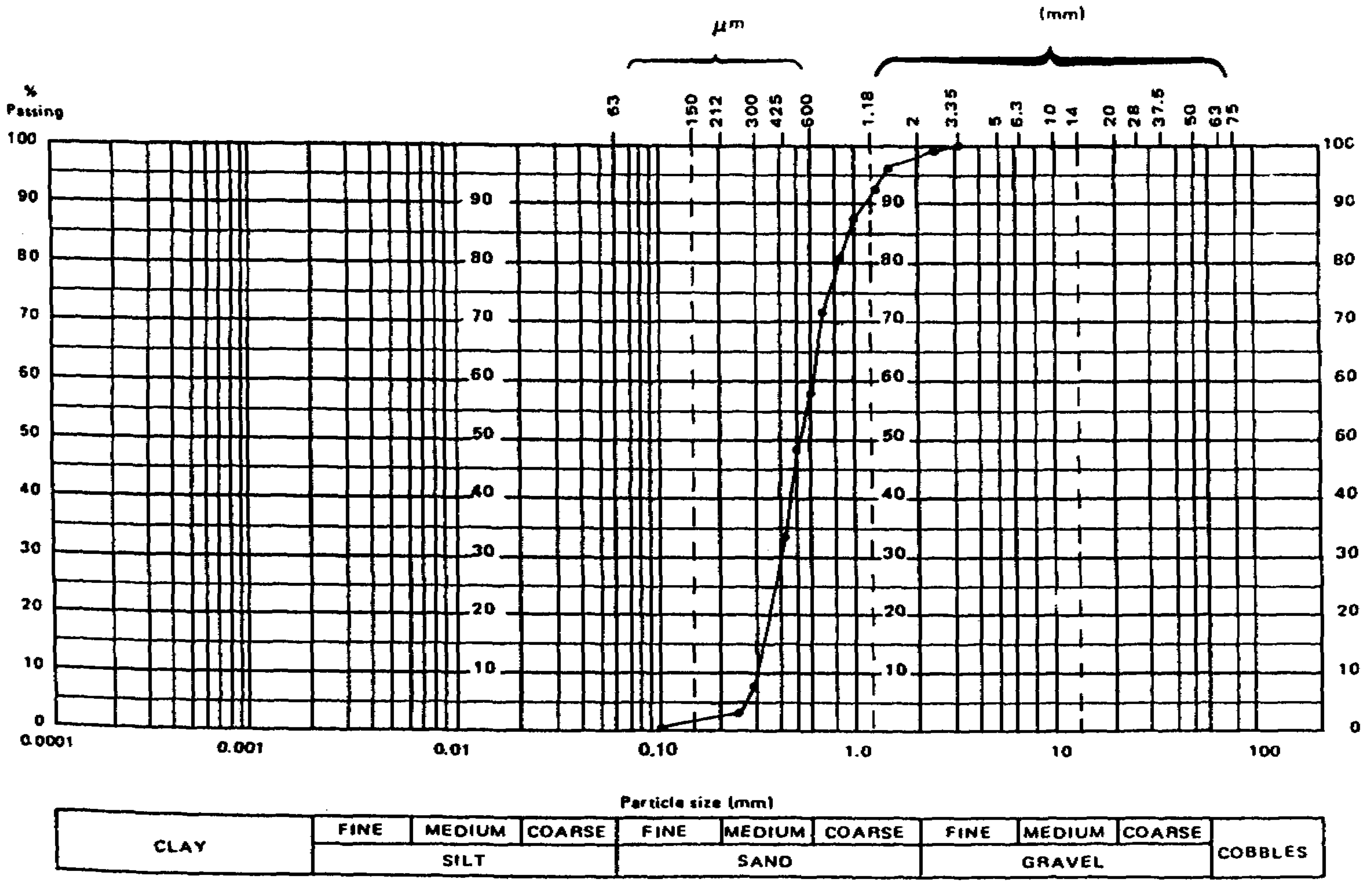

Fig.4 The Sieve Analysis Curve for SSF Sand.

Plate. 3 Cross Section of Virgin Lab. No. 28 (x40).

Plate. 4 Close-Up of Virgin Lab. No. 28 Cross Section (x151)

PLATE 5 A Cross Section of a Virgin NWF Lab. No. 32 .

PLATE 6 Surface Appearance of a Used NWF Lab. No. 32.

TABLE 2 : Fabric characteristics

FABRIC	28	32
Fibre composition*	PP	PE/PVC/PA
Fibre diameter (μm)	33	50/40/40
Thickness of single fabric layer (mm)	4.8	14.0
Fabric porosity (%)	89	98
Specific surface area (m^2/m^3)	13,266	1,671

* PP - Polypropylene; PE - Polyester; PVC - Polyvinylchloride PA - Polyamide;

2.6 General Conduct of the Experiments

In terms of time schedule the clarifiers were commissioned on the 30 November 1987 which in this report will be regarded as the reference day for monitoring all water quality parameters. As regards the SSF units, the first day of operation was on the 30 December 1987 as indicated in Table 3.

During the research programme, three sets of filter media and operation conditions were investigated as detailed in Table 3. It can be noted that Phase 1 simultaneously compared the performance of two fabric protected units with almost equal fabric thicknesses and also with the reference unit having 600 mm depth of sand only. Phase 2 involved optimization of fabric thickness and configuration by introducing 3 layers of fabric lab. No.28 in order to check whether it was really necessary to use 5 layers as in unit S1. The configuration of 2 layers fabric lab. No.32 over 3 layers fabric lab. No.28 was meant to combine the high storage ability of lab. No.32 with the better capture efficiency of lab. No.28 in order to collect particles

TABLE 3 : Fabric Specification and operational conditions of the slow sand filters

SLOW SAND FILTER UNIT	FABRIC SPECIFICATION		
	30/12/87 - 08/3/88 (Phase I)	08/3/88 - 7/5/88 (Phase II)	13/5/88 - August 1988 (Phase III)
S1	5 layers fabric 28 (t = 24 mm, v = 0.15 m/h)*	5 layers fabric 28 (t = 24 mm, v = 0.15 m/h)	2 layers fabric 32 over 3 layers fabric 28 (t = 40.4 mm, v = 0.3 m/h)
S2	2 layers fabric 32 (t = 26 mm, v = 0.15 m/h)	3 layers fabric 28 (t = 14.4 mm, v = 0.15 m/h)	3 layers fabric 28 (t = 14.4 mm, v = 0.15 m/h)
S3	No fabric (reference) (v = 0.15 m/h)	2 layers fabric 32 over 3 layers fabric 28 (t = 40.4 mm, v = 0.15 m/h)	2 layers fabric 32 over 3 layers fabric 28 (t = 40.4 mm, v = 0.15 m/h)

* t - total thickness of fabric layer
v - flow velocity

which would bleed through lab. No.32. Besides consolidating data obtained in Phase 1 and 2, Phase 3 helped to check the influence of operation of the SSF units at a higher rate in terms of both hydraulic and treatment performance.

As regards the PAC dose in the pilot plant mixing tanks no optimization experiments were carried out because the intention was to produce a poor clarifier effluent quality with substantial floc carry-over. Therefore the doses used in the main works were used as a guideline to start with. In December 1987, the main works average PAC dose was 4.0 mg/l (as Al_2O_3) but during spells of heavy rain which led to increased river water turbidity, the dose was sometimes increased up to a maximum of 10 mg/l. On the basis of these observations and also on actual inspection of the blanket formed in the pilot plant clarifiers, the average PAC dose was usually at 6.0 mg/l (as Al_2O_3). During spells of heavy rain, the dose was increased by a factor of about 1.3.

3. EXPERIMENTS - PHASE 1 AND 2

3.1 Procedures and Analysis Methods

Initial investigations of surface overflow rates and inlet valves coarseness suited the operation of clarifiers C1 and C2 at rates of 1.7 and 2.0 m/h, respectively. During this period, the depth of sludge blankets was kept at only 10 cm from the base of Vee-notch weirs along the collection channel in order to ensure sufficient floc carry-over. During both phases, the SSF units were generally operated at a rate of 0.15 m/h which was ususally proceeded by one day operation at about 0.10 m/h after cleaning the fabrics or filter bed. All units were initially operated at a rate of less than 0.10 m/h for seven days during initial maturation in December 1987/January 1988 in order to allow for biological maturation of the filter beds. This is why these initial filter runs were not used for average filter runs evaluation.

Routine sampling of raw river water, clarifier effluent and SSF filtrates for pH, turbidity, bacteriological and colour analysis were taken. In addition to these analyses, particle size analysis was done at least once per week. Temperature measurements of raw water in the chemical mixing tank, clarifiers and SSF boxes were done. Maximum and minimum ambient temperatures were also recorded daily. The actual methods of analysis were as follows:

(i) pH - by a probe connected to an Orion Research Ioanalyser Model 4074

(ii) Turbidity - by a Hach Model 21004 turbidimeter (Camlab, UK), measured in NTU.

(iii) Temperature - by a mercury thermometer with a range of -10 to +40°C. The maximum and minimum thermometer covered the temperature range from -20 to +40°C.

(iv) Bacteriological Analysis - Faecal coliforms analysis by membrane filtration technique using the "Delagua" field testing kit, University of Surrey, Guildford, UK (8). Duplicates of each sample were analysed and the average results used.

(v) Colour - only apparent colour was analysed on a LKB, Biochrom Ultrospec 4050 spectrophotometer at 400 nm wavelength according to specifications given in "Analysis of Raw, Potable and Waste Waters", UK 1972 (9).

(vi) Particle Size Analysis - with a TA II/PCA I coulter counter using diameter 100 and 400 μm orifice tubes as a routine. For characterisation of the particle size of clarifier effluents diameter 50, 140, 280 and 400 μm orifice tubes were used in multiple-tube analyses.

The six manometer tubes provided in each SSF box were used to monitor the head losses across the filter media during the filter runs.

3.2 Raw Water Characteristics

Since the clarifiers were commissioned on the 30 November 1987, this is regarded as the reference day for monitoring the raw water and clarifier effluent quality. While Figure 5 shows the variation of Turbidity during the period of experiments, Figure 6 shows the variation of pH. Figure 7 shows the particle size distribution of river water as analysed by a 400 μm diameter orifice tube on a coulter counter.

3.3 Hydraulic Performance

The hydraulic performance is discussed separately for phases 1 and 2 in view of the differences in filter media and operation conditions applied.

3.3.1 Phase 1

3.3.1.1 Filter run time

Reference should be made to Table 3 for filter media composition in the three SSF units. Table 4 gives the filter run times of the three filters during the initial phase. Note that the end of filter

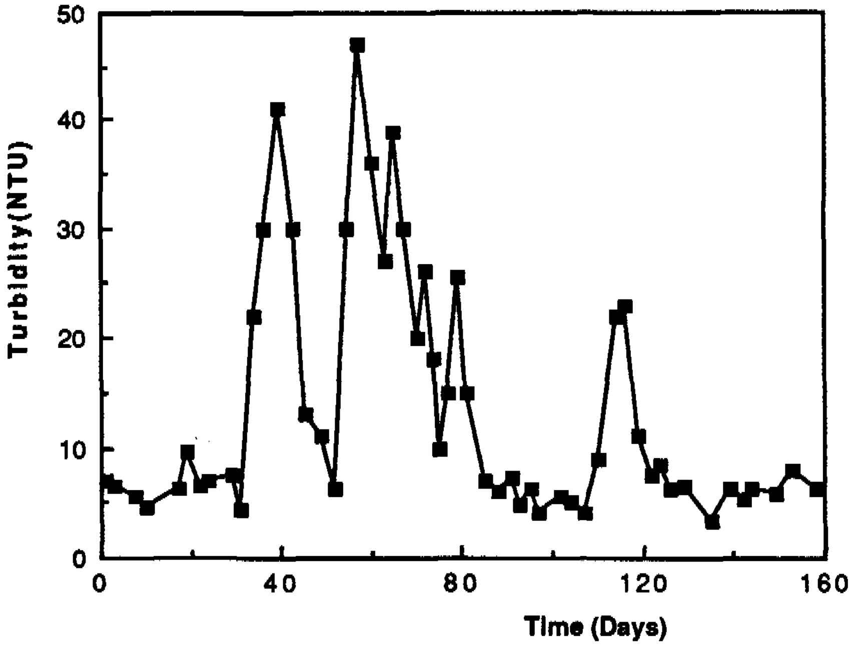

Fig. 5 Raw Water Turbidity Variation .

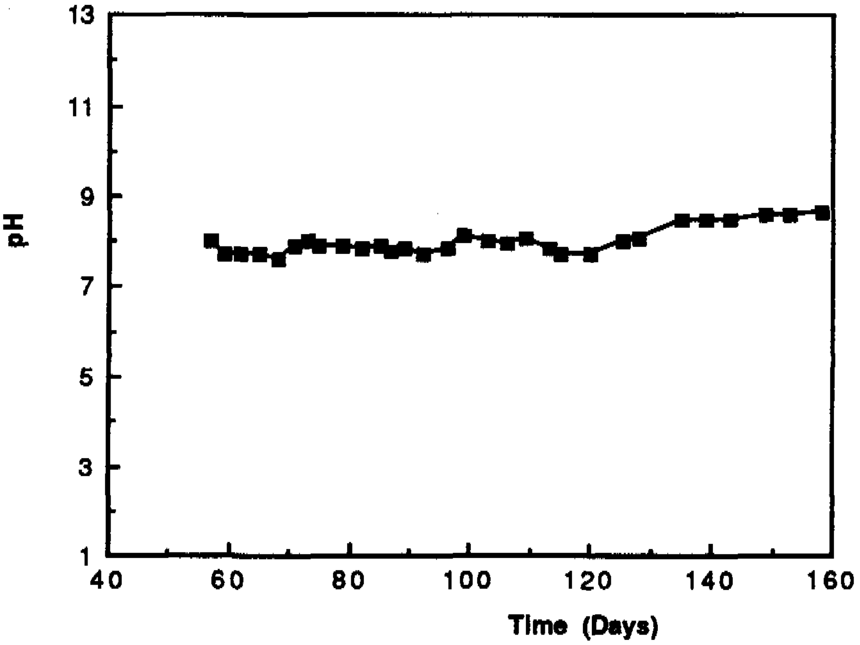

Fig.6 Raw Water pH Variation .

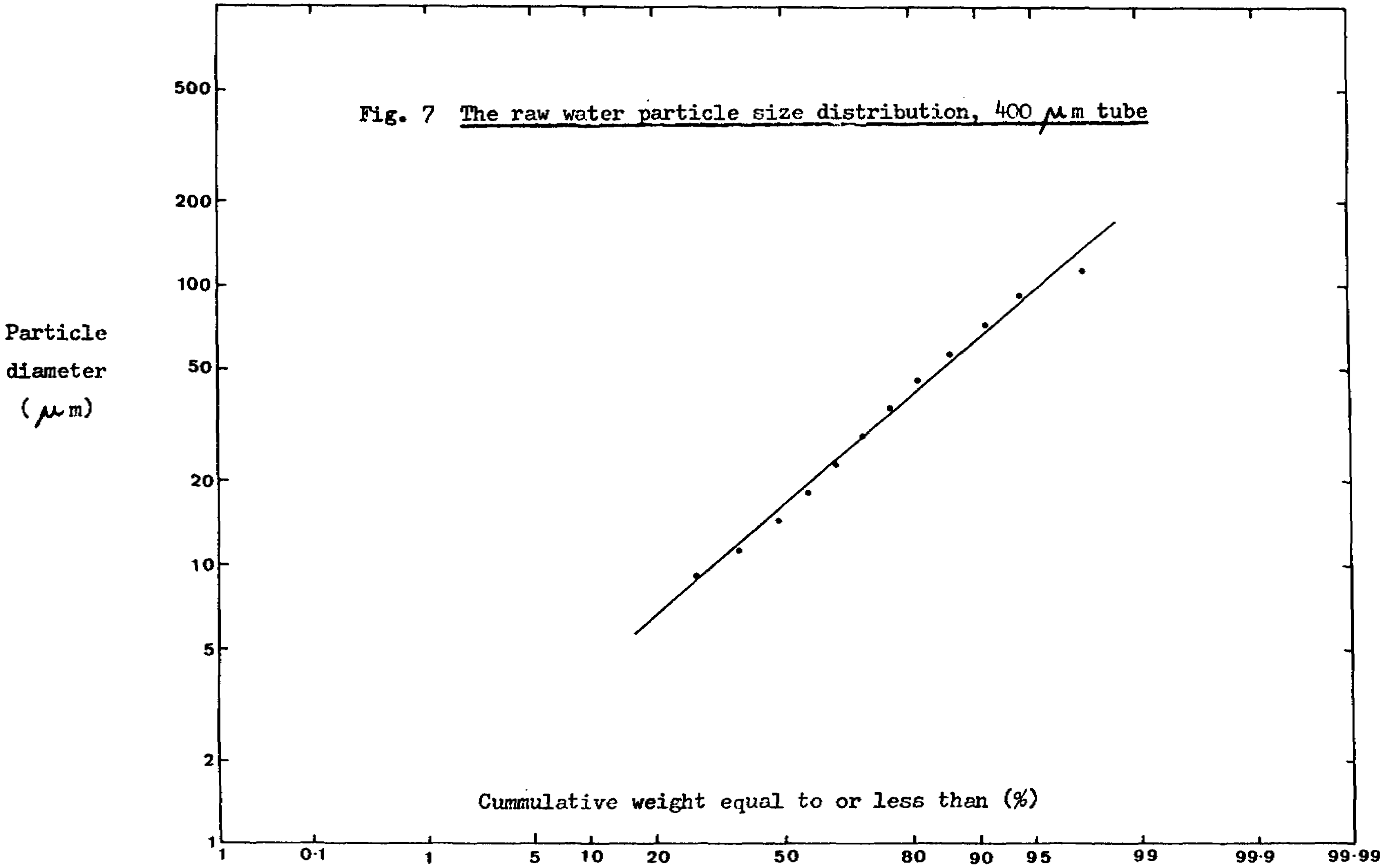

Fig. 7 The raw water particle size distribution, 400 μm tube

runs was based on inability to operate at the design filtration rate with the effluent valve fully open. The results show that the fabrics offer a very good protection to SSF receiving water with floc carry-overs. As a result of this the filter run times of fabric protected SSF units were much longer than conventional SSF. Occasionally excess carry-over of flocs into SSF units occurred due to inadvertent blockage of the sludge extraction lines. During such incidences, the fabric protected filters showed an excellent resilience against increase in rate of blocking the filter media. Under these circumstances, the weakness of conventional SSF became very apparent as the unit S3 blocked within a matter of a few days only. On the basis of the averages of results given in Table 4, fabric lab. No.28 increased the filter run time by a factor of 3.1 while lab. No.32 did so by a factor of 4.4. The penetration of impurities through lab. No.32 and the subsequent sloughing upon

TABLE 4 : Phase 1 filter run times

SLOW SAND FILTER UNIT	FABRIC SPEC.	SUCCESSIVE FILTER RUN TIMES (h)	REMARKS
S1	5 layers 28	552*, 245, 416, 164* (mean 331 h (13.8 d))	Excess floc carry over during last filter run
S2	2 layers 32	522*, 444, 505, 116* (mean 475 h (19.8 d))	
S3	None	284*, 119, 96, 115, 70* 120, 93, 118, 68*, 92 (mean 108 h (4.5 d))	Excess carry over of flocs during 5th and 9th runs

* not used for evaluation of means

lifting were the major factors against its use as a sole fabric type above sand beds.

3.3.1.2 Filter headloss

Figures 8 and 9 show the first filter runs for S1 and S3. While it is clear that almost all impurities are captured in the fabric lab. No.28 in S1, the conventional unit S3 captures its impurities on sand with manometer No.2 registering no headloss at all. Note the large contribution of the running-in (maturation) period to these two runs and especially for S3. This is partially the reason as to why the first runs were not used for mean filter run time evaluation, Figures 10 through 12 show the second filter runs for all the SSF units. It can be noted that the gap between manometers No.2 and 3 in Figure 11 probably indicates the penetration of impurities into the sand bed. Figures 13 and 14 show typical headlosses in the units S1 and S3. Distinct differences in the headloss distribution pattern were apparent between units S1 and S2. The denser lab. No.28 captured nearly all the impurities within the fabrics while the more porous lab. No.32 allowed extensive penetration of impurities into the sand bed thus requiring washing of both sand and the fabrics at the end of runs. Depending on whether the sand was refilled after sampling or not, either manometer No.3 or 4 registered most of the headloss in unit S3.

3.3.2 Phase 2

3.3.2.1 Filter run time

Table 5 gives the filter run times of the SSF units during the second phase. In general, all three sand beds were well protected and apart from minor edge penetrations, there was no need to clean sand at

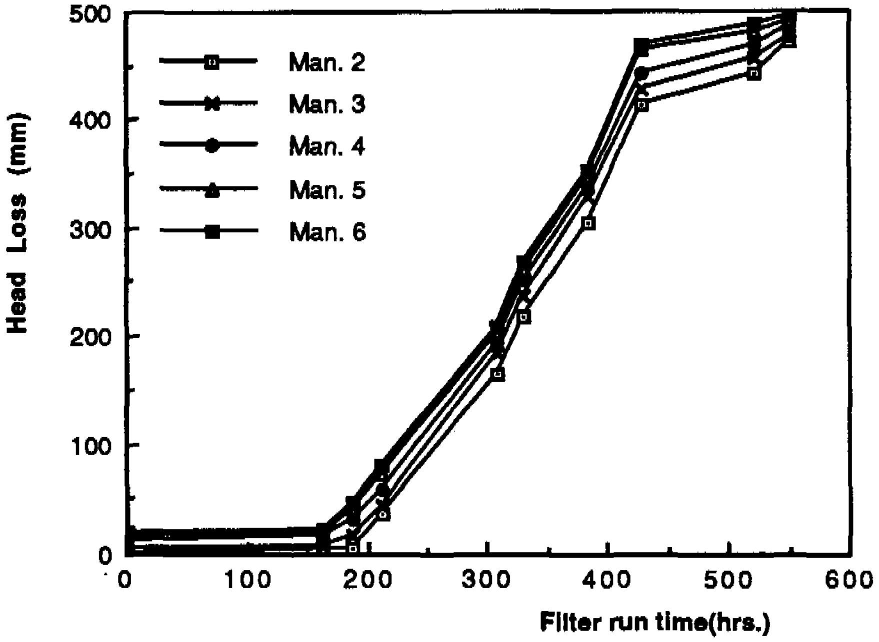

Fig. 8 S1 Filter Head Loss (Run 1).

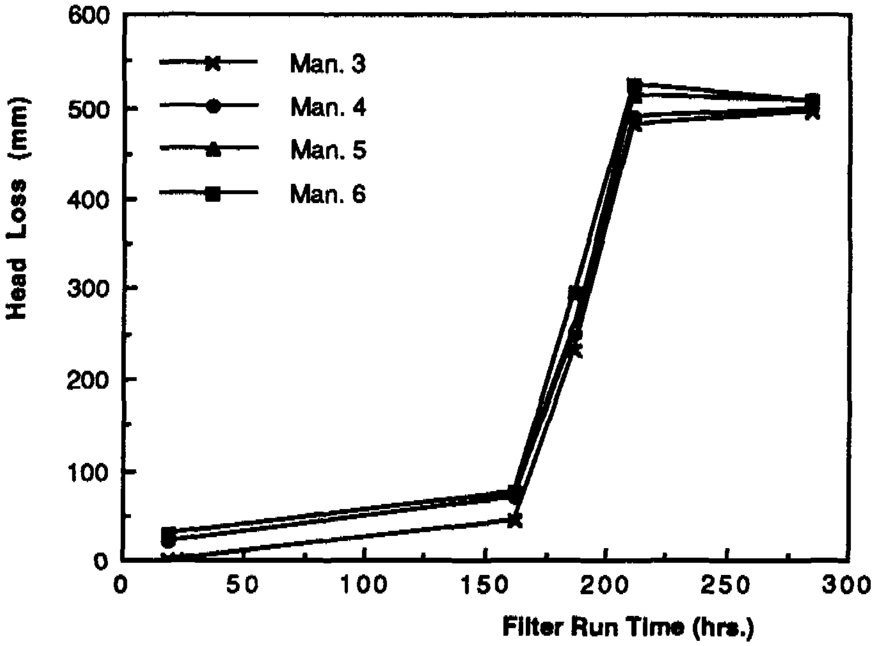

Fig. 9 S3 Filter Head Loss (Run 1).

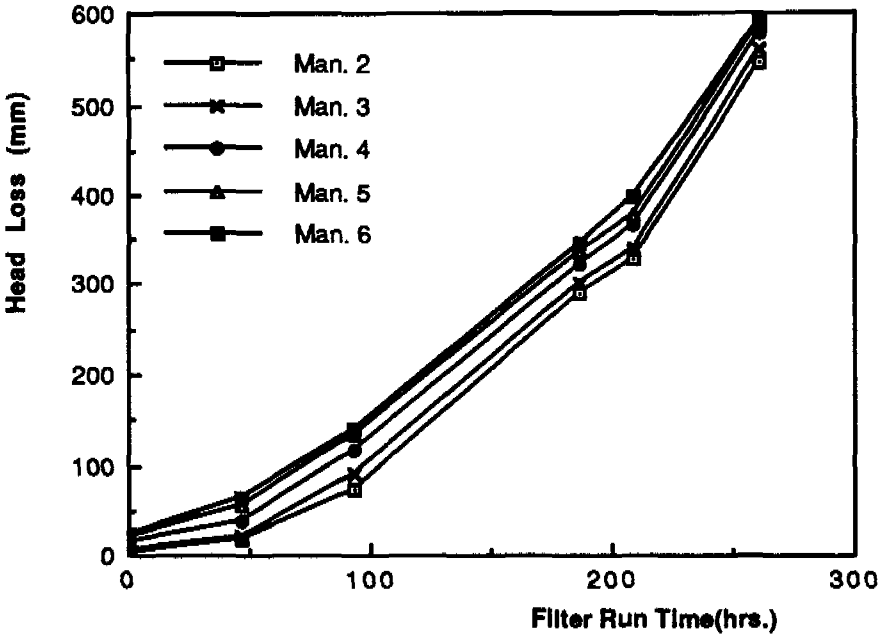

Fig. 10 S1 Filter Head Loss (Run 2) .

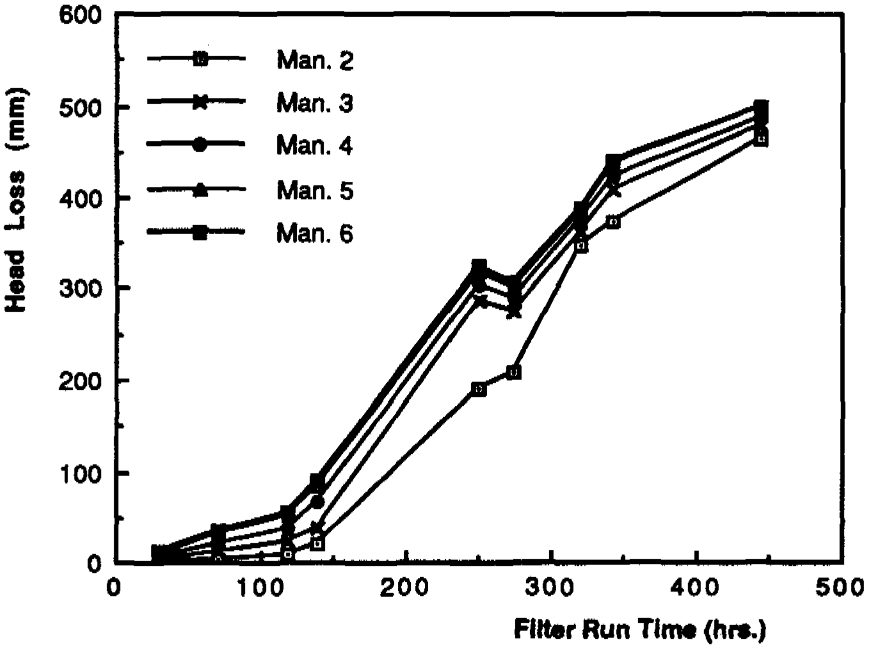

Fig. 11 S2 Filter Head Loss (Run 2) .

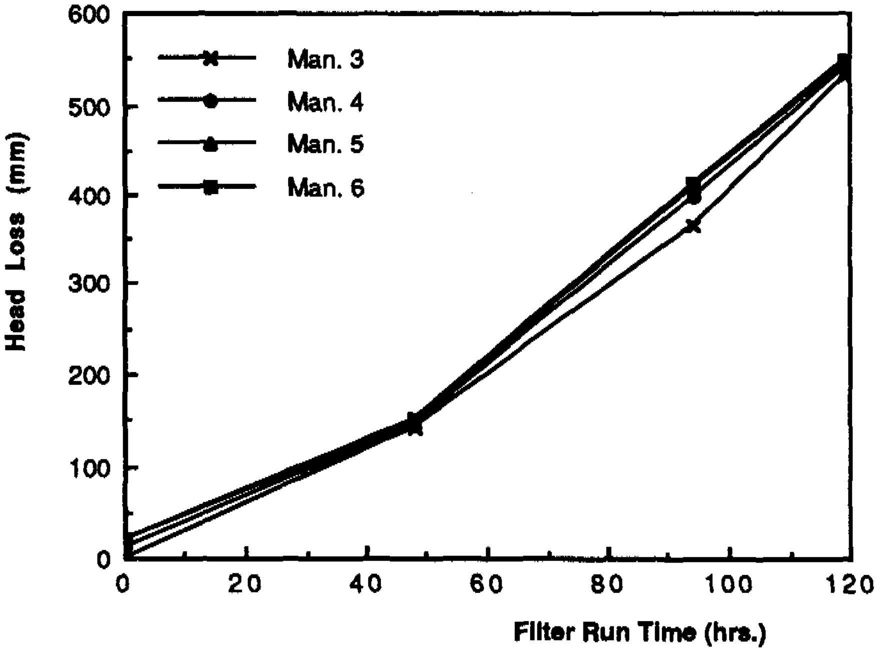

Fig.12 S3 Filter Head Loss (Run 2).

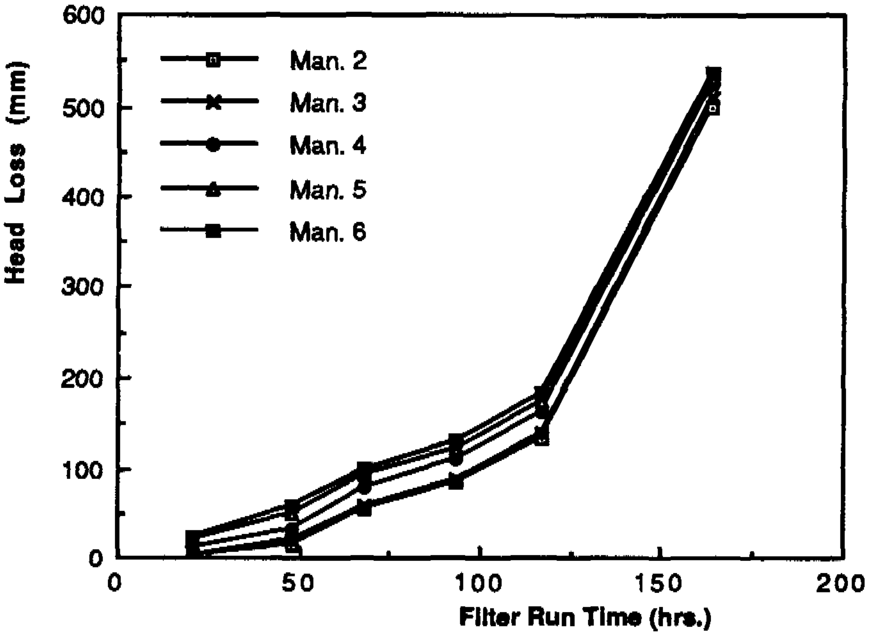

Fig. 13 S1 Filter Head Loss (Run 4).

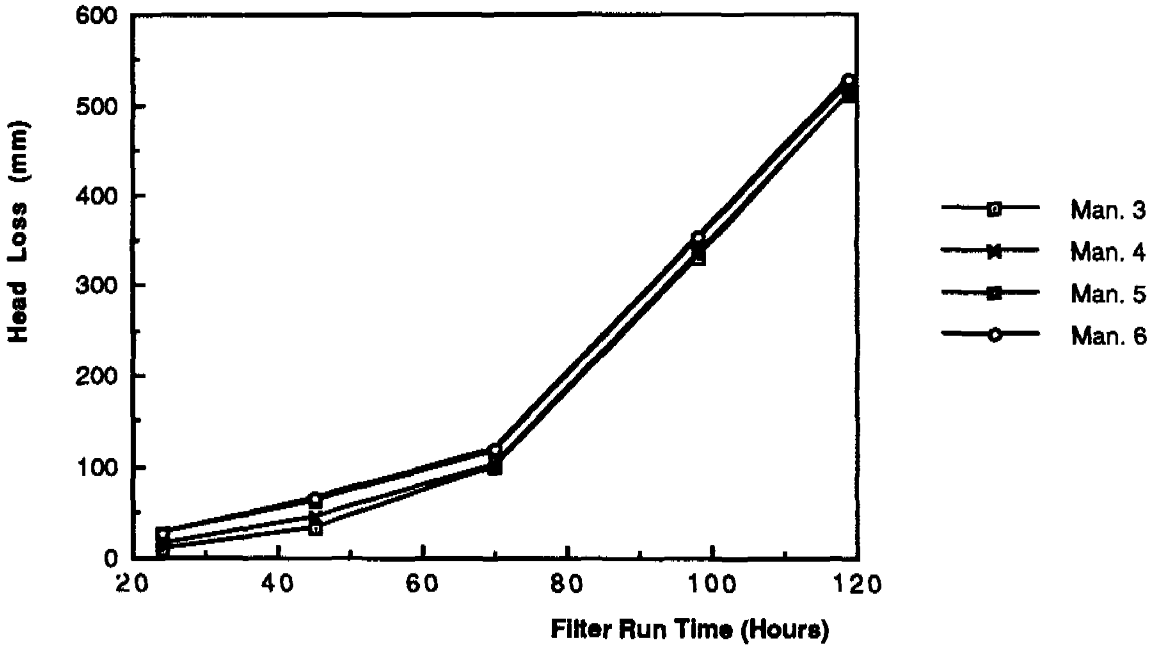

Fig. 14 S3 Filter Head Loss (Run 8)

the end of the runs. Predictably, the benefit of using five layers of lab. No.28 in S1 as opposed to three in S2 was the increase in filter run time as shown in Table 5.

TABLE 5 : Phase 2 filter run times

SLOW SAND FILTER UNIT	FABRIC SPEC.	SUCCESSIVE FILTER RUN TIMES (h)
S1	5 layers 28	281, 354, 331 (Mean 322 h (13.4 d))
S2	3 layers 28	209, 332, 295, 278 (Mean 279 h (11.6 d))
S3	2 layers 32 over 3 layers 28	631, 528 (Mean 580 h (24.2 d))

S3 with the composite of lab. No.28 and 32 showed a much slower build up of headloss especially during incidences of shock loads of flocs. The ratio of average filter run times for S3:S2 and S3:S1 were 2.1 and 1.8 respectively which showed the superiority of the composite layers arrangement. However, it must be noted that the total fabric thickness of S1, S2 and S3 were not the same, 24.0, 14.4 and 40.4 mm respectively, and fabric thickness is an important factor. Another interesting comparison parameter is in terms of the total fabric area per square metre. For the three configurations compared above, the same were 317, 190 and 237 m^2, respectively. This proves the remarkable performance of S3 in comparison to S1 besides having a total area of just about 75% of that provided by the latter.

It is interesting to note that the mean run time for S1 was approximately the same for Phase 1 and 2, suggesting that influent water quality was similar for the two phases. This allows direct comparison between run times for the two phases.

3.3.2.2 Filter headloss

During this phase most of the headloss was registered by manometer tube No.2 in all three units thus showing effective protection of the sand beds. Figures 15 through 20 show some typical headloss distribution graphs for the three units. In all cases, the absence of major gaps between the manometer tubes proves the high level of protection of sand beds afforded. The small differences between manometers No.2 and 3 generally proved the potential of the fabrics in protecting the sand beds. There was some indications of a development of negative pressure in units S1 and S3 at the end of the runs. This might have been a result of the final level of the fabric layers and deposits being just above the effluent weir levels.

3.4 Water Quality Improvement/Changes

Water quality changes are discussed with respect to five main parameters monitored. Prior to this, water and ambient temperature changes are reviewed.

3.4.1 Temperature

This parameter was monitored from 31 December 1987 until 5 May 1988. The ambient recorded temperature ranged from 1.0 to 16.0°C while during the same time the clarifier effluent and SSF water temperatures ranged from 3.5 to 13.0°C. The maximum and minimum temperatures taken only from 30 January 1988 until 5 May 1988 were as follows:

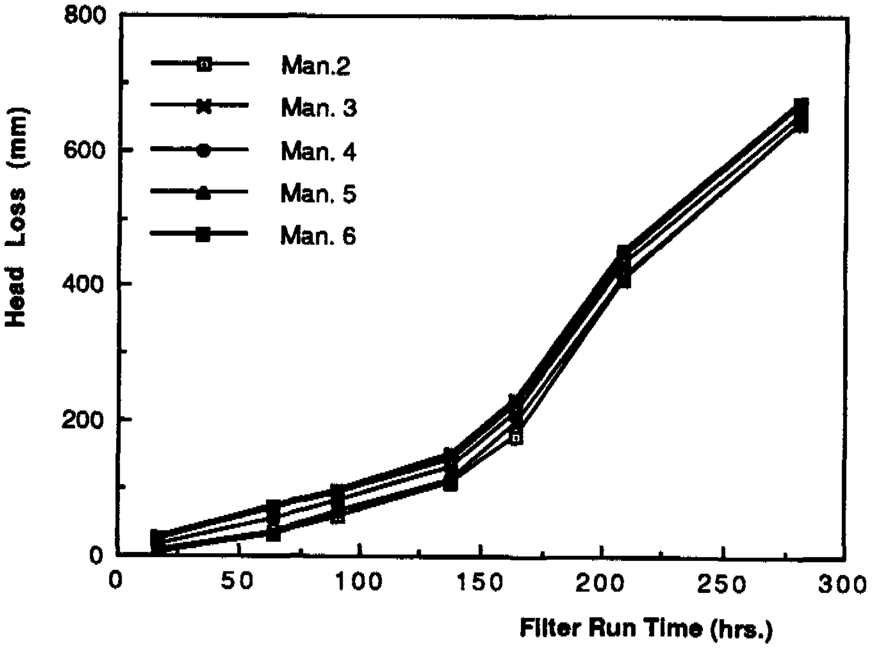

Fig. 15 S1 Filter Head Loss (Run 1).

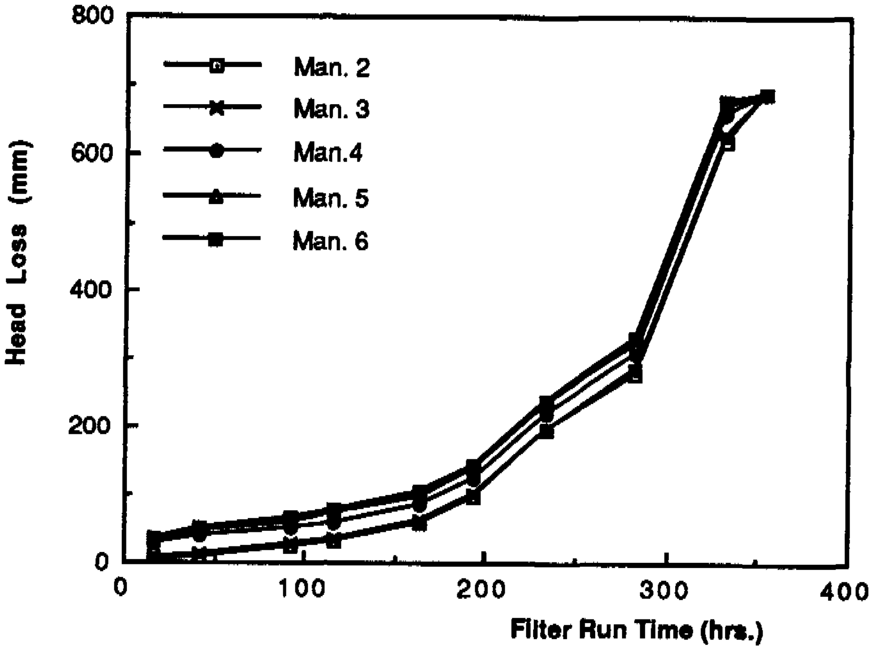

Fig. 16 S1 Filter Head Loss (Run 2).

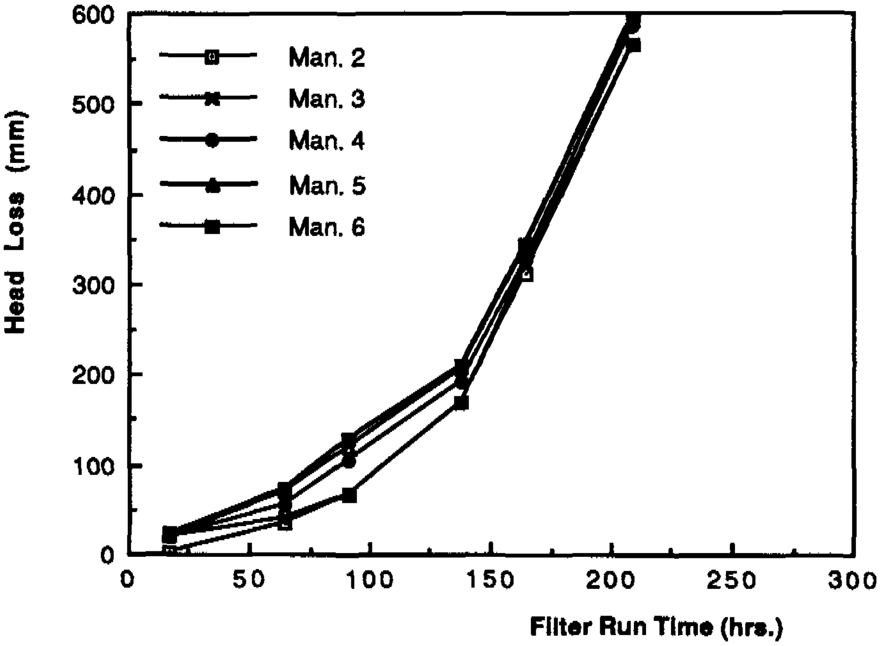

Fig. 17 S2 Filter Head Loss (Run 1) .

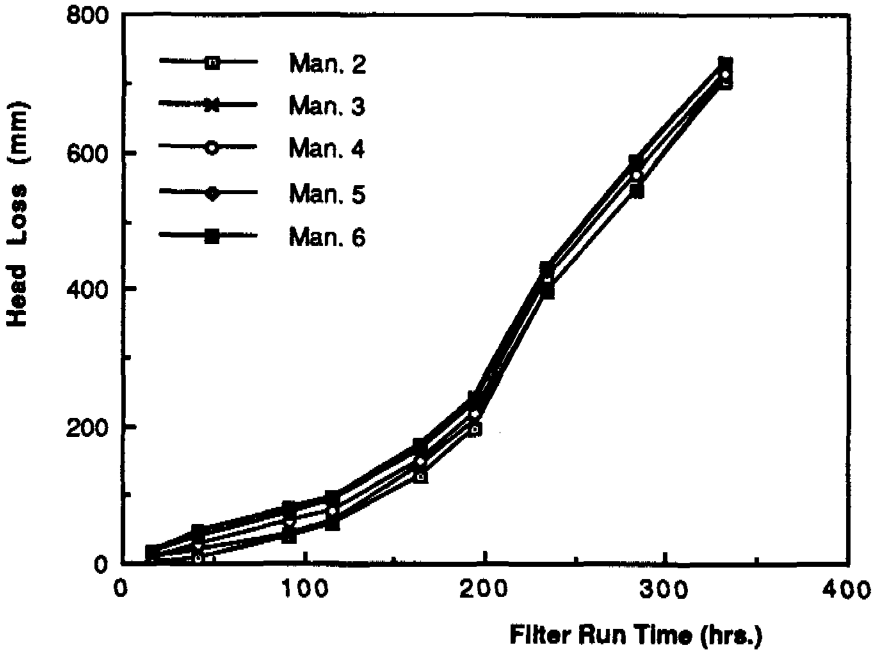

Fig. 18 S2 Filter Head Loss (Run 2) .

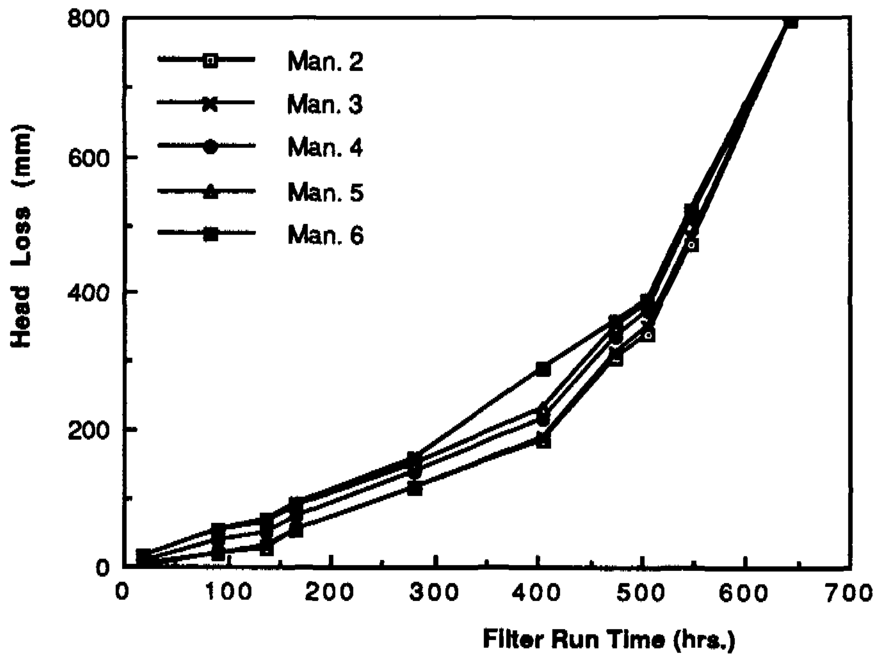

Fig. 19 S3 Filter Head Loss (Run 1) .

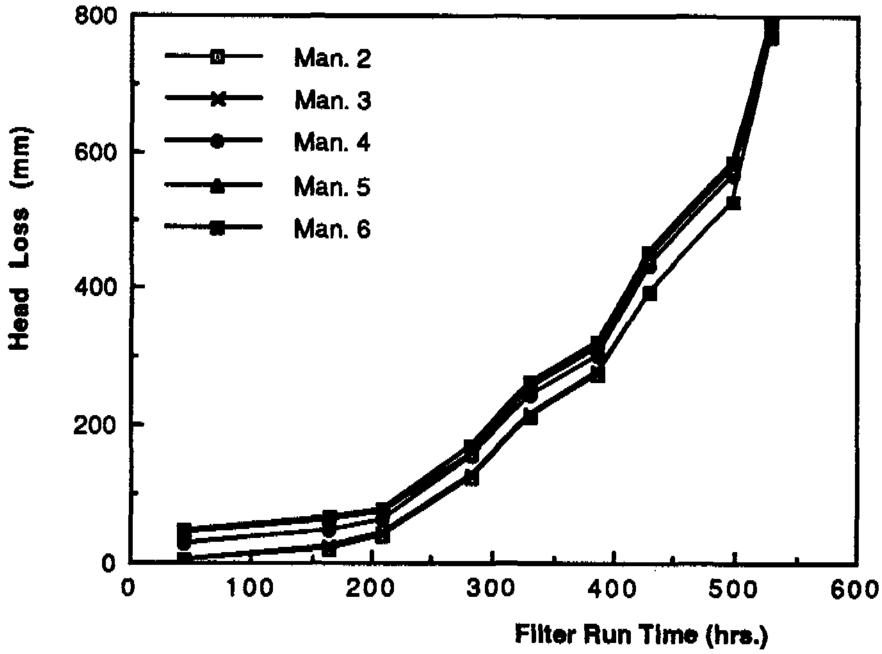

Fig. 20 S3 Filter Head Loss (Run 2) .

MAX: ranged from +4.5 to 21.0°C

MIN: ranged from -4.5 to +9.5°C

3.4.2 pH

From 25 January 1988 until 4 May 1988, the raw water pH ranged from 7.6 to 8.65. At the same time, clarifier effluent pH varied from 6.6 to 7.85 for all days when PAC dose was set to be $\geq$ 3.0 ml/min. Low pH levels in clarifiers correspond to high PAC doses during spells of heavy rainfall. Literature (10) suggests that as opposed to alum or other iron salts, PAC can be expected to work well over a much wider range of raw water pH. It is suggested that the most effective range is pH 6-9 although satifactory operations can be obtained between pH 5-10.

3.4.3 Colour

Apparent colour was monitored only from 6 January 1988 until 29 February 1988. During this period, the raw water apparent colour ranged from 33.3 to 212.6 Hazen Units. The mean clarifier effluent apparent colour varied from 12.4 to 108.5 Hazen units with higher readings taken after loss of sludge blankets. The mean SSF filtrate apparent colour ranged from 1.3 to 27.9 Hazen units. Figure 21 shows the apparent colour removed across the pilot plant. It can be noted that the removals were consistent with fluctuations in the raw water.

3.4.4 Turbidity

This parameter was monitored from 31 December 1987 until 4 May 1988. Raw water turbidity ranged from 3.3 to 48.0 NTU with maximum values in January 1988 and minimum values in April 1988. The

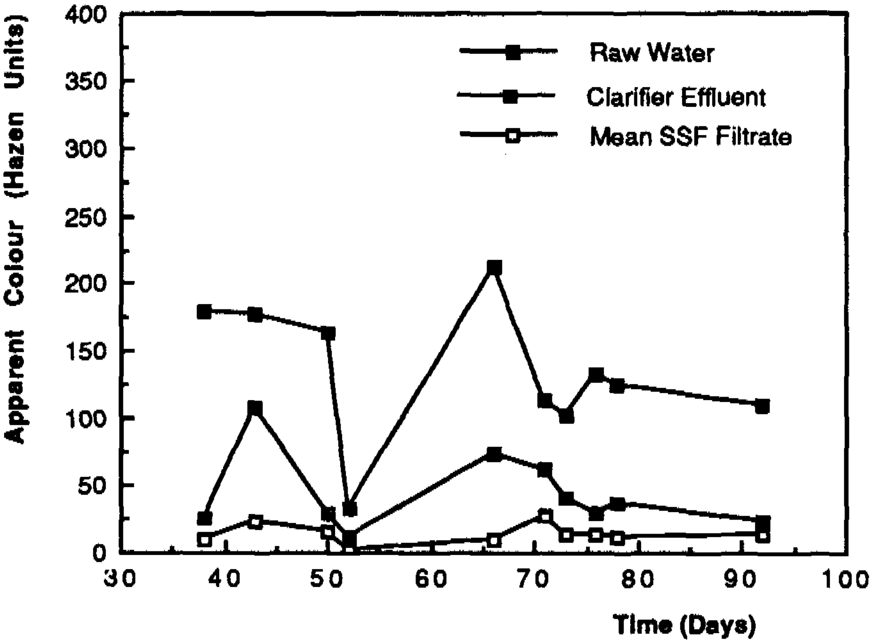

Fig. 21 Apparent Colour Removal .

turbidity of clarified water passing to the SSF range from 1.0 to 9.2 NTU. This range was wide due to periodic instability in the sludge blankets. All SSF filtrates were never more than 0.60 NTU. Table 6 gives the ranges of turbidity of SSF filtrates during both phases.

TABLE 6 : SSF Filtrate Turbidity

SSF UNIT	FILTER MEDIA	FILTRATE TURBIDITY RANGE (NTU)
S1	5 Layers Lab. No.28 (Phase 1 and 2)	0.13 - 0.45
S2	2 Layers Lab. No.32 (Phase 1)	0.14 - 0.59
S2	3 Layers Lab. No.28 (Phase 2)	0.14 - 0.32
S3	600 mm sand only (Phase 1)	0.13 - 0.32
S3	2 Layers Lab. No.32 over 3 Layers Lab. No.28 (Phase 2)	0.14 - 0.41

Figure 22 gives the turbidity removal during phase 1 with the reference day as 31 December 1987. Figure 23 gives the same for Phase 2 with the 8 March 1988 as the reference day.

3.4.5 Faecal coliforms

Faecal coliform enumeration was done from 3 February 1988 to 4 May 1988. During this period, the raw water counts ranged from 965 to 3200 per 100 ml. The mean removed through clarifers was 80% with a variation extent indicated by the relative standard deviation 18.3%.

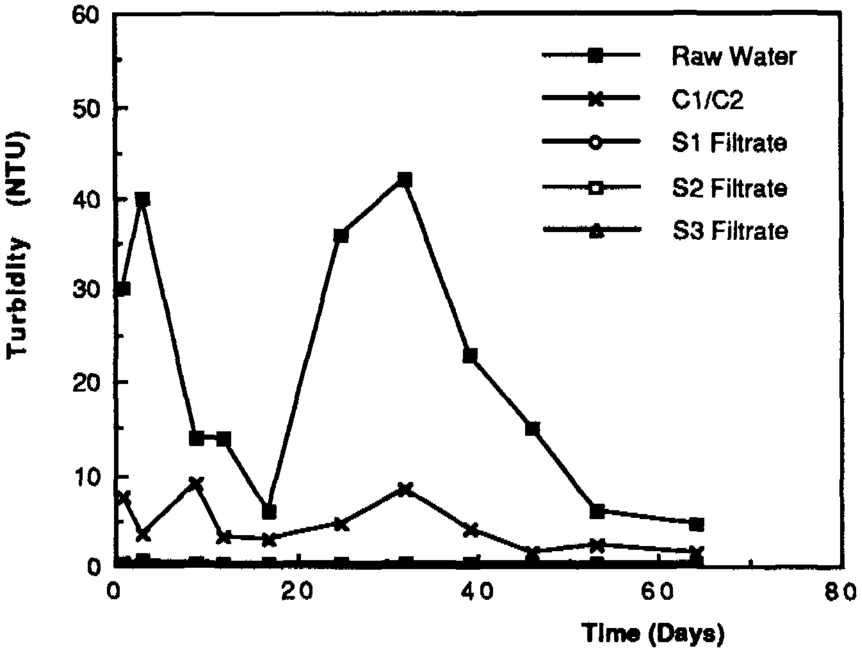

Fig. 22 Turbidity Removal (Phase 1) .

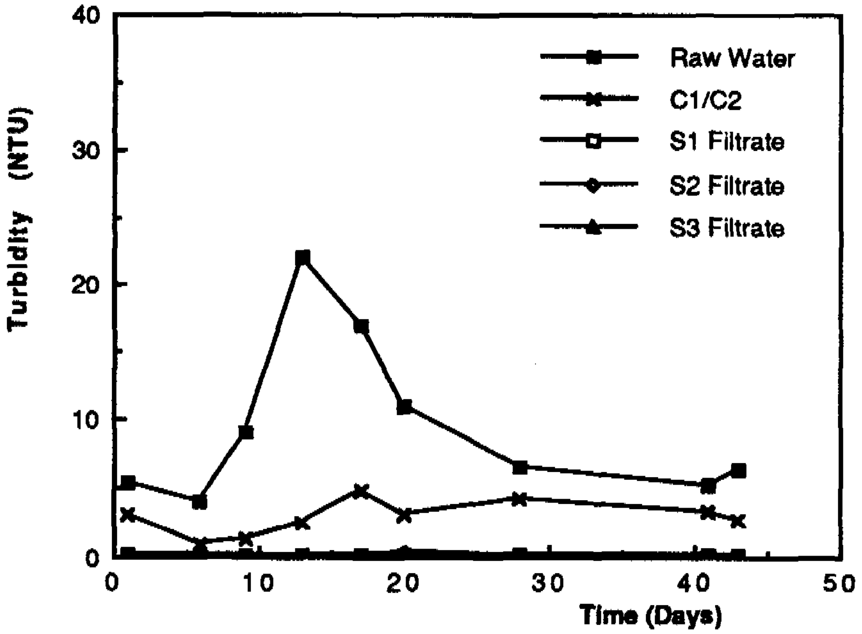

Fig. 23 Turbidity Removal (Phase 2) .

All SSF units were able to achieve a two-log reduction in faecal coliform concentrations. Concentrations above 1 per 100 ml were usually found in the immediate few days following filter cleaning, otherwise counts were typically zero per 100 ml. Table 7 gives the mean faecal coliform removal in the pilot plant during both phases. Figure 24 gives the bacteriological quality improvement in the clarifiers. Note the close relationship with raw water fluctuations of faecal coliform counts.

TABLE 7 : Mean faecal coliform removals

SSF UNIT	FILTER MEDIA	MEAN REMOVALS (%)	MINIMUM REMOVALS (%)	RSD (%)
S1	5 Layers Lab.28	99.4	98.9	0.9
S2	2 Layers Lab.32	99.0	98.4	1.0
S2	3 Layers Lab.28	99.4	98.0	1.1
S3	600 mm sand only	98.75	97.7	1.3
S3	2 Layers Lab.32 over 3 Layers Lab.28	99.6	98.5	0.8
Clarifier Effluent	-	80	55.8	18.3

3.4.6 Particle size analysis

Prior to and during analysis of the clarifier effluent particle size distribution, microscopic observation of the flocs was carried out. This was done on a M15C Vickers Light microscope with

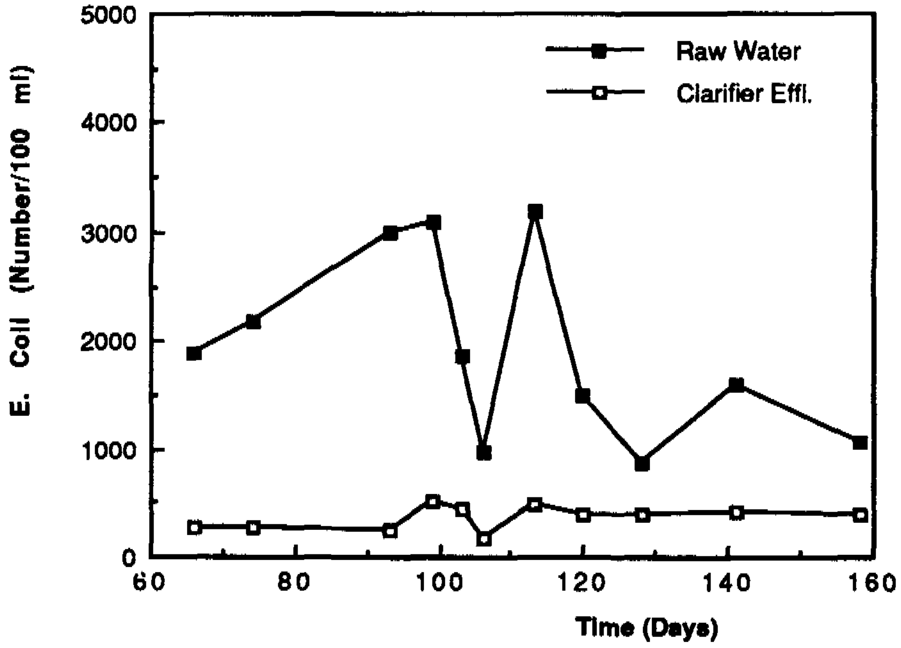

Fig. 24 Bacteriological Quality Improvement in the Clarifiers

magnifications of x100 and x400. The eyepiece was provided with a graticule divided into 10 grids of either 66 µm or 18 µm depending on whether low or high power magnification is set, respectively. The observation was carried out in order to get an initial idea of the particle size range of flocs and hence help decide on the suitability of using the TA II/PCA I coulter counter with a maximum available orifice diameter of 400 µm for analysis of flocs. Observations showed that the majority of flocs had a maximum diameter of less than 180 µm. A normal maximum diameter of floc agglomerates was found to be 220 µm. However, a few floc agglomerates were noted to have a diameter of up to 462 µm. The appearance of most of the particles observed was generally of irregular agglomerates. Observations were done in a chamber of two slides with a wide capillary space in between.

Routine analysis with the coulter counter were carried out for raw water, clarifier effluents and SSF filtrates from 26 February 1988 until 10 May 1988. The raw water and clarifier effluent were analysed with a 400 µm orifice tube while SSF filtrates were analysed with a 100 µm orifice tube. On two occasions, the particle size analysis of the clarifier effluent was done with the multiple-tube technique for 50, 140, 280 and 400 µm orifice diameter tubes. Figure 25 shows the cummulative volume distribution for the clarifier effluent as analysed by the multiple-tube technique. The raw data closely fits an assumed log-normal probability distribution.

3.5 Filter Media Cleaning

While for the reference (conventional) SSF all impurities were deposited directly in the sand, for fabric protected units at the end of filter runs there always was a small amount of edge penetration of

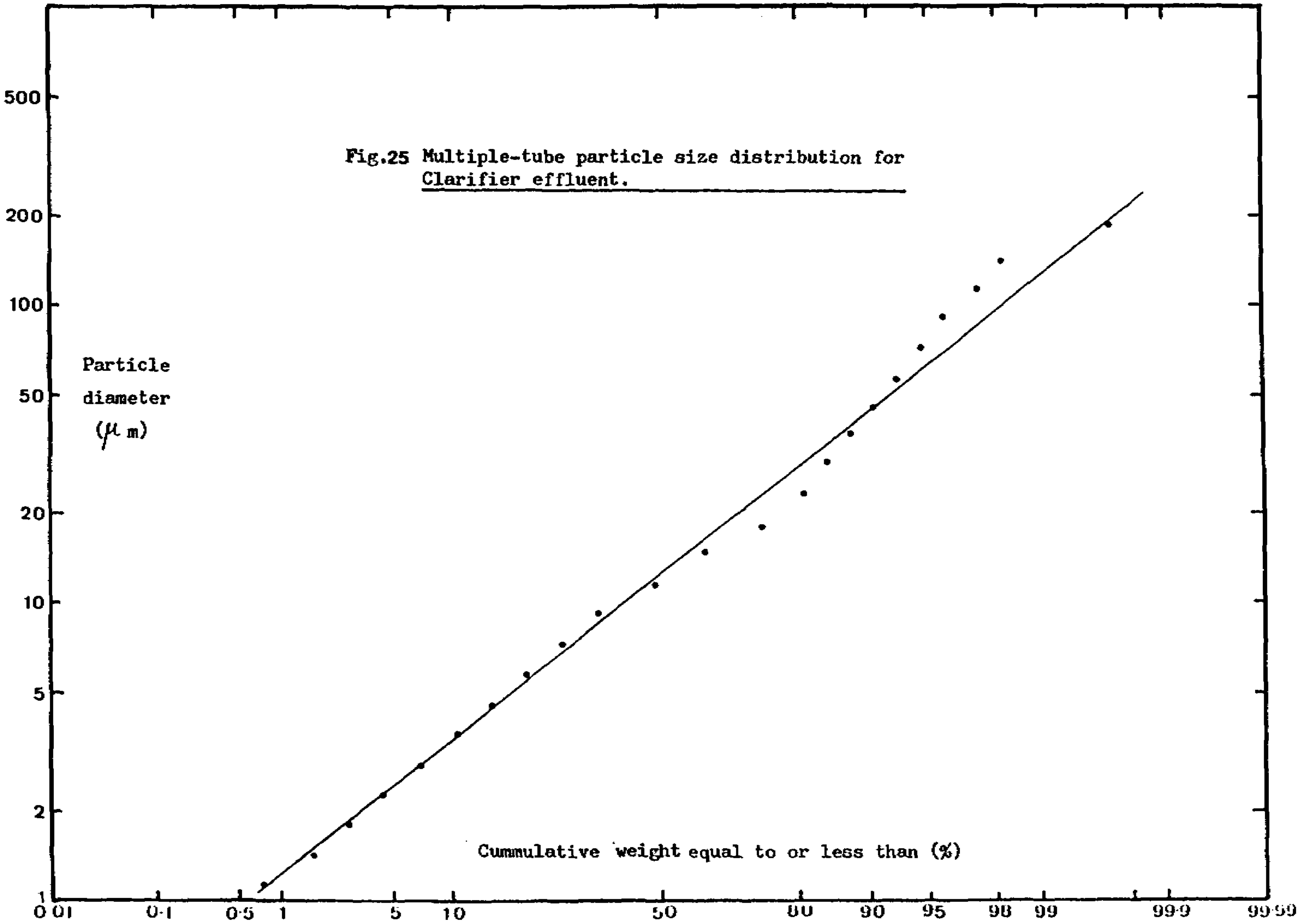

Fig.25 Multiple-tube particle size distribution for Clarifier effluent.

PLATE 7 A Plan View of the Fabric Protected SSF Unit After Drainage of Water , Egham Pilot Plant .

impurities into the sand. The amounts involved were so small that just light sampling of the deposited matter was sufficient. The sludge deposited on the filter media was very difficult to handle when wet (Plate 7), therefore the units were left to drain overnight such that the following day only a small depth (say 5-10 mm) of semi-dry sludge remained on the top fabric surface.

3.6 Fabrics Washability

At the end of the filter runs the fabrics were cleaned with a high pressure water hose passed over the fabric surface beared against a clean surface. This method of washing proved to be the most effective and seems to open a new direction towards automation of fabrics washing. Although it was far more easy to clean fabric lab. No.32 than No.28, the extent to which the pressure hose could also clean the latter fabric was quite encouraging. With time, the fabrics became gradually tainted. However, the poor mechanical strength of lab. No.32 is a negative factor against suitability for long-term use in practice.

4. EXPERIMENTS - PHASE 3

4.1 Procedures and Analysis Methods

Reference should again be made to Table 3 in order to see the filter media composition and operational set-up of this phase of experiments. For the SSF units S2 and S3 operated at 0.15 m/h and the standard procedure of restart after cleaning was to run at a rate less than 0.10 m/h for one day prior to increasing it to 0.15 m/h. The unit S1 operated at 0.30 m/h but this was preceded by operation at less than 0.10 m/h and 0.20 m/h during the first and second day after restarting, respectively. During this phase, the maximum sludge blankets level was kept lower (i.e. 250 mm) in order to reduce floc carry-over.

The raw water, clarifier effluent and SSF filtrates were regularly sampled for measurement of the following water quality parameters:

(i) Temperature - by a mercury thermometer capable of registering temperatures ranging from -10 to +40°C. A minimum and maximum thermometer was also available.

(ii) pH - with a pH probe connected to a PTI-20 digital water analyser (Data Scientific, UK).

(iii) Turbidity - with a Hach turbidimeter model 2100A (Camlab, UK) measured in NTU.

(iv) Colour - both true and apparent colour were determined using a LBK Biochrom Ultrospec 4050, spectrophotometer at 400 nm wavelength according to reference (9). For the analysis of true colour the samples were subjected to filtration through an FG/C filter paper (Whatman Ltd., UK). The measurements were expressed in Hazen units.

(v) Bacteriological - Faecal coliform enumeration by membrane filtration technique using the Delagua field water testing kit, University of Surrey, Guildford, UK (8). Duplicates of each water sample were analysed and the average results used.

4.2 Hydraulic Performance

4.2.1 Filter runs

The end of filter runs were determined by the inability to maintain the designated filtration rate. Thus, in practice, the SSF units were left to run until the design filtration rate could not be maintained with a fully open valve. Table 8 gives the details of the filter runs obtained during this phase.

TABLE 8 : Filter runs summary

SSF UNIT	FABRICS COMPOSITION	FILTRATION RATE (m/h)	FILTER RUN TIME (days)	MEAN (days)
S1	2 Layers Fabric Lab. No.32 over 3 Layers Lab. No.28	0.3	Run 1: 13 Run 2: 13 Run 3: 19 Run 4: 21 Run 5: >8	16.5
S2	3 Layers Fabric Lab. No.28	0.15	Run 1: 13 Run 2: 20 Run 3: 34 Run 4: >10	22.3
S3	2 Layers Fabric Lab. No.32 over 3 Layers Lab. No.28	0.15	Run 1: 23 Run 2: 52	37.5

4.2.2 Filter headloss

Figures 26 through 34 give the filter headlosses for the main filter runs of the SSF units S1, S2 and S3. Clearly a comparison of the pattern of headloss shows pronounced differences between the top three manometer tubes for S1 on Figure 26 through 29. This is suspected to be linked up with more pronounced penetration of

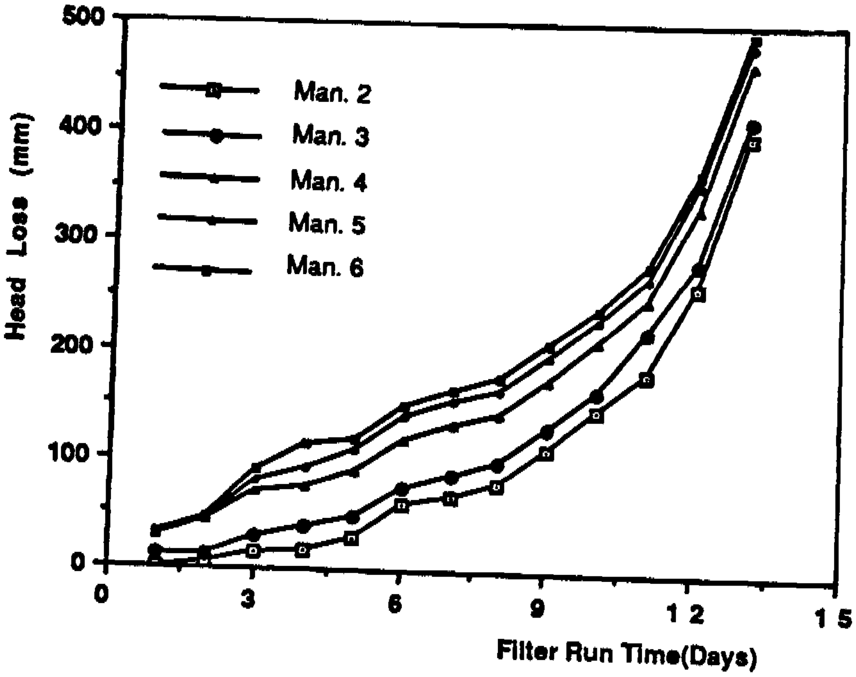

Fig. 26 S1 Filter Head Loss (Run 1) .

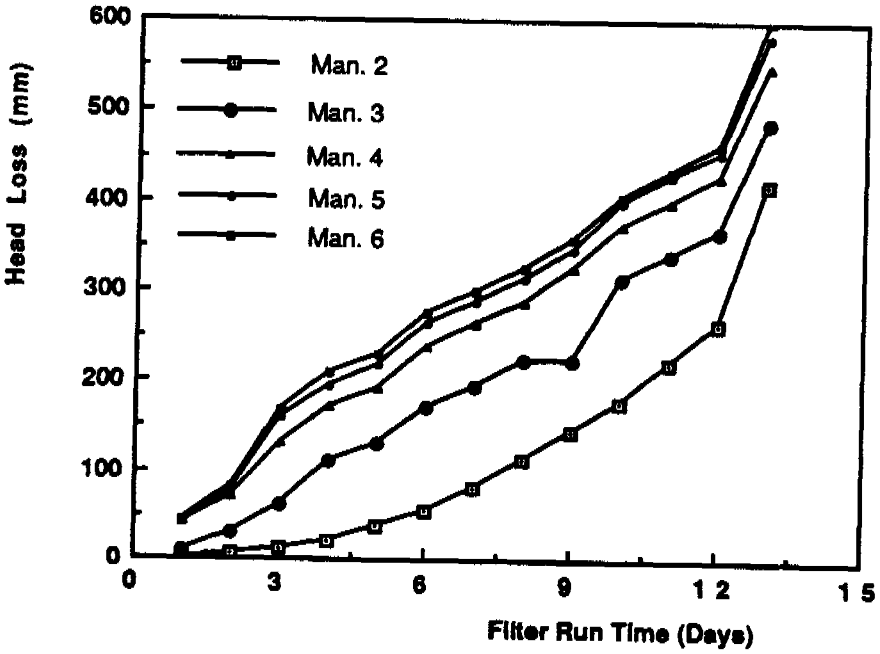

Fig. 27 S1 Filter Head Loss (Run 2) .

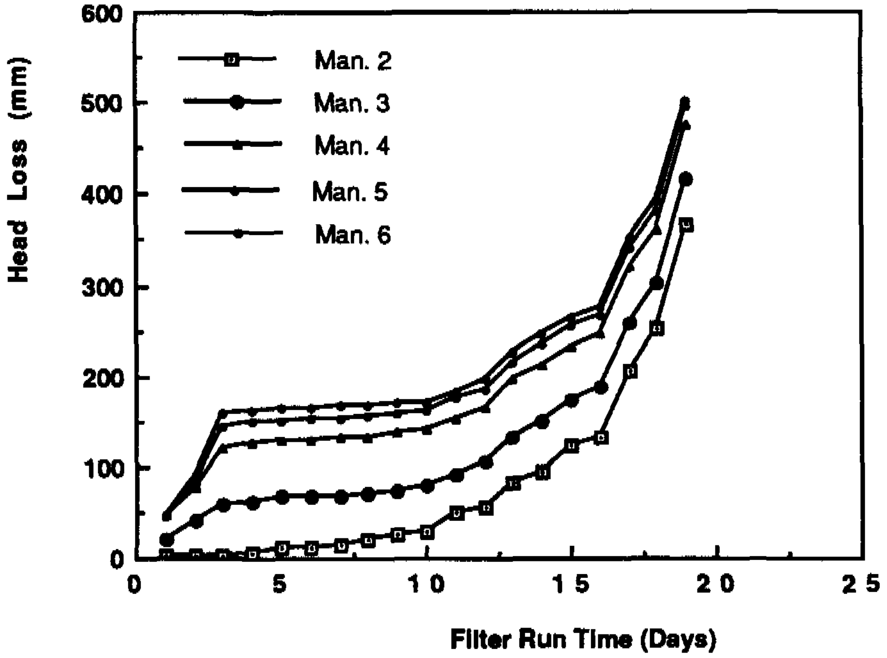

Fig. 28 S1 Filter Head Loss (Run 3) ·

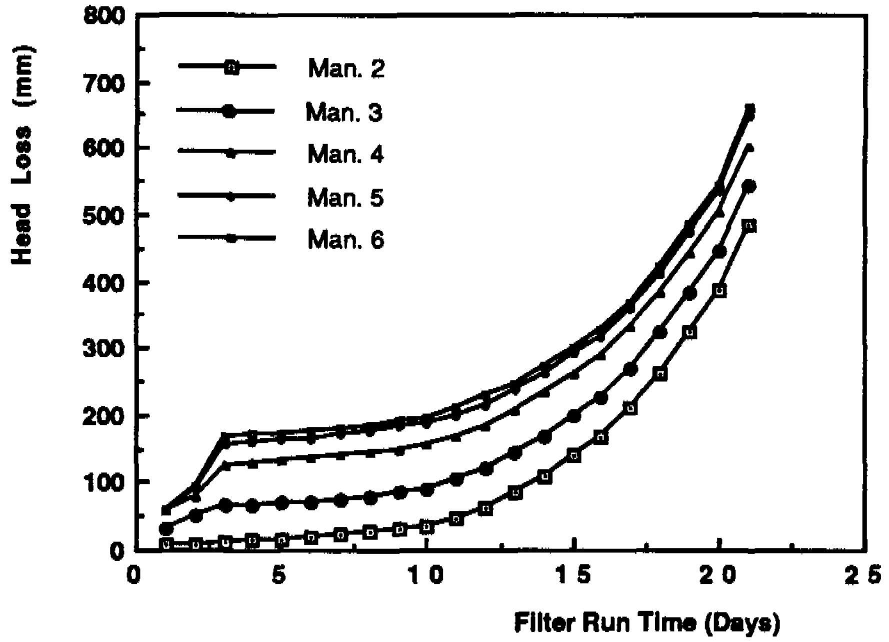

Fig. 29 S1 Filter Head Loss (Run 4) ·

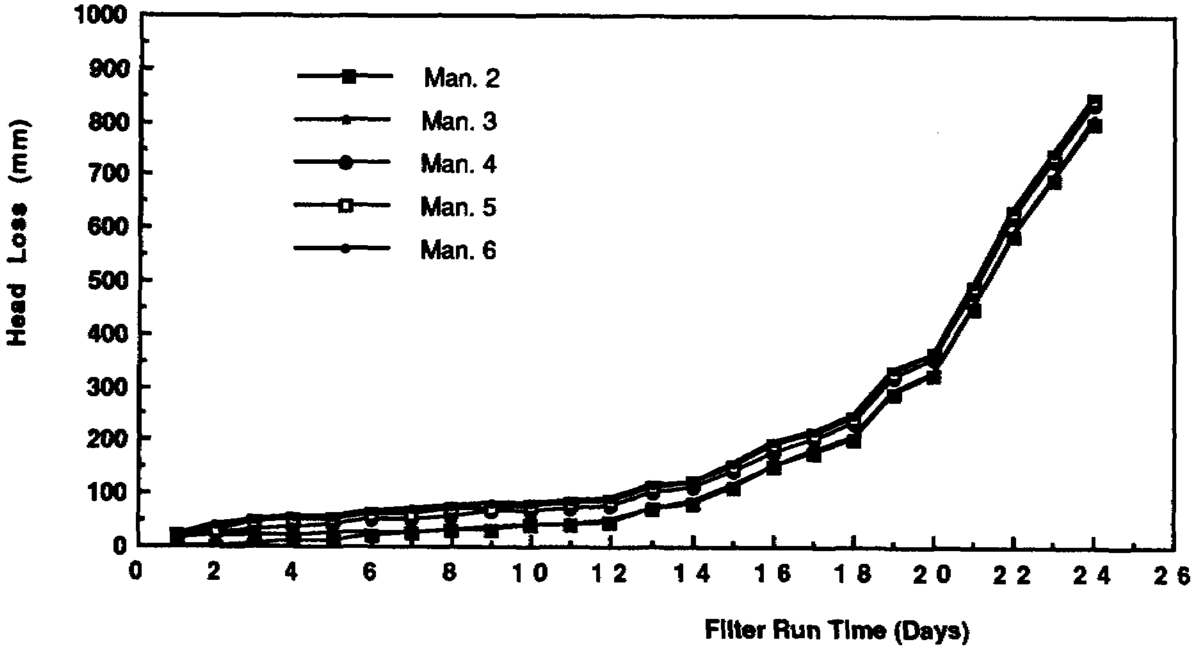

Fig. 30 S3 Filter Head Loss (Run 1) .

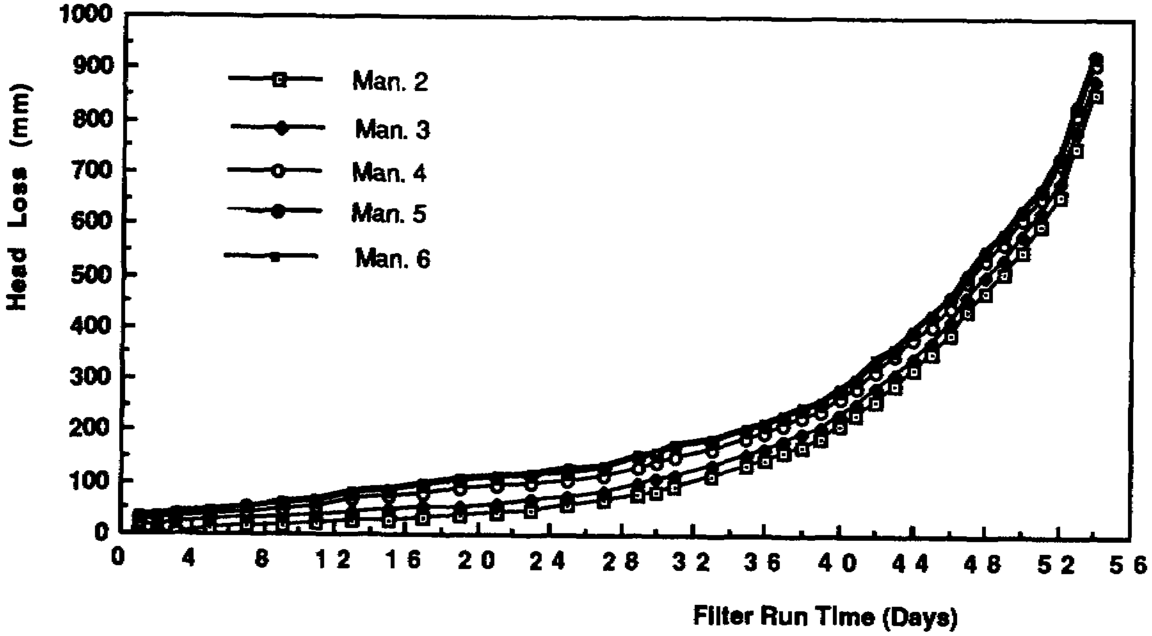

Fig. 31 S3 Filter Head Loss (Run 2) .

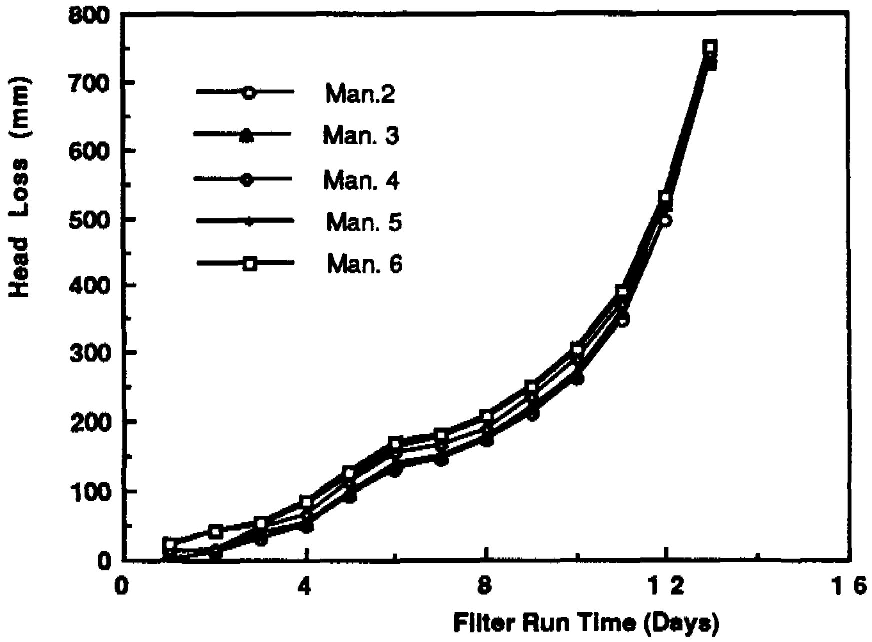

Fig. 32 S2 Filter Head Loss (Run 1) ·

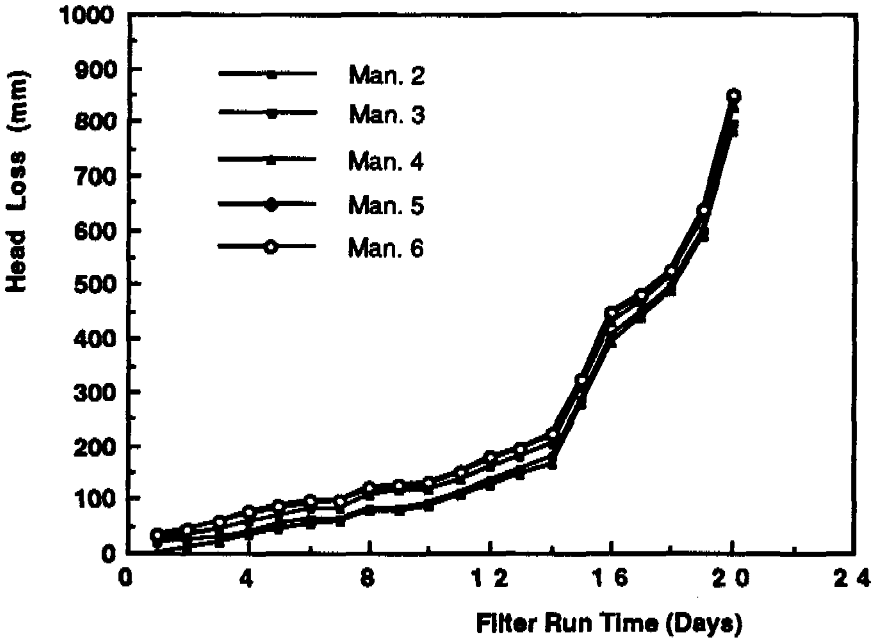

Fig. 33 S2 Filter Head Loss (Run 2) ·

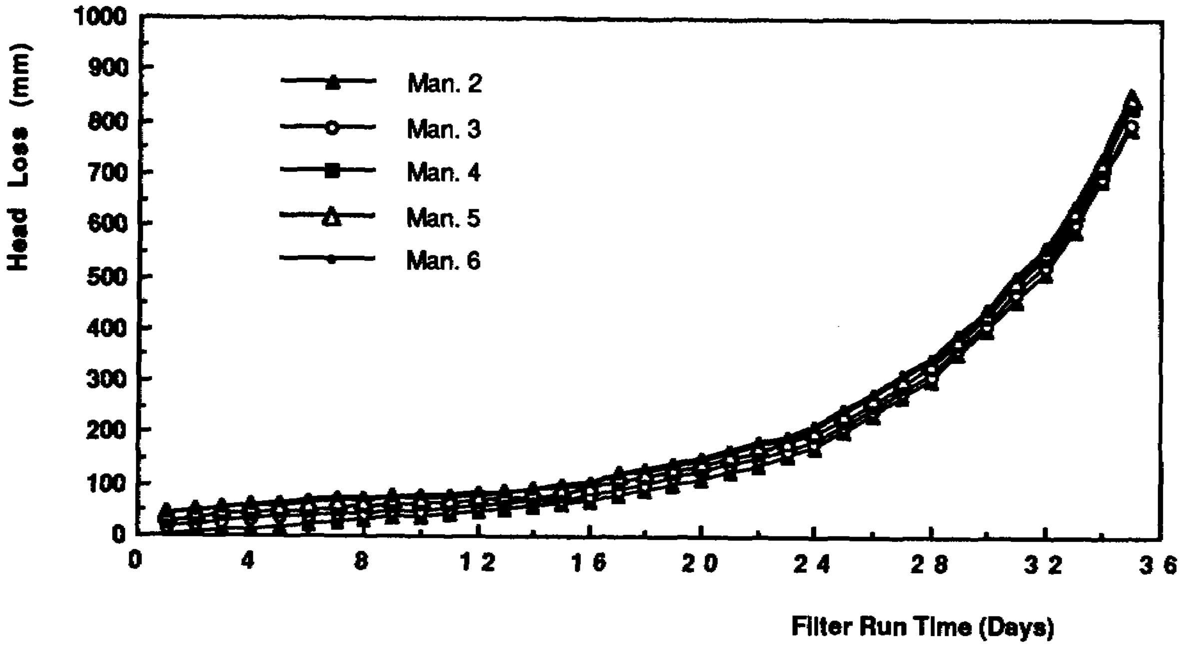

Fig. 34 S2 Filter Head Loss (Run 3).

impurities through the fabric layers probably as a result of operation at a filtration of 0.3 m/h. The filter headloss profiles of S2 and S3 do not show the differences depicted in the profiles of S1.

4.3 Water Quality Improvement/Changes

With respect to water quality parameters, the reference day for Phase 3 experiments is 13 May 1988. The last day of monitoring water quality parameters was on 8 August 1988.

4.3.1 Temperature

The SSF supernatant water temperature varied between 14°C and 18.5°C while the maximum ambient temperature varied between 13°C and 25°C. The variations in ambient and the filter supernatant temperatures are shown in Figure 35.

4.3.2 Turbidity

The raw water turbidity varied from 4.5 to 13.0 NTU while at the same time the clarifier effluent turbidity ranged from 0.5 to 2.9 NTU. In comparison to the previous phases the clarifier effluent turbidity was much lower possibly as a result of lowering the sludge blanket level and also a decrease in raw water turbidity as such. Figure 36 shows turbidity improvement in the clarifier. The average turbidity removed as a result of coagulation and upflow clarification was about 83%. Table 9 gives a summary of the SSF filtrate turbidity which indicates that the turbidity never exceeded 0.35 NTU at any time.

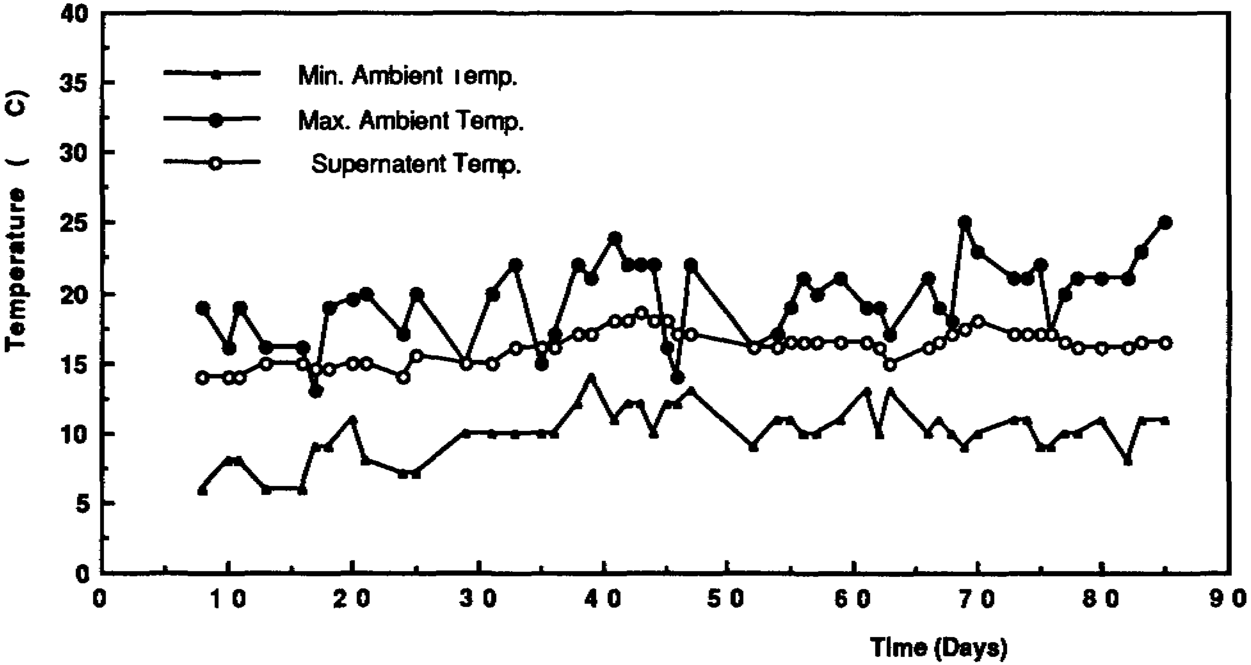

Fig. 35 Pilot Plant Temperature Variation.

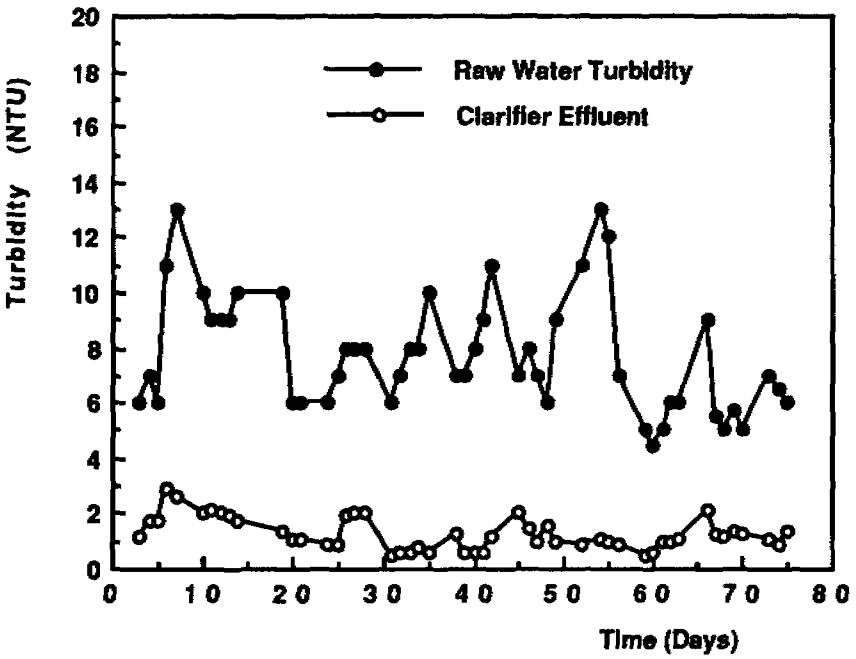

Fig. 36 Clarifiers Turbidity Removal.

TABLE 9 : SSF Filtrate turbidity

SSF UNIT	TURBIDITY RANGE (NTU)	MEAN (NTU)
S1	0.11 - 0.35	0.21
S2	0.12 - 0.35	0.22
S3	0.11 - 0.34	0.21

4.3.3 Colour

Variations in raw water and clarifier effluent true colour is shown in Figure 37. The raw water true colour varied from 4 to 16.4 Hazen units while the same for clarifier effluent ranged from 2.6 to 11.3 Hazen units. In general, coagulation and clarification reduced the true colour of raw water by 37%. SSF filtrates showed almost similar colour levels as seen in Table 10. The average colour removed in SSF was only 17%.

TABLE 10 : SSF Filtrate true colour

SSF UNIT	COLOUR RANGE (Hazen units)	MEAN (Hazen units)
S1	3.5 - 10.4	5.7
S2	1.9 - 8.6	5.4
S3	2.2 - 9.5	5.5

4.3.4 pH

The maximum, minimum and mean pH values of the raw water, clarifier effluent and SSF filtrates are given in Table 11.

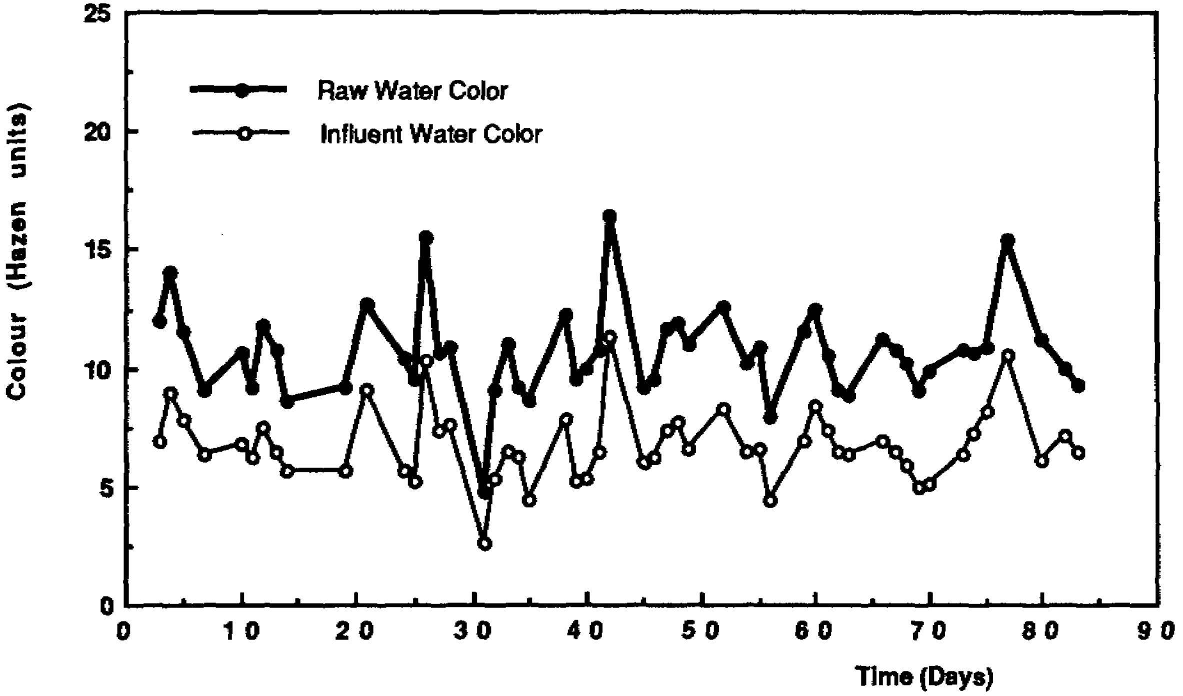

Fig. 37 Colour Improvement in the Clarifiers .

TABLE 11 : Water samples pH

SAMPLE	MAXIMUM	MINIMUM	MEAN
Raw water	8.7	7.6	8.1
Clarifier Effluent	8.2	7.4	7.7
S1 Filtrate	7.8	7.3	7.6
S2 Filtrate	7.9	7.3	7.6
S3 Filtrate	7.9	7.2	7.6

4.3.5 Bacteriological analysis

Faecal coliforms were enumerated from 2 June 1988 until 4 August 1988. Table 12 presents the faecal coliform counts of raw water, clarified effluent and SSF filtrates. Raw water faecal coliform counts ranged from 160 to 2300 per 100 ml. The pre-treatment stage improved the bacteriological quality by about 77% while SSF removed only 17% of the true colour. In general, the SSF filtrate bacteriological quality did not depend on the filtration rate.

TABLE 12 : Bacteriological analysis - faecal coliform counts

DATE OF SAMPLING	FAECAL COLIFORM PER 100 ml*									
	RAW WATER		INFLUENT WATER		SSF1		SSF2		SSF3	
	1	2	1	2	1	2	1	2	1	2
2/6/88	200	160	80	60	0	0	0	1	0	0
7/6/88	210	180	65	70	0	0	0	0	0	0
15/6/88	2100	1500	196	166	0	2	0	0	0	0
16/6/88	1890	1840	254	230	1	1	0	0	0	0
20/6/88	1000	920	170	194	0	0	-	-	0	0
23/6/88	960	700	114	108	0	0	0	0	0	0
27/6/88	920	1050	130	160	0	0	0	0	0	0
30/6/88	1800	2200	344	380	0	0	0	0	0	0
3/7/88	910	1020	250	300	0	0	0	0	0	0
7/7/88	850	880	290	276	-	-	0	0	0	0
11/7/88	350	400	210	178	1	0	0	0	0	0
14/7/88	480	740	126	135	0	0	0	0	0	0
18/7/88	620	780	330	312	0	0	0	0	0	0
21/7/88	380	620	210	156	0	0	0	0	0	0
25/7/88	240	180	78	72	0	0	0	0	0	0
27/7/88	2300	2200	540	484	0	0	0	0	0	0
1/8/88	1120	1150	168	178	0	0	0	0	0	0
4/8/88	1450	1730	526	550	0	0	0	0	0	0

* 1 and 2 represent the first and second samples enumerated

5. DISCUSSION

The results of the experimental work carried out in phases 1 and 2 have clearly demonstrated that the presence of a 25 mm layer of fabric on a conventional SSF can increase the filter run time by a factor of between 3.1 and 4.4, depending on the type of fabric. A 14.4 mm thickness of lab. No.28 fabric was found to extend the filter run time by a factor of 2.7. Clearly, this work has demonstrated that it is possible to select a suitable fabric type(s), thickness and configuration for the protection of conventional SSF beds. Thus, the filter run time has been further extended (65%) by a combination of a basic thickness of a selected fabric below a layer of very porous fabric. However, a doubling of the filtration velocity to 0.30 m/h was found to lead to a reduction in filter run time by a factor of 2.3.

During phase 1, only lab. No.28 fully protected the sand bed by capturing most of the impurities in the fabrics. Although substantially extending the SSF run time, lab. No.32 failed to protect the sand bed from penetration by impurities. During phase 2, the large majority of the filter headloss was recorded across the fabrics in all units, indicating very little penetration into the sand. Thus, it is clear that virtually all the influent turbidity is retained within the fabric and that, as a consequence, filter cleaning only concerns the fabric(s) and does not involve sand scraping.

Throughout the experimental period the filtrate quality from the three SSF units were invariably consistent. This was not unexpected since the quality performance through a conventional SSF is so high that possible additional improvements arising from the presence of fabrics are not likely to be discernible.

Overall, this study has demonstrated that a fabric protected SSF can cope with poorly operated pretreatment units which allow substantial amounts of unsettled flocs to be carried over to the SSF. These types of problems are not unusual in most developing countries with SSF preceded by chemical pre-treatment (11). The poor ability of SSF to remove colour which has been demonstrated means that the use of chemical pre-treatment in conjunction with SSF is necessary for highly coloured water sources.

As a rapid method of improving the performance of overloaded SSF, the application of fabrics is very simple, relatively cheap and very efficient. The UK price of synthetic fabrics is considered to be in the range of £2 to £6 per m^2, but final costs are very difficult to estimate and it may be possible to use local fabrics provided they have the necessary properties. Such fabrics can be applied directly to the surface of existing SSF but experience so far has only considered SSF units of bed areas up to 30 m^2. It is possible that handling problems might arise when applying fabrics to SSF units of greater bed area.

Although this investigation has shown that the application of fabrics to SSF units treating coagulated water leads principally to benefits of reliability in treated water quality and the avoidance of sand washing, potential economic benefits lie in being able to significantly reduce the depth of the SSF, and thus the capital cost. This has yet to be quantified and current work by Brian Clarke of Kingston Polytechnic, in association with Dr Nigel Graham, is investigating this aspect.

6. CONCLUSIONS

The following conclusions can be drawn on the basis of the work done during phase 1 , 2 and 3 of this research programme:

(i) Properly designed layers of NWF can protect conventional SSF beds from excessive clogging when filtering water with substantial floc carry-over.

(ii) The very porous fabric lab. No.32 was found to be unsuitable for protection of SSF sand beds on its own due to penetration of impurities during filtration and sloughing of deposited impurities upon lifting during cleaning.

(iii) There were very few differences in the extent of protection of the sand bed by 5 or 3 layers of lab. No.28.

(iv) The combination of multiple layers of NWF lab. No.32 and lab. No.28 (total thickness 40.4 mm) was found to be the best for filtration of clarifier effluent with a lot of floc carry-over at both 0.15 and 0.30 m/h.

(v) A NWF protected SSF bed can cope well with poorly operated pre-treatment units.

(vi) Increasing the filtration rate from 0.15 m/h to 0.30 m/h did not result in deterioration of quality of the filtrate of fabric protected SSF, but run times were significantly decreased.

(vii) While SSF alone reduced true colour by 17%, the combination of coagulation, upflow sludge blanket clarification and SSF reduced the true colour by 54%.

7. REFERENCES

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ADDITIONAL INFORMATION (Requested by ODA)

1. Cost of Fabrics

The attached Table 13 gives the 1985 prices of typical NWF commercially available in the UK market. It can be observed that at that time the prices ranged from £0.21 to £6.30 per m^2. While the price of fabric lab. No. 28 was £1.5, the price of lab. No. 32 was £5.2 per m^2.

2. Method of Fabric Washing

2.1 In general, since the SSF units used were fairly small (i.e. less than $3m^2$), the removal of the fabrics did not present any substantial difficulties. Two methods were employed in removal of the fabrics. The first involved manual lifting of the NWF layer immediately after water has been drained down to a depth of about 10 cm below the top level of the sand bed. Although this method had the advantages of reduced down time, its shortfall is the difficulty of handling the heavy weight of the impurities captured in the fabrics when still wet. For bigger SSF, the NWF will have to be placed in strips which are not too heavy to lift manually at the end of the filter run times. In this case, if the NWF layer is not properly designed, the chances of sloughing of materials into the sand underneath are bigger.

The second method involved leaving the SSF unit to drain down overnight such that the following day, the deposited material became semi-dry and formed a thin layer on the top NWF layer. The NWF became much easier to lift manually (or even rolling) under these circumstances. However, the longer down time of the SSF units would be the main disadvantage of this approach. It should be noted that although fabric cleaning was investigated during this study, the handling and cleaning of the NWF protecting huge SSF beds (say about 100 m^2 per bed) is a subject for further investigations. Where possible, the feasibility of application of mechanized in-situ cleaning should be studied. It is felt that since there is no contact between the cleaning accessories and the sand, mechanisation might prove to be more popular than manual cleaning in industrialised countries.

2.2 Experience from field tests showed that although high pressure water was the most reliable for cleaning the fabrics at the end of the filter runs, the use of low flow velocity water accompanied with superficial brushing is also acceptable. However, if hydraulic rams are available, they can be used to pump water into a storage tank located on an elevation or a riser. This would be only possible where the quantity of water in the river source is sufficient for installation of the hydraulic rams. Otherwise, the raw water pump(s) can be used to fill a storage tank also located at a high level when the water is required for cleaning the fabrics. It should be noted that one does not need to use filtered water to clean to NWF, raw water is quite suitable for this purpose. The use of a low flow velocity water would have to be considered only for NWF with very sound mechanical characteristics as otherwise prolonged brushing can wear the fabric surface.

Table 13 NON-WOVEN FABRIC SAMPLES CHARACTERISED.

SUPPLIER NUMBER	LAB. NUMBER	FIBRE POLYMER COMPOSITION	PRODUCTION TECHNIQUE	(d) APPR. FIBRE DIAMETER (μm)	(t) AVR. FABRIC THICKNESS (mm)	$[\rho_f]$ FIBRE SPEC. GRAVITY	$[\rho_b]$ AVR. FABRIC BULK DENSITY (g/cm^3)	$[1 - \rho_b/\rho_f]$ CALCULATED POROSITY (%)	[A] SPEC. SURF. AREA PER SQ. MTR. (m^2)	[S] SPEC. SURFACE AREA PER CU. MTR. (m^2)	1985 PRICE PER SQ. MTR. FABRIC (p)	1985 PRICE PER CU.MTR. FAB. (£)
1	11	PE	NF - SB	27.3	1.5^{-}	1.38	0.100	93	15.93	10, 620	–	–
	12	PE	NF - SB	27.3	1.9^{-}	1.38	0.111	92	22.30	11, 737	–	–
	13	PE	NF - SB	27.3	2.3^{-}	1.38	0.117	92	28.67	12, 465	–	–
	14	PE	NF - SB	27.3	2.8^{-}	1.38	0.121	91	36.10	12, 893	–	–
	15	PE	NF - SB	27.3	4.4^{-}	1.38	0.125	91	58.40	13, 273	–	–
2	21	PP	NF - CT	29	4.4^{**}	0.91	0.070	93	27.6	10, 568	120	462
	22	PP	NF - CT	33	4.4^{*}	0.91	0.087	90	51.2	11, 625	140	318
	23	PP	NF - CT	33	4.4^{*}	0.91	0.080	91	46.8	10, 626	135	307
	24	PP	NF - CT	33	4.4^{*}	0.91	0.106	88	61.9	14, 077	150	341
	25	PP	NF - CT	48	4.1^{*}	0.91	0.116	87	43.4	10, 609	200	488
	26	PP	NF - CT	48/100	6.0^{**}	0.91	0.182	80	74.8	10, 833	350	583
	27	PP	NF - CT	33	3.6^{**}	0.91	0.108	88	51.95	14, 431	150	417
	28	PP	NF- CT	33	4.8^{**}	0.91	0.100	89	63.4	13,266	150	313
3	31	PE/PVC	RSPB$^{(x)}$	50/40	9.0	1.38/1.392	0.0178	99	9.9	1, 100	240	267
	32	PE/PVC/PA	2SPB$^{(x)}$	50/40/40	13.0	1.38/1.39/1.14	0.0257	98	23.4	1, 671	520	372
	33	PE/PVC	R3PB$^{(x)}$	50/40	20.0	1.38/1.392	0.026	98	22.3	1, 115	630	315
4	41	PP	NF - TB	27.9	0.6	0.91	0.167	82	15.76	26, 267	35	583
	42	PP	NF - TB	27.9/30.5	0.95	0.91	0.147	84	23.92	25, 179	39	411
	43	PP	NF - TB	27.9/30.5/41.4	1.2	0.91	0.192	79	31.66	26, 381	58	483
	44	PP	NF - TB	27.9/30.5/41.4	1.3	0.91	0.231	75	43.21	33, 238	76	585
	45	PP	NF	27.9/30.5/41.4	3.2	0.91	0.094	90	43.21	13, 504	85	266
5	51	PP/PET	TB	40	0.4^{+}	0.90/0.92	0.175	81	6.2	15, 500	29.9	748
	52	PP/PET	TB	40	0.5^{+}	0.90/0.92	0.200	78	8.8	17, 600	35.3	706
	53	PP/PET	TB	40	0.7^{+}	0.90/0.92	0.200	78	12.4	17, 714	39.8	587
	54	PP/PET	TB	40	0.8^{+}	0.90/0.92	0.238	74	16.8	21, 000	< 100	<1250
	55	FP/PET	TB	40	1.0^{+}	0.90/0.92	0.230	75	20.3	20, 300	70.7	707

Table 13 NON-WOVEN FABRIC SAMPLES CHARACTERISED (Contd.)

SUPPLIER NUMBER	LAB. NUMBER	FIBRE POLYMER COMPOSITION	PRODUCTION TECHNIQUE	(d_f) APPR. FIBRE DIAMETER (μm)	(z) AVR. FABRIC THICKNESS (mm)	$[\rho_f]$ FIBRE SPEC. GRAVITY	$[\rho_b]$ AVR. FABRIC BULK DENSITY (g/cm^3)	$[1-\rho_b/\rho_f]$ CALCULATED POROSITY (%)	[A] SPEC. SURF. AREA PER SQ. MTR. (m^2)	[S] SPEC. SURFACE AREA PER CU. MTR. (m^2)	1985 PRICE PER SQ. METRE FABRIC (p)	1985 PRICE PER CU.MTR. FAB. (£)
5	56	PP/PET	TB	40	1.2$^+$	0.90/0.92	0.233	74	24.7	20, 583	< 100	<1250
	57	PE	NF	30	1.5$^+$	1.38	0.140	90	20.3	13, 533	52	347
	58	PE	NF	30	2.0$^+$	1.38	0.145	90	28.0	14, 000	67	335
	59	PE	NF	30	2.5$^+$	1.38	0.140	90	33.8	13, 520	96	384
6	61	PE/PVA	RSPB(CB)	39.6	15.0	1.38/1.19	0.0387	97	38.17	2, 545	280	187
	62	PP/PE	TB	21.6/17.6	7.0	0.91/1.38	0.0286	98	36.83	5, 261	530	757
7	71	PP	SB	55.5/39.2	0.36$^+$	0.91	0.189	79	6.1	16, 944	21	583
	72	PP	SB	- do -	0.40$^+$	0.91	0.225	75	8.1	20, 250	26	650
	73	PP	SB	55.5/39.2	0.45$^+$	0.91	0.249	73	10.1	22, 444	31.5	700
	74	PP	SB	- do -	0.48$^+$	0.91	0.283	69	12.3	25, 625	35.5	740
	75	PP	SB	55.5/39.2	0.49$^+$	0.91	0.306	66	13.5	27, 551	43.5	887
	76	PP	SB	- do -	0.53$^+$	0.91	0.321	65	15.3	28, 868	-	-
	77	PP	SB	55.5/39.2	0.56$^+$	0.91	0.339	63	17.1	30, 536	51.5	920
	78	PP	SB	- do -	0.63$^+$	0.91	0.365	60	20.7	32, 857	55.0	873
	79	PP	SB	55.5/39.2	0.71$^+$	0.91	0.394	57	25.3	35, 634	70.0	986
	80	PP	SB	- do -	0.72$^+$	0.91	0.403	56	26.1	36, 250	74.0	1028

LEGEND:

PP = Polypropylene
PA = Polyamide
PE = Polyester
PET= Polyethylene
PVA= Poly-Vinyl-Acetate
PVDC=Poly-Vinyldine-Chloride
PVC = Poly-Vinyl-Chloride

RSPB= Resin spray-bonded
NF-CT = Needle-felted on carrier thread
NF = Needle - felted
SB = Spun - bonded
RB = Resin bonded
TB = Thermic bonded
(x)= Acrylate PVDC binder

* = By dial gauge
** = Measured at IC Laboratory.
+ = At 2.0 KN/m^2 load
\- = At 5.0 KN/m^2 load
p = Pence
S =(A/z) m^2/ m^3