Performance of Fabric-Protected Slow Sand Filters Treating a Lowland Surface Water

By T. S. A. MBWETTE, BSc, DipSE, MSc, PhD, DIC*, M. A. R. STEITIEH, BSc (Eng), MSc, DIC**, and N. J. D. GRAHAM, MA, MSc, PhD, DIC, CEng, MICE *(Member)****

ABSTRACT

The performance of slow sand filtration can be substantially improved by the application of a non-woven synthetic fabric layer to the surface of the sand. By means of pilot-scale experiments, using the River Thames as the source water and pretreatment by sludge blanket clarifiers, the comparative performance of fabric-protected slow sand filters has been evaluated over an eight-month period. Under conditions designed to simulate poorly-controlled pretreatment, a correctly-specified fabric type, configuration and thickness can extend filter run times by a factor of 3–5 compared to a conventional slow sand filter. Furthermore, this can be achieved, together with the avoidance of any significant change in the hydraulic behaviour of the underlying sand, thereby avoiding the need to remove and clean sand. Fabric washing is relatively simple and efficient.

Key words: Filtration; non-woven fabric; slow sand filter.

INTRODUCTION

Slow sand filtration is an important process of drinking water treatment which can produce water of a very high quality, provided that the process is operated properly and that 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. 0.1–0.2 m/h, they can achieve a 90% reduction in turbidity and a 90–99% reduction in faecal coliform concentrations. Thus, to achieve a water quality approaching World Health Organization (WHO) standards, the influent turbidity and faecal coliform concentrations should not exceed 10 NTU and 100 organisms/100 ml, respectively. 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%[1,2]. Therefore, 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 high proportion of the direct operational costs for slow sand filters (over 70% estimated by Thames Water[2]) are associated with filter cleaning and resanding. It is clear, therefore, that any modification of the process which 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[3].

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[4] has reported 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.

*Lecturer, Dept. of Civil Engineering, University of Dar es Salaam, Tanzania.

**P.O. Box 7083, Amman, Jordan.

***Senior Lecturer, Dept. of Civil Engineering, Imperial College, London.

NON-WOVEN SYNTHETIC FABRICS

It is well-known that the process of purifying contaminated influent waters by slow sand filters is principally localized in the top 20–30 mm 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 treatment process within the fabric layer, instead of within the top layers of the sand. The reason for this is that the structural properties of non-woven fabrics offer a considerably more efficient filtration medium than sand, and the speculated benefits are two-fold:

(*a*) 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 from short duration peaks in influent suspended-solids concentrations; and

(*b*) The simplification of the filter cleaning by the removal and washing of the fabric alone.

The structural properties of non-woven synthetic fabrics which can easily be measured or calculated are the porosity, mean fibre diameter and specific fibre surface area; these properties, in particular, determine the filtration performance and permeability of the fabric medium. Theoretically, it can be shown that all three properties are interrelated and that the filtration efficiency of a fabric (in the absence of biological effects) is principally dependent on the specific surface area[5]. Laboratory tests[5] have also shown that the permeability of (clean) non-woven fabrics increases greatly with their porosity, approximately in accordance with Happel's cell model for fibrous media[6].

OBJECTIVES

The general aim of the research study was to quantify the performance benefits of protecting slow sand filters with a non-woven synthetic fabric layer when treating coagulated and settled raw river water. In particular the work was designed to simulate the typical problem of variability in clarifier performance, which results in floc carry-over on to the slow sand filters, as well as to examine alternative specifications for the fabric layer.

The research was based on pilot-plant experiments undertaken at the Egham water treatment works of the North Surrey Water Company. The pilot plant was assembled and commissioned during the first six months of the project, and operated continuously over 9 months (December to August) to include seasonal changes in the raw water – the River Thames; the quality of the river varies considerably during each year.

The specific 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 coagulant dosing, two upflow sludge blanket clarifiers and three slow sand filter units;

(ii) To operate the plant with one filter unit initially as a reference (with no fabric), and the other two units with different types of fabric protection – to compare treatment performances in terms of filter run times and filtrate water quality;

(iii) To assess the ability of various fabric arrangements to prevent solids penetration into the top of the sand layer of the filter; and

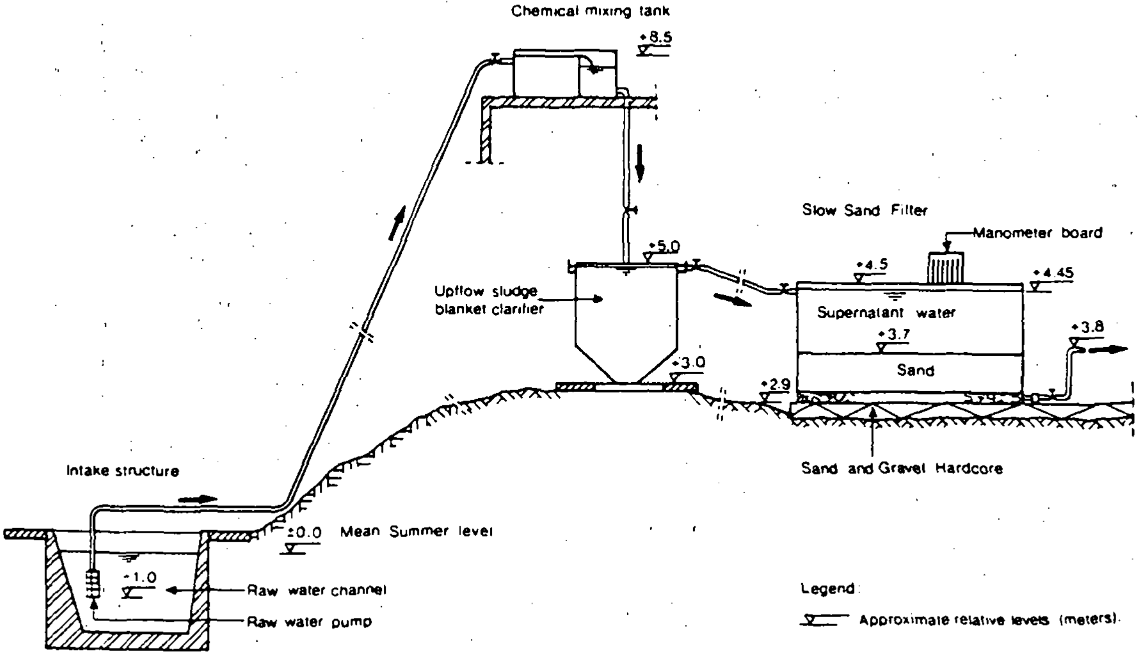

Fig. 1. Schematic hydraulic profile of Egham pilot plant

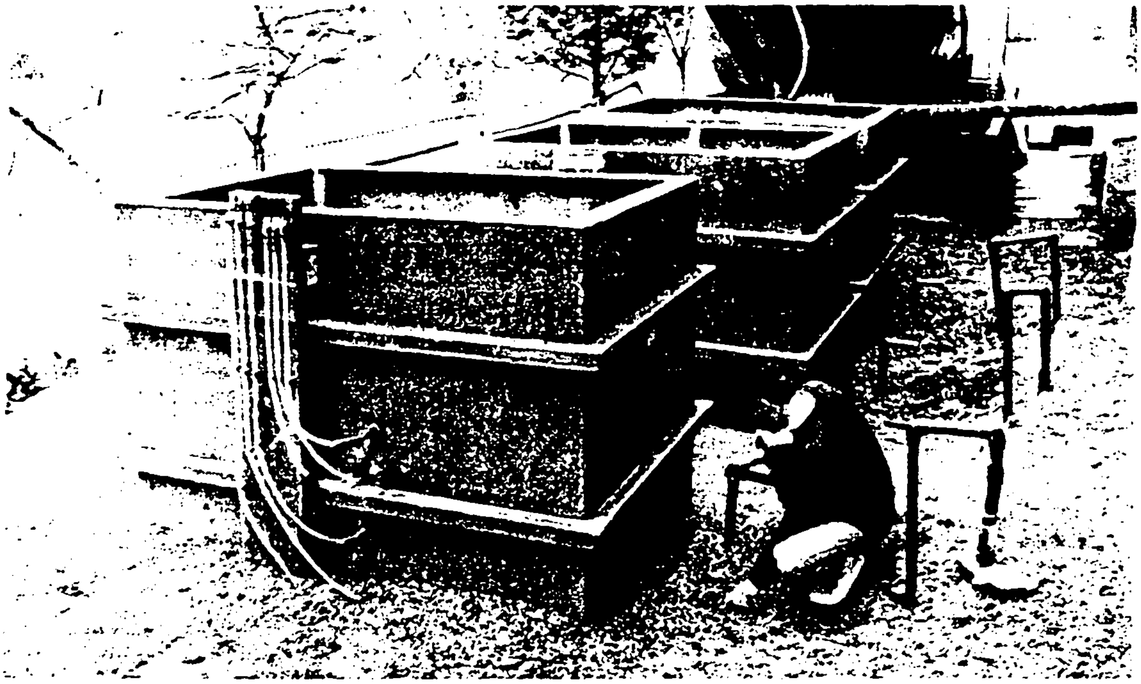

Fig. 2. Pilot-scale slow sand filter units

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

PILOT PLANT

A schematic hydraulic profile of the Egham pilot plant is shown in Fig. 1. A vortex impeller submersible pump was used to abstract raw water from the Egham main works' intake (which draws water from the River Thames), and to discharge the flow into a mixing tank located at a height of about 5 m above ground level. A 10% strength (wt/wt as Al_2O_3) polyaluminium chloride (PAC) solution was dosed into the mixing tank downstream from a 60° V-notch weir in correct proportion, to coagulate impurities in the raw water. From the mixing tank, the coagulated water passed into two, conical, 1 m diam., upflow sludge blanket clarifiers (designated C1 and C2) whose design is described elsewhere[7]. The clarifiers were operated in parallel under steady flow conditions in such a way as to encourage some floc carry-over into the subsequent slow sand filter units by means of raising the top of the sludge blanket close to the clarified water overflow level. The combined clarified flow was then led into three parallel operated filter units (Fig. 2) (designated S1, S2 and S3) provided with identical sand media composition. Fig. 3 shows a typical cross section of the filter units installed in the pilot plant. The filter units measured 1.8 m × 1.2 m × 1.6 m, and each unit was provided with an underdrainage system comprising perforated PVC pipes within a 200-mm layer of pea gravel. Each filter unit contained six manometer tubes, for head-loss measurement, located individually at 50 mm above the sand bed (No. 1), at the top level of sand (No. 2), and then successively at 50 mm (No. 3), 200 mm (No. 4), 500 mm (No. 5) and 700 mm (No. 6) below the top level of sand, respectively. The filtrate from the filter units was subsequently led to waste.

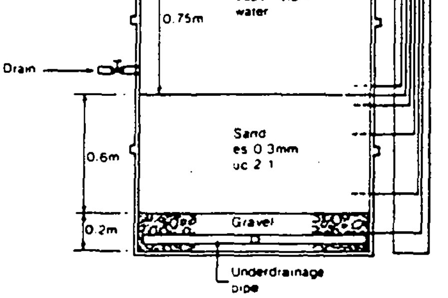

Fig. 3. Cross-section of slow sand filter units

TABLE I. Principal Characteristics of Fabrics

Fabric no.	28	32	Remarks
Fibre composition	PP	PE/PVC/PA	
Fibre diameter (μ)	33	50/40/40	from supplier
Nominal fabric thickness (mm)	4.8	14.0	measured
Fabric porosity (%)	89	98	calculated
Specific surface area (m^2/m^3)	13 266	1671	calculated

PP = Polypropylene PE = Polyester PVC = Polyvinyl chloride PA = Polyamide

Filter Media and Fabrics

Each filter unit was provided with a depth of 600 mm of sand having an effective diameter* of 0.30 mm and a uniformity coefficient† of 2.1. On the basis of experience gained earlier in different pilot-plant studies[7], only two fabrics (i.e. fabrics No. 28 and 32) were used during this study. Table I lists the principal characteristics of these fabrics. Fabric No. 28 has properties which lie in the mid-range of various commercial fabric materials which have been previously studied[5], and fabric No. 32 represents a high-porosity material which has a relatively low specific surface area.

Raw Water Quality

Table II gives the physicochemical and bacteriological quality of River Thames water at the Egham works' intake during the period 1984–1987[8–10]. Although the mean turbidity and colour values are not very high, the periodic fluctuations are quite pronounced with maximum/mean ratios of 8 : 5 : 1 and 3 : 5 : 1, respectively. With regard to the bacteriological quality, the maximum recorded values indicate that the river can be highly polluted. From 1986 to August 1988 the total organic carbon (mg/l as C) of the raw water was 2.66–5.07, with a mean value of 4.01.

CONDUCT OF EXPERIMENTS

The investigations were carried out in three phases during which the filter fabrics and/or the operational conditions of the filter units were changed. Details of the three phases are shown in Table III. With the exception of one of the filters in the final phase, all the filters were operated at a filtration velocity of 0.15 m/h. In phase 1, the performance of two fabric protected filter units, with approximately equal total fabric thicknesses but different fabric properties, was compared to a conventional reference unit. In phase 2, the effect of decreasing the total thickness of fabric No. 28 was considered, together with the possible benefits of combining the two types of fabric. Thus, the configuration of two layers of fabric No. 32 over three layers of fabric No. 28 in unit S3 was proposed as combining the high porosity/low filtrability of fabric No. 32 with the higher filtrability/lower porosity of fabric No. 28.

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*sieve-opening size corresponding to 10% of sand passing through.
†ratio of sieve size for 60% of sand passing through divided by sieve size of 10% passing through.

TABLE II. Water Quality of River Thames at Egham Intake 1984–1987

Parameter	Recorded range		
	Maximum	Minimum	Mean
Turbidity (JTU)	97	1.8	11.4
pH	8.9	7.4	8.0
Conductivity (μs/cm)	700	520	624
Nitrate (as N) (mg/l)	15.7	4.3	8.4
Nitrite (as N) (mg/l)	0.23	0.01	0.07
Amm. N (mg/l)	1.02	<0.01	0.15
Colour (Hazen units)	46	3	13
Chloride (as Cl) (mg/l)	59	29	40.5
Sulphate (as SO_4) (mg/l)	72.2	48.2	61.4
Permanganate oxidizability (as O_2) (mg/l)	9.7	1.0	3.3
Dissolved oxygen saturation rate (%)	129	62	97.5
Phosphorus (as P) (mg/l)	2.14	0.32	1.04
Dissolved iron (as Fe) (μg/l)	677	10	70
Manganese (as Mn) (μg/l)	46	<5	9.5
Coliform bacteria (No./100ml)	310 000	800	n/a
E. coli bacteria (No./100 ml)	20 000	<25	n/a

n/a – not available.

TABLE III. Composition and Filtration Velocity of Fabrics for Programme of Tests

Filter unit	Fabric specification		
	Phase 1 (30.12.87–08.3.88)	Phase 2 (08.3.88–07.5.88)	Phase 3 (13.5.88–06.8.88)
S1	5 × No. 28 (t = 24, v = 0.15)	5 × No. 28 (t = 24, v = 0.15)	2 × No. 32 over 3 × No. 28 (t = 40.4, v = 0.3)
S2	2 × No. 32 (t = 26, v = 0.15)	3 × No. 28 (t = 14.4, v = 0.15)	3 × No. 28 (t = 14.4, v = 0.15)
S3	No Fabric (v = 0.15)	2 × No. 32 over 3 × No. 28 (t = 40.4, v = 0.15)	2 × No. 32 over 3 × No. 28 (t = 40.4, v = 0.15)

t – total thickness of fabric layer (mm).
v – filtration velocity (m/h).

In phase 3, units S2 and S3 continued unchanged from phase 2 to extend the period of performance data to include the spring and summer conditions. In addition, the fabric arrangement in unit S1 was replaced with the same combination of fabrics No. 32 and No. 28 as unit S3, but the filtration velocity was increased to 0.3 m/h.

During the operation of the pilot plant the PAC dose was not routinely optimized, since the intention was to simulate poorly-controlled operational conditions whereby significant floc carry-over might occur. Thus, the PAC dose was generally held constant, except for occasions when the dose needed to be altered in response to instability in the sludge blankets. As a result, during this study, while the average PAC dose was 6.0 mg/l (as Al_2O_3), overall it was varied from 4 mg/l to 10 mg/l (as Al_2O_3).

Initial investigations of the surface overflow rates indicated that optimal operation of the clarifiers was possible at upflow velocities ranging from 1.7 m/h to 2.0 m/h. During phases 1 and 2 the top of the sludge blanket was set at 100 mm below the base of the V-notch weirs located on the inner edge of the collection channel, to ensure excess floc carry-over into the filter units. However, since unit S1 was to be operated at a higher filtration rate during phase 3, the top of the sludge blanket was lowered to a depth of 250 mm for phase 3, to reduce the amount of floc carry-over and thereby avoid short filter run times in unit S1.

The filter head losses were monitored daily for all the filter units. The raw water, clarified water and filtered water were regularly sampled for turbidity, colour and bacteriological analyses. Turbidity was measured in NTU with a Hach, model 2100A turbidimeter (Camlab, UK). True colour was determined by absorbance using an LBK Biochrom Ultrospec 4050 spectrometer at a wavelength of 400 nm, and faecal coliforms were enumerated by membrane filtration using the Delagua field water testing kit[11].

CLEANING OF FABRICS

At the end of the filter runs the fabrics were cleaned with high-pressure water passing over the fabric surface; this method of washing proved to be the most effective. Although it was more easy to clean fabric No. 32 than No. 28, the extent to which the pressure hose could also clean the latter (more dense fabric), was encouraging. However, with time, the fabrics became gradually tainted. The poor mechanical strength of fabric No. 32, and its consequent deterioration with repeated washings, is a negative factor against its suitability for long-term use in practice.

RESULTS

HYDRAULIC PERFORMANCE

Filter Run Time

Table IV is a summary of the filter run times of the filter units during the three phases of field tests which were investigated. It can be observed that, in general, the filter run times of phase 3 were longer than the other two phases. This was largely due to the reduction of floc carry-over from the clarifiers, brought about by the lowering of the top sludge blanket level during phase 3.

The results of the phase 1 investigations showed that the filter run times of the two fabric-protected units were much longer than the conventional unit, which had short run times (~4.5 days) reflecting the significant turbidity which was present in the clarified influent water. The presence of five layers of fabric No. 28 in unit S1 increased the mean filter run time by a factor of 3.1, while two layers of fabric No. 32 in unit S2 increased the run time by a factor of 4.4. However, there was significant penetration of impurities through the layers of fabric No. 32 into the top of the underlying sand. This fact, together with subsequent sloughing of deposited material from the fabric into the sand bed when lifting the

TABLE IV. FILTER RUN TIMES

Filter Unit	Successive filter run times (h)		
	Phase 1	Phase 2	Phase 3
S1	552*, 245, 416, 164* mean 331 h (13.8 days)	281, 354, 331 mean 322 h (13.4 days)	312, 312, 456, 504 mean 396 h (16.5 days)
S2	522*, 444, 505, 116* mean 475 h (19.8 days)	209, 332, 295, 278 mean 279 h (11.6 days)	312, 480, 816 mean 536 h (22.3 days)
S3	284*, 119, 96, 115, 70* 120, 93, 118, 68*, 92 mean 108 h (4.5 days)	631, 528 mean 580 h (24.2 days)	552, 1248 mean 900 h (37.5 days)

*not used for evaluation of mean run times.

fabric for cleaning, seriously questions the suitability of fabric No. 32 for protecting slow sand filters. Occasionally, excess carry-over of flocs into the filter units occurred due to inadvertent blockage of the sludge extraction lines on the clarifier. During such incidents, the fabric-protected filters did not display a rapid increase in the rate of head-loss development, in contrast to the conventional filter unit which blocked within a few days.

In phase 2, the mean run time of unit S1 (fabric arrangement unchanged) was in close agreement with that found for phase 1, reflecting a similar pattern of influent water quality and a stable fabric performance. The effect of diminishing the overall thickness of fabric No. 28 from 24 mm to 14.4 mm reduced the mean run time by 13%, suggesting that penetration of impurities was occurring. In contrast, the combination of fabrics No. 32 and No. 28 in unit S3 demonstrated the ability to extend the mean filter run time of the filter unit by a factor of 1.8 compared to unit S1. Since the mean filter runs of unit S1, protected by five layers of fabric lab. No. 28, were virtually the same in both phases 1 and 2 (i.e. 13.8 and 13.4 days), it can be deduced that, overall, the combination arrangement of fabrics No. 32 and 28 extended the filter run time by a factor of approximately 5.5, compared with the conventional slow sand filter unit of phase 1.

By changing the operating conditions of the clarifiers in phase 3, it is not possible to compare directly the performance of the filter units between phase 2 and phase 3. However, a comparison of the ratio of the mean filter run times of units S3 and S2, 2.1 in phase 2 and 1.7 in phase 3, shows the extent of the improvement in filter run time which is achieved by placing 26 mm of fabric No. 32 over the 14.4 mm of fabric No. 28. In addition, this prevented significant particle penetration into the underlying sand. The results of phase 3 also showed the extent of the reduction in mean run time of the filter unit protected by the combined fabrics, i.e. 56%, by doubling the filtration velocity to 0.3 m/h.

Filter Head Loss

Figs. 4-6 are representative of the development of head loss in the units S1, S2 and S3 during the filter runs in phase 1. It can be seen (Fig. 4) that the development of head loss in the conventional filter unit S3 displayed the well-established exponential form, and that the head loss occurs characteristically within the top 50 mm of the sand. With the application of 24 mm of fabric No. 28 on the sand bed (Fig. 5), there is a slow development of head loss initially, followed by a more rapid exponential rise. Throughout the filter run it is clear that the development of head loss has been contained within the fabric layer. This is not entirely the case with filter unit S2 (Fig. 6), where there is clearly some head loss development within the top 50 mm of sand, suggesting the penetration of impurities through the layers of fabric No. 32.

The head-loss development of the filter units with the combination arrangement of fabric No. 28 and No. 32 are exemplified in Figs. 7 and 8, which correspond to the phase 3 period of experimentation. With the filter unit operating at 0.15 m/h (Fig. 7) there was a low head-loss development in the first half of the filter run, and even at 67% of the filter run time the head loss was only 17% (150 mm) of the final value. All the head loss was occurring within the fabric layers.

Fig. 8 exemplifies the head-loss development in the unit operating at 0.3 m/h. The wider spacing between the lines, corresponding to the different depths, arises from the greater clean media head loss at the higher flow rate, and there was no indication of material penetration through the fabric layers.

WATER QUALITY IMPROVEMENTS

Turbidity

Figs. 9 and 10 show the turbidity variation in the raw, clarified and filtrate waters during phases 1 and 2, respectively. The raw water turbidity varied from 3.3 to 48.0 NTU, and the turbidity of the clarified water ranged from 1.0 to 9.2 NTU. The turbidity range of the clarified water was wide, due to the periodic instability of the sludge blankets caused by blockage of the sludge extraction hoses. The typical range of the filtrate water turbidity was 0.1-0.3 NTU, and maximum turbidities never exceeded 0.6

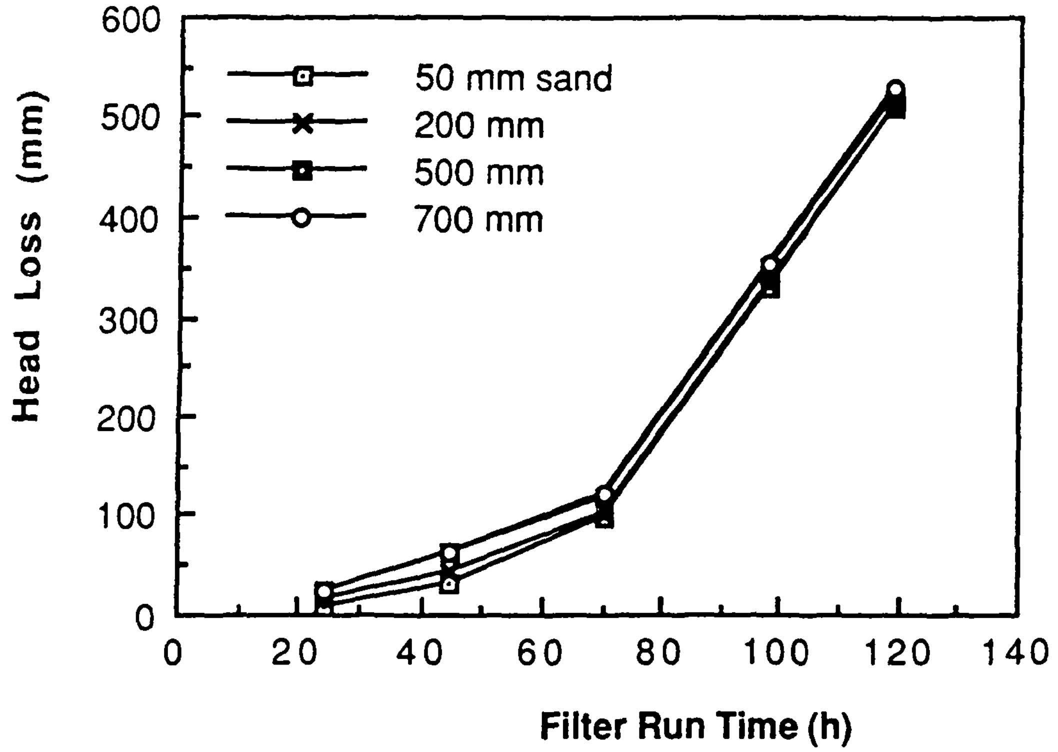

Fig. 4. Head loss development v. filter run time for filter unit S3 (Run 8, Phase 1)

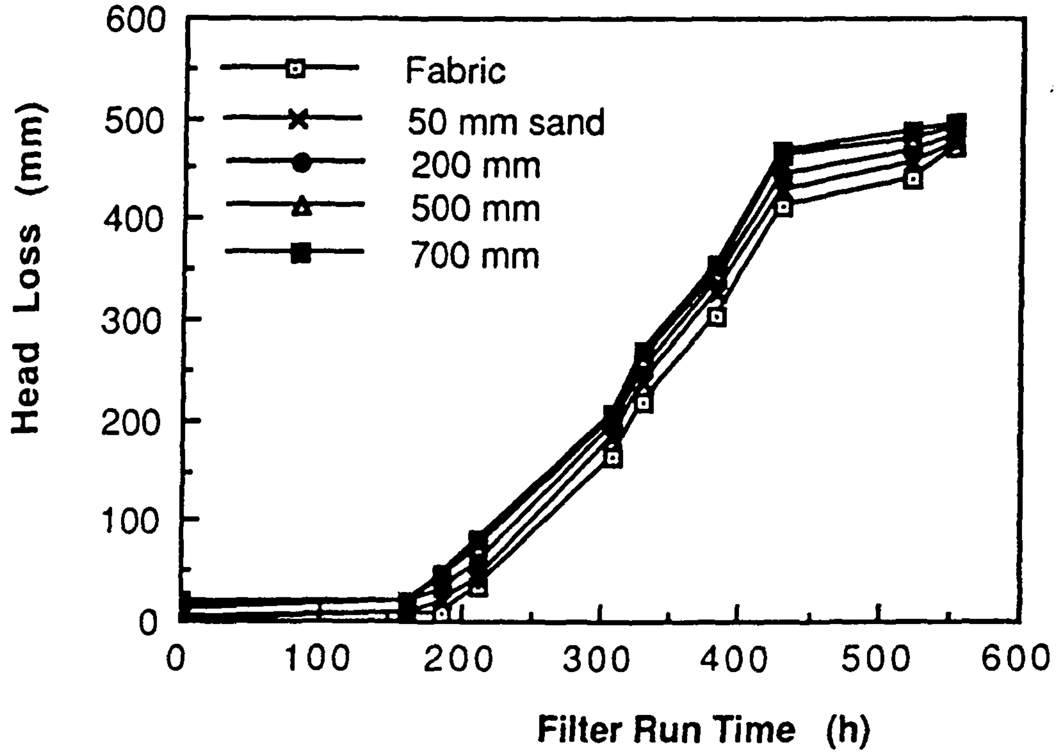

Fig. 5. Head loss development v. filter run time for filter unit S1 (Run 1, Phase 1)

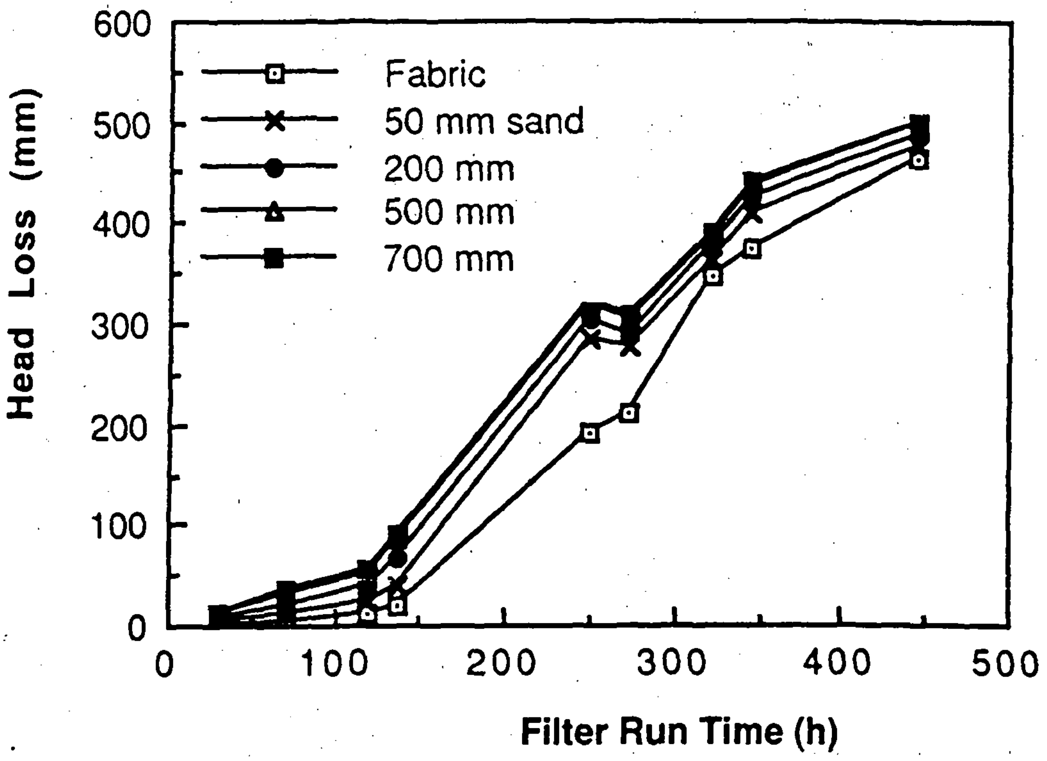

Fig. 6. Head loss development v. filter run time for filter unit S2 (Run 2, Phase 1)

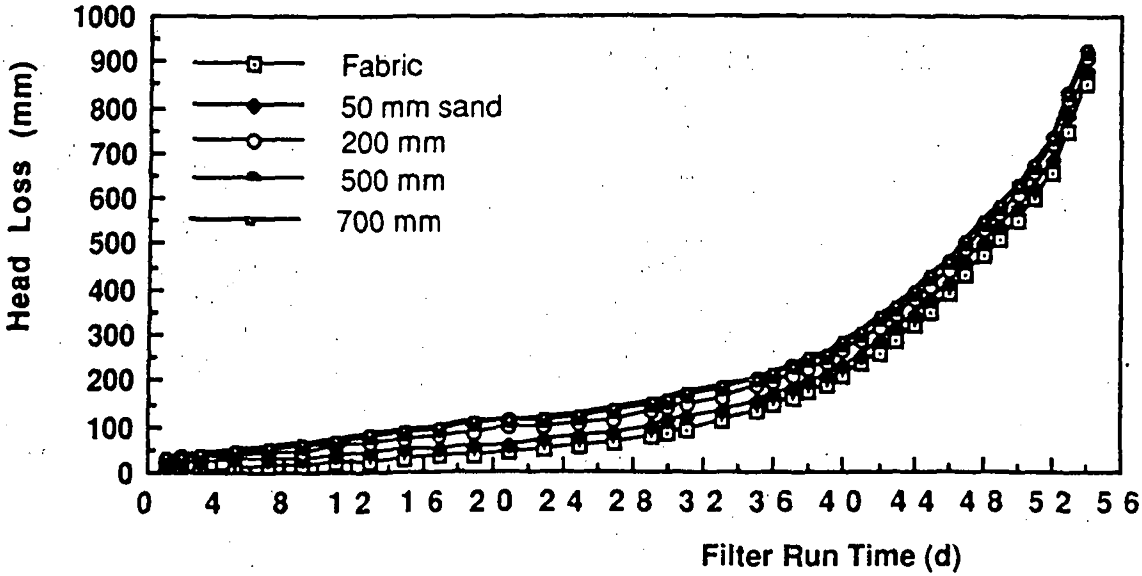

Fig. 7. Head loss development v. filter run time for filter unit S3 (Run 2, Phase 3)

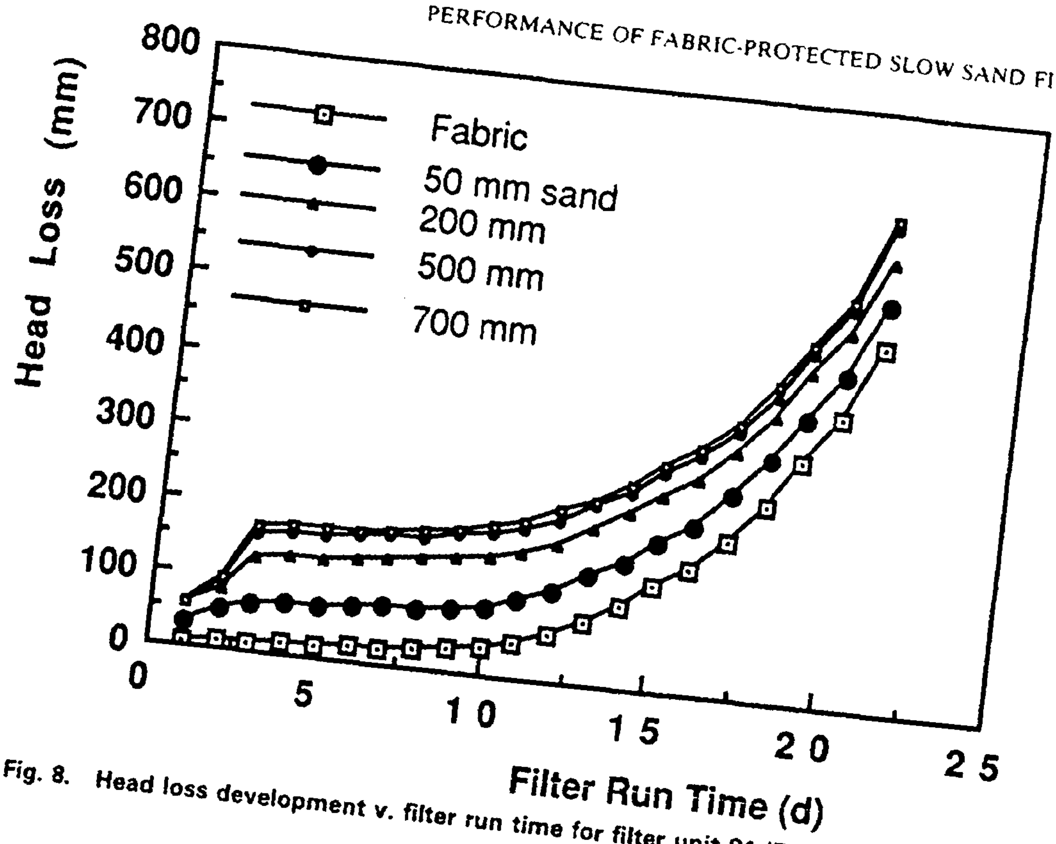

Fig. 8. Head loss development v. filter run time for filter unit S1 (Run 4, Phase 3).

NTU. During phase 3 the raw water turbidity ranged from 4.5 to 13.0 NTU, the clarified water turbidity varied from 0.5 to 2.9 NTU, and the mean filtrate turbidity was 0.22 NTU (never exceeding 0.35 NTU).

During each of the three phases, it was observed that there was no significant difference between the filtrate turbidities of the three filter units.

Colour

This parameter was principally monitored during phase 3, when the true colour of the raw water varied from 4.0 to 16.4 Hazen units and the range of the clarified water was 2.6–11.3 Hazen units[12]. In general, coagulation and clarification reduced the true colour of raw water by an average of 37%, while the average true colour removal in the filter units was only 17%. There was no significant difference in the true colour of the filtrate waters during phase 3.

Bacteriological Quality

During phases 1 and 2 the range of faecal coliform counts of the raw water was 965–3200/100 ml. While the mean faecal coliform removal through the clarifiers was approximately 80%, all the filter units were able to achieve at least a 99% reduction. Filtrate coliform concentrations exceeding 1/100 ml were usually observed only a few days following cleaning or re-starting, otherwise counts were typically zero/100 ml. In phase 3, the raw water counts ranged from 160 to 2300/100 ml, and the performance of the clarifiers and filter units was very similar to phases 1 and 2.

DISCUSSION

The results of the experimental work, carried out in phases 1 and 2, have demonstrated that the presence of a 25-mm layer of fabric on a conventional slow sand filter can increase the filter run time by a factor of 3.1–4.4, depending on the type of fabric. A 14.4-mm thickness of fabric (No. 28) was found to extend the filter run time by a factor of 2.7. In terms of the operational viability of the slow sand filter process under the experimental conditions prevailing in this project, the application of the 25-mm fabric layers increased the mean filter run time from a non-viable 4.5 days to a minimum viable run time of approximately two weeks. The filter run time can be further extended (65%) by using a combination of a basic thickness (14.4 mm) of fabric No. 28 below a layer of the porous fabric No. 32. Alternatively, the

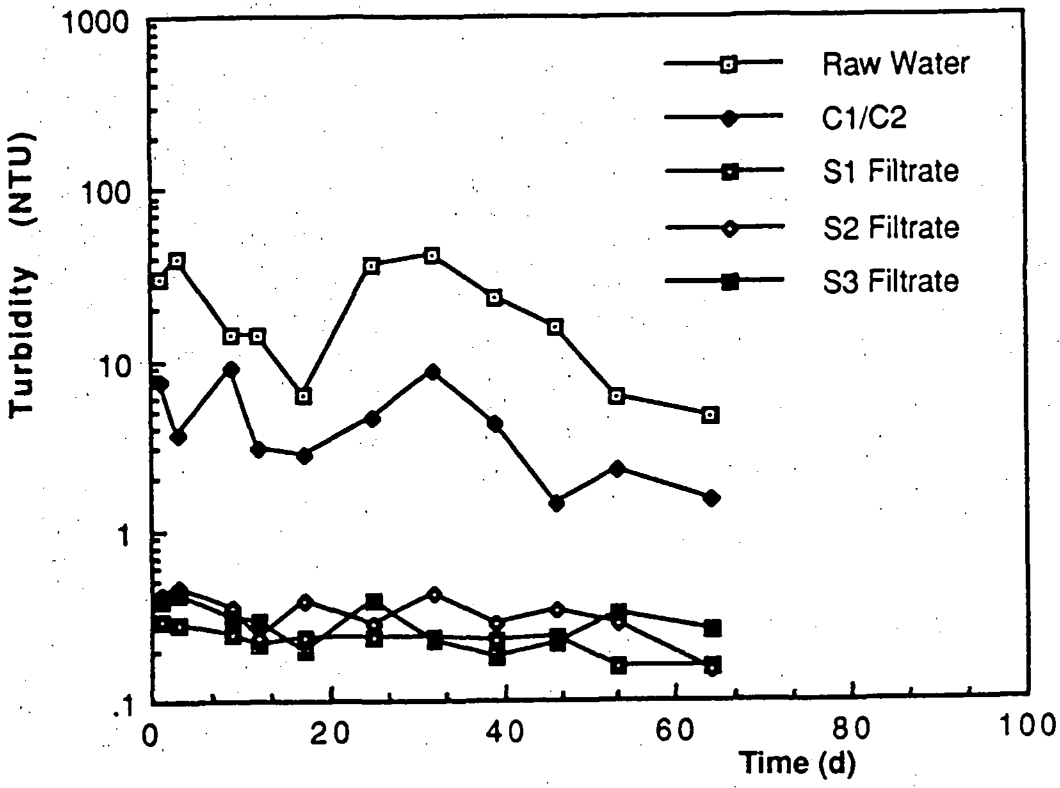

Fig. 9. Turbidity removal through pilot plant in Phase 1

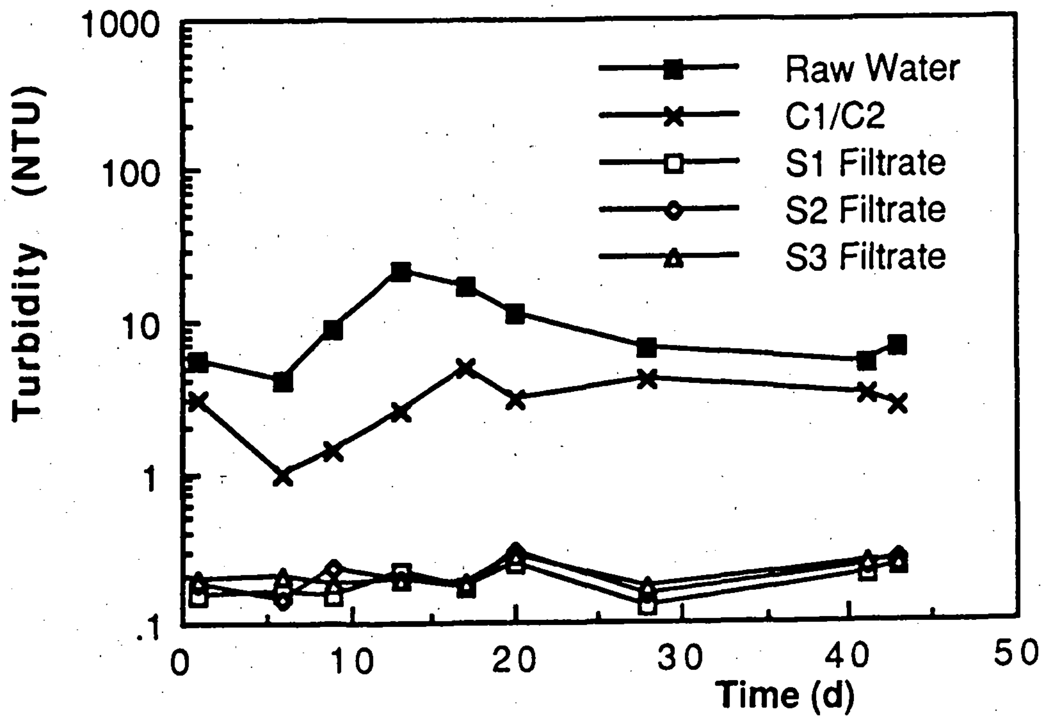

Fig. 10. Turbidity removal through pilot plant in Phase 2

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results of phase 3 have shown that such a combination arrangement of fabrics can permit the doubling of the filter hydraulic loading rate (to 0.3 m/h) whilst also maintaining a viable filter run time.

During phase 1, only 5 layers of fabric No. 28 (25 mm) fully protected the sand bed by retaining most of the impurities and biomass in the fabric layers. Although substantially extending the filter run time, 2 layers of fabric 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 minimal penetration into the sand. It is therefore clear that virtually all the influent turbidity and biomass development is retained within the fabric layers and that, as a consequence, filter cleaning only concerns the fabrics and does not involve sand scraping.

Throughout the experimental period, the quality of filtrate from the three filter units was invariably consistent. This was not unexpected, since the performance through a conventional slow sand filter is so high that possible additional improvements arising from the presence of a 25–40 mm thickness of fabrics are not likely to be discernible.

Overall, this study has demonstrated that a fabric-protected slow sand filter can perform satisfactorily with poorly-operated pretreatment units which allow substantial amounts of unsettled flocs to be carried over to the filter. This type of problem is not unusual in most developing countries with slow sand filtration preceded by chemical pretreatment[13]. The poor ability of slow sand filtration to remove colour means that the use of chemical pretreatment in conjunction with slow sand filtration is necessary for significantly coloured water sources.

As a rapid method of improving the performance of overloaded slow sand filters, the application of fabrics is simple, relatively cheap and efficient. The UK price of synthetic fabrics is £2–6/m^2; however, final costs are difficult to estimate, and in developing countries it may be possible to use local fabrics, provided that they have the necessary properties. Such fabrics can be applied directly to the surface of existing slow sand filters, but experience so far has only considered filter units of bed areas up to 30m^2 [14]. It is possible that fabric handling and cleaning problems might arise when applying fabrics to filter units of greater bed area when manual, labour-intensive methods may be less cost-effective and practicable compared with mechanized methods.

Although this investigation has shown that the application of fabrics to slow sand filter 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 reduce significantly the depth of the sand filter, and thus the capital cost. This has yet to be quantified, and is the subject of continuing work by the authors.

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