With compliments of

Dave Wheeler
Research Officer
Department of Microbiology
University of Surrey
Guildford GU2 5XH
Tel Guildford [illegible]

# ASPECTS OF PREFILTRATION CONCERNED WITH THE APPLICATION OF SMALL SCALE SLOW SAND FILTRATION IN RURAL COMMUNITIES

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Authors :

David Wheeler

Mauricio Pardon

Barry J Lloyd

Christopher N Symonds

Department of Microbiology

University of Surrey

Guidford UK

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## GENERAL CONCLUSIONS

1 Where suspended solids are variable in mineral and organic quality, and where turbidity does not exceed 100 NTU, horizontal gravel filtration using media in the diameter range 10 - 40mm functions most efficiently in the laminar flow mode (velocity less than 0.5 m/h).

2 In the above conditions 10mm gravel appears to be the most efficient single medium in comparison with 20mm and 40mm gravel in horizontal filter applications with respect to both physical and microbiological improvements.

3 The efficiency of all media decreased as velocities increased above 0.5 m/h.

4 There is considerable value in linking horizontal coarse medium filters in series in order to obtain high overall reductions both in turbidity and microbiological loading.

5 The most efficient portion of filter length in these studies appeared to be the first portion of medium, and a law of diminishing returns appears to operate with regard to efficiency per unit length.

6 The process of horizontal gravel filtration may involve considerable biological activity, and while this is welcome when reflected by useful improvements in microbiological loading, the depletion of dissolved oxygen within the filter can be substantial.

7 A maturation period was noted with respect both to physical and microbiological performance, and this feature, together with oxygen depletion should be considered when horizontal gravel filtration is to be applied in advance of other processes.

8 Where suspended solids are mostly mineral, vertical in-series filtration may be most appropriate up to a maximum influent turbidity of 300 NTU provided that velocity does not exceed 0.3 m/h.

9 When vertical in-series filtration is applied to exclusively minerally turbid water, the greatest percentage improvement in water quality does not necessarily occur in the last section of small diameter medium - this contrasts with observations made on water of variable quality in horizontal gravel treatment.

10 Both horizontal and vertical in-series gravel filtration provide excellent prospects for water treatment where the raw water source is surface water with high turbidity. Maintenance requirements are low and provided that flow rates remain low and are matched to effluent requirements, efficiency is high.

11 Protection of small scale slow sand filtration by discrete squares of filter fabric 12 x 12cm does not appear to be very effective in increasing filter run length.

# INTRODUCTION

The work described in this report primarily concerns research conducted at The University of Surrey over the twelve month period September 1984 - September 1985. However, the work was conducted in parallel with research initiated by the Centro Panamericano de Ingenieria Sanitaria y Ciencias del Ambiente (CEPIS-PAHO/WHO) in Lima. A description of the latter work forms part of Section III of this report and helps place the work at the University in an international context. An appendix (Appendix I) describes the proceedings of an afternoon seminar on gravel filtration at which many of the theoretical and applied considerations appertaining to the pretreatment of surface waters were raised and discussed. This seminar was conducted at the University in October 1984.

All work undertaken by Mr. Symonds at the University was supported by the UK Water Research Centre (Research Contract SL 410/07/01). The other authors of this report are currently supported by the UK Overseas Development Administration. The support of both organisations is gratefully acknowledged.

# SECTION I

## Ii: THE APPLICATION OF FILTER FABRIC IN THE PROTECTION OF SMALL SCALE SLOW SAND FILTRATION.

For various historical and economic reasons, the process of slow sand filtration gradually fell into disfavour with many water works engineers during this century. However, those public health arguments which recommended the process so strongly in the mid- to late-nineteenth century still appertain. Evidence of the relevance of maintaining simple but multiple stage treatment systems has been collected (1) and is reproduced in full in Appendix II. It is argued that the retention of the philosophy of multiple barrier treatment is vital to the supply of consistently high quality drinking water and that nowhere is this more necessary than in the rural sector.

One conclusion arising from this line of reasoning is that the process of slow sand filtration, which affords both physico-chemical and microbiological improvements in water quality, is particularly appropriate in the treatment of contaminated surface waters in rural locations. Thus, due to its relative technical simplicity slow sand filtration is receiving renewed interest in both developing and industrialised countries. This interest is further reinforced by the recent restatement of water quality guidelines for rural water supplies by the World Health Organisation (2), and the iminent enactment of water quality legislation in Europe which mandates greater vigilance of water supplies outside regional distribution networks than existed previously (3).

A major consideration in the effective application of slow sand filtration is that the influent suspended solids loading should not be so great as to cause premature blockage of filters (4). Short filtration runs are generally acknowledged to be unproductive owing to the biological nature of the process. For this reason, most authorities consider a mean influent turbidity of 10 NTU to be the maximum for the cost effective and efficient operation of SSF systems (5,6). While we are in general agreement with this proposition, we would also point out the importance of other parameters : for example filterability and the qualitative nature of suspended solids, in affecting filtration run length and filter efficiency.

However, it is reasonable to state with total certainty, that where mineral turbidity exceeds 10 NTU, some form of pretreatment is required. This may be coagulation, rapid sand filtration, micro-straining (mostly industrialised countries), reservoir storage, infiltration, gravel filtration or sub-sand abstraction (universal). Whether or not pretreatment is indicated, it is possible to further protect and enhance the slow sand filtration process by the emplacement of layers of non-biodegradable, robust fabrics directly on the sand surface. This has been demonstrated both at the University of Surrey and at WRC Medmenham (7). In general terms it is apparent that simple combinations of fabric layers may increase filtration run length by a factor of up to threefold.

Virtually all experience of the efficiency of loose, spray-bonded polyester fabric has been confined to relatively small scale or experimental filters, the largest being the OXFAM slow sand filter package for disaster relief. This package had a circular filtration area of 28.3 $m^3$ and was covered by four parallel strips of 'Bondina' fabric. Thus the unit was protected by both sub-sand abstraction and a single layer of filter fabric overlaid directly on the sand surface (8). Experience with various combinations of spray- bonded fabrics on filter bed areas between 0.7 and 1.5 $m^2$ has also been described (9,10). It was demonstrated that an alternating sequence of fabric densities afforded the best protection to SSF. The efficiency of single layer protection was confirmed in parallel experiments conducted in Medmenham using raw water from the River Thames.

## Iii: POTENTIAL APPLICATIONS ON FULL SCALE FILTERS

While some preliminary investigations of fabric protection of full scale slow sand filtration have been undertaken by the Thames Water Authority (pers. comm.), there have been no attempts to date to cover an entire filter. Certain handling problems which are expected to arise from the coverage of full scale filters prompted the investigation in this project of a means of reducing such difficulties.

Because the maximum size of silt laden fabric which can conveniently be handled without the employment of specialised machinery is approximately 6 x 2m, there is clearly a need for some method of anchoring long lengths of fabric in conventional filters. At present the best option for anchorage appears to be plastic wire net of the garden fencing type. But it is entirely conceivable that means of weighting the fabric by incorporating metal rods or minerals into the weave could be designed. The minimum size of fabric which will be retained in place by the least expensive commercially available netting is approximately 5 x 5 cm.

It has been suggested that another mechanism for handling fabric for cleaning and maintenance purposes would be the development of plant which could lift relatively small pieces of fabric by vacuum or mechanical means before cleaning and returning them in semi-random fashion to the sand bed. WRC, Stevenage, has obtained a patent on this concept. Thus it was decided to place some priority on the evaluation of the protection of sand filtration by semi-randomly distributed fabric squares in varying quantities.

## Iiii METHODS

Filter fabric INSUL 305 (Universal Filters, London), a spray-bonded polyester insulation fabric was found in earlier trials to perform well in comparison with other available materials. Therefore, this fabric was selected for evaluation of fabric square protection in this study.

INSUL 305 was provided by WRC Stevenge in 12 x 12 cm squares in quantities equivalent to one, two and three entire layers of filter fabric sufficient to cover a filter of approximately 1.5 $m^2$. The fabric has a slight thickening in density on the lower side and this side was marked in indelible ink in order to identify any bias in how pieces fall into the bed surface when semi-randomly distributed. Fabric squares were cast onto the sand bed from a height of approximately 2m. Plates 1-3 show the coverage of sand achieved in this way. Table 1 describes the coverage in approximate percentage terms.

TABLE 1: ORIENTATION OF FABRIC SQUARES (THICKENED SIDE UP OR DOWN) AND OVERALL COVERAGE OF SAND FILTER SURFACE FOR ONE, TWO, AND THREE FABRIC LAYER EQUIVALENTS.

| Number of Fabric Layer Equivalents | Orientation of Fabric Squares (Percentage Down) | (Percentage Up) | Total Coverage of Sand Bed (Percentage) |
|---|---|---|---|
| 1 | 51 | 49 | 87 |
| 2 | 45 | 55 | 91 |
| 3 | 53.5 | 46.5 | 93 |

Parallel (though not identical) filters were operated at an identical flow rate of 0.33 m/h and protected by various amounts of fabric in squares or entire layers. The filters had a similar filtration bed area of 1.5 $m^2$, but in common with experience of full scale sand filters, no two filters perform identically whatever efforts are made to match their loading and operation. Thus all experiments were repeated in reverse replication in order to eliminate bias between filters.

The following analyses were conducted during filtration runs : head loss accumulation, turbidity reduction, filterability and qualitative solids type.

Plate 1 : Slow sand filter coverage by one fabric layer equivalent in fabric squares.

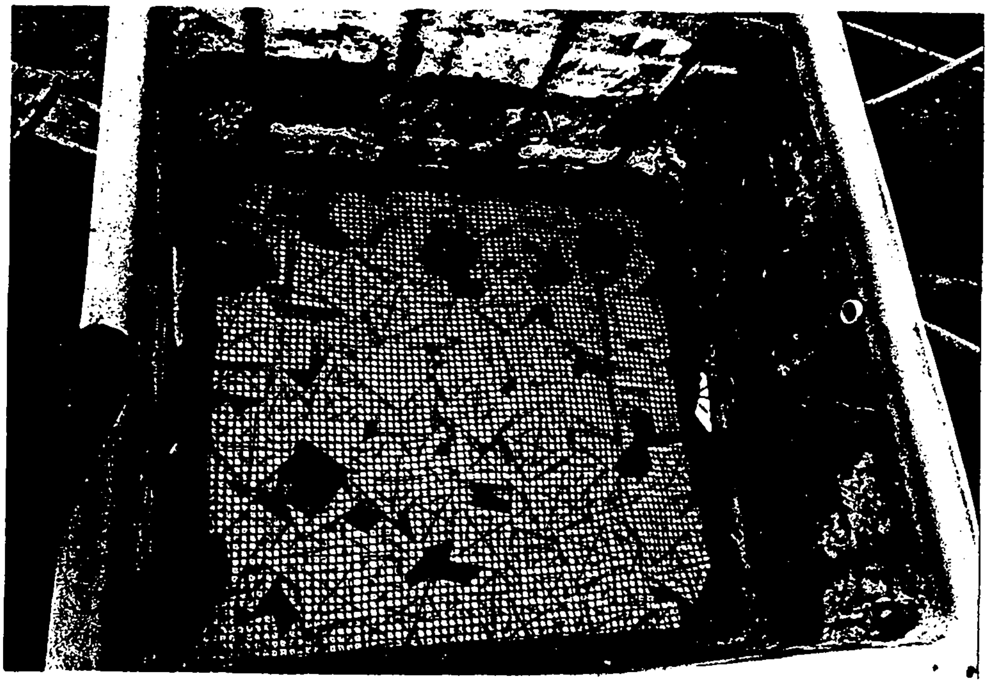


Plate 2 : Slow sand filter coverage by two fabric layer equivalent in fabric squares.

Plate 3 : Slow sand filter coverage by three fabric layer equivalent in fabric squares.

Head loss was measured in the outer well of the outlet constant flow controller. Turbidity was measured using a conventional nephelometer (HF Instruments, Canada). Filterability was accomplished by a membrane filtration method described in Appendix III. Solids type was a measure of the relative quantities of organic and inorganic suspended matter in the raw water. The technique was also based on membrane filtration. Sufficient water sample was passed through a membrane (Gelman GN6) to effect discolouration. The filter was dried and subsequently made translucent by the addition of immersion oil on a glass microscope slide. The membrane was viewed at a power of x 500 and trapped particles scored according to their type and size. Four simple categories of particle distribution were selected : 0-25%, 25-50%, 50-75% and 75-100% inorganic or mineral suspended matter. A score of 0% would imply 100% organic suspended matter eg microbiological debris, algae etc.

## Iiv RESULTS

Results are depicted graphically in Figures 1-23. A general key to the graphs is also provided. Table 2 summarises the data in the form of standardised filter run lengths. Because starting and finishing head losses were not usually the same, a standard filter run length was taken to be that time (in hours) over which head loss increased from 10 to 40 cms. Filtration velocity may be considered constant over this range for both filters. Since influent water quality was by no means constant, standard filter run lengths cannot be compared directly between experiments, and for reasons already alluded to, standard run lengths cannot be compared directly between filters.

Data have been standardised with regard to the comparative degree of protection afforded by fabric squares. By taking the mean of the percentage increases or decreases in filter run length compared with the parallel filter in both experiments, the overall effect of fabric square protection is derived.

## Iv DISCUSSION

From Figure 1, the potential disparity in run length performance of the two unprotected filters is apparent. This difference is not reflected in a noticeable difference in turbidity removal however (Figure 2).

Figures 3 and 5 illustrate the disparity in run length performance by showing a wide divergence in the apparent effect of single fabric layer protection in squares compared to no protection. The 26.2% increase in filter run length compared with the unprotected filter is clearly assisted by the greater inherent efficiency of filter Z. However, the reverse experiment balances the picture (Figure 5) leaving a modest net increase in filter run length of 1.6 3.2%. Turbidity removal was not affected by a single layer of fabric squares.

| | FILTER F | | FILTER Z | | | |
|---|---|---|---|---|---|---|
| FIGURE | PROTECTION* | STANDARD RUN LENGTH (hours) | PROTECTION | STANDARD RUN ** LENGTH (hours) | EFFECT OF FABRIC SQUARE PROTECTION ON STANDARD FILTRATION RUN LENGTH | |
| | | | | | per cent. | mean per cent. |
| 1 | 0 | 26.5 | 0 | 42.6 | - | - |
| 3 | 0 | 37.4 | 1S | 47.2 | +26.2 | + 3.0 |
| 5 | 1S | 80.7 | 0 | 101.3 | -20.3 | |
| 6 | 1E | 68.9 | 1S | 63.6 | - 7.7 | - 7.2 |
| 7 | 1S | 79.0 | 1E | 84.6 | - 6.6 | |
| 9 | 2S | 52.5 | 0 | 81.9 | -35.9 | -32.0 |
| 11 | 0 | 47.1 | 2S | 33.9 | -28.0 | |
| 13 | 2S | 139.1 | 2E | 141.6 | - 1.8 | +20.3 |
| 15 | 2E | 75.0 | 2S | 106.8 | -42.4 | |
| 17 | 3S | 76.7 | 0 | 80.3 | - 4.5 | - 0.7 |
| 19 | 0 | 45.2 | 3S | 46.6 | + 3.1 | |
| 20 | 3S | 55.7 | 3E | 104.3 | -46.6 | -18.0 |
| 22 | 3E | 51.3 | 3S | 55.6 | +10.6 | |

* Number refers to number of fabric layer equivalents

S indicates squares and E indicates entire layers of filter fabric.

** Standard run lengths represent the time in hours for head loss to increase from 10 cm to 40cm

TABLE 2: SUMMARY OF EFFECTS ON FILTRATION RUN LENGTH OF PROTECTION BY FILTER FABRIC SQUARES

## General Key

### Filtration Runs:-

—■————■— Filter 'F'

—▼————▼— Filter 'Z'

### Turbidity Data:-

|  |  |  |
|---|---|---|
| —□————□— | Influent Turbidity | Filter 'F' |
| —■————■— | Effluent Turbidity |  |
| —▽————▽— | Influent Turbidity | Filter 'Z' |
| —○————○— | Effluent Turbidity |  |

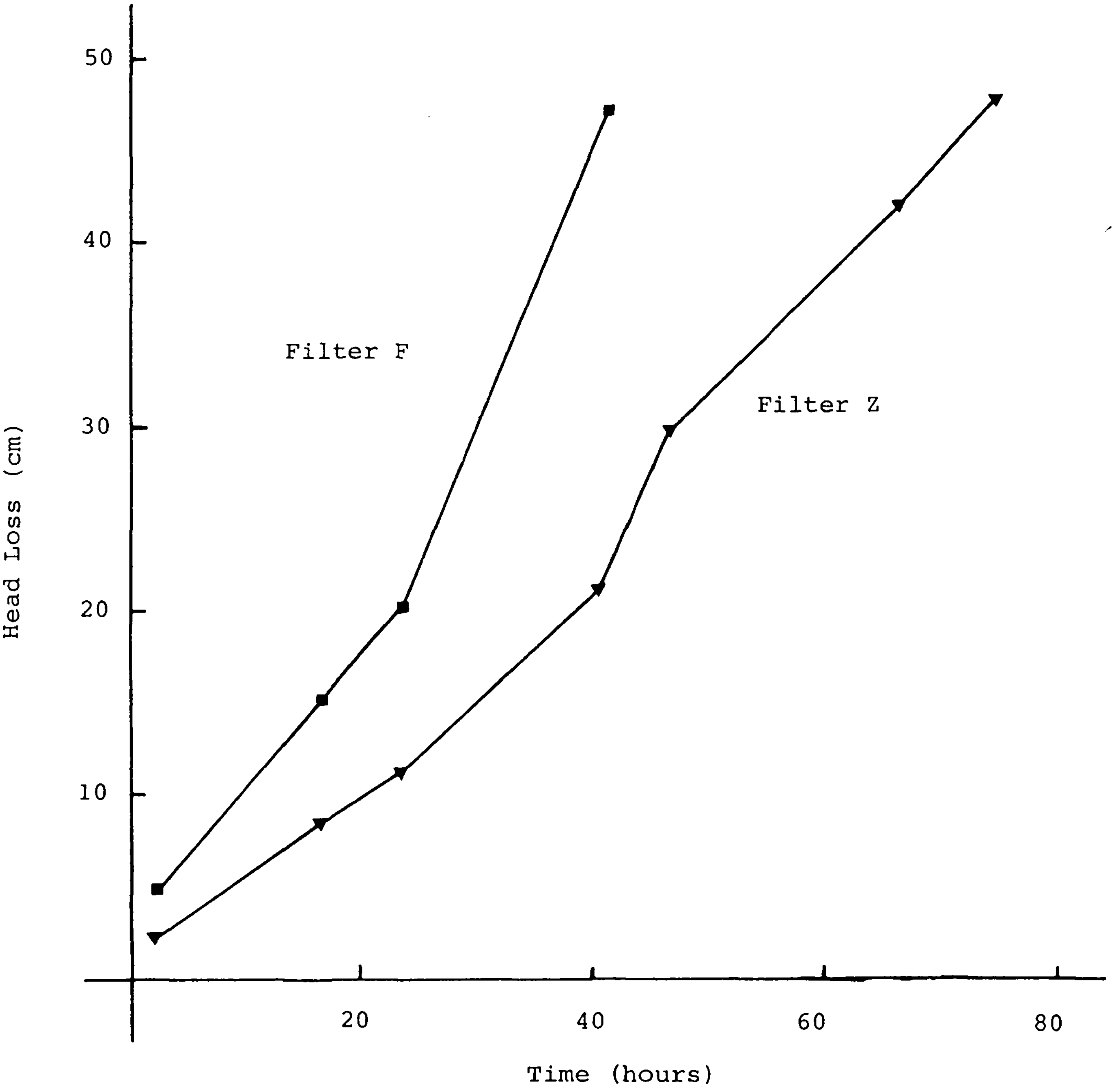


Figure 1 Progress of Filtration Runs: Comparison of unprotected filter F with filter Z .

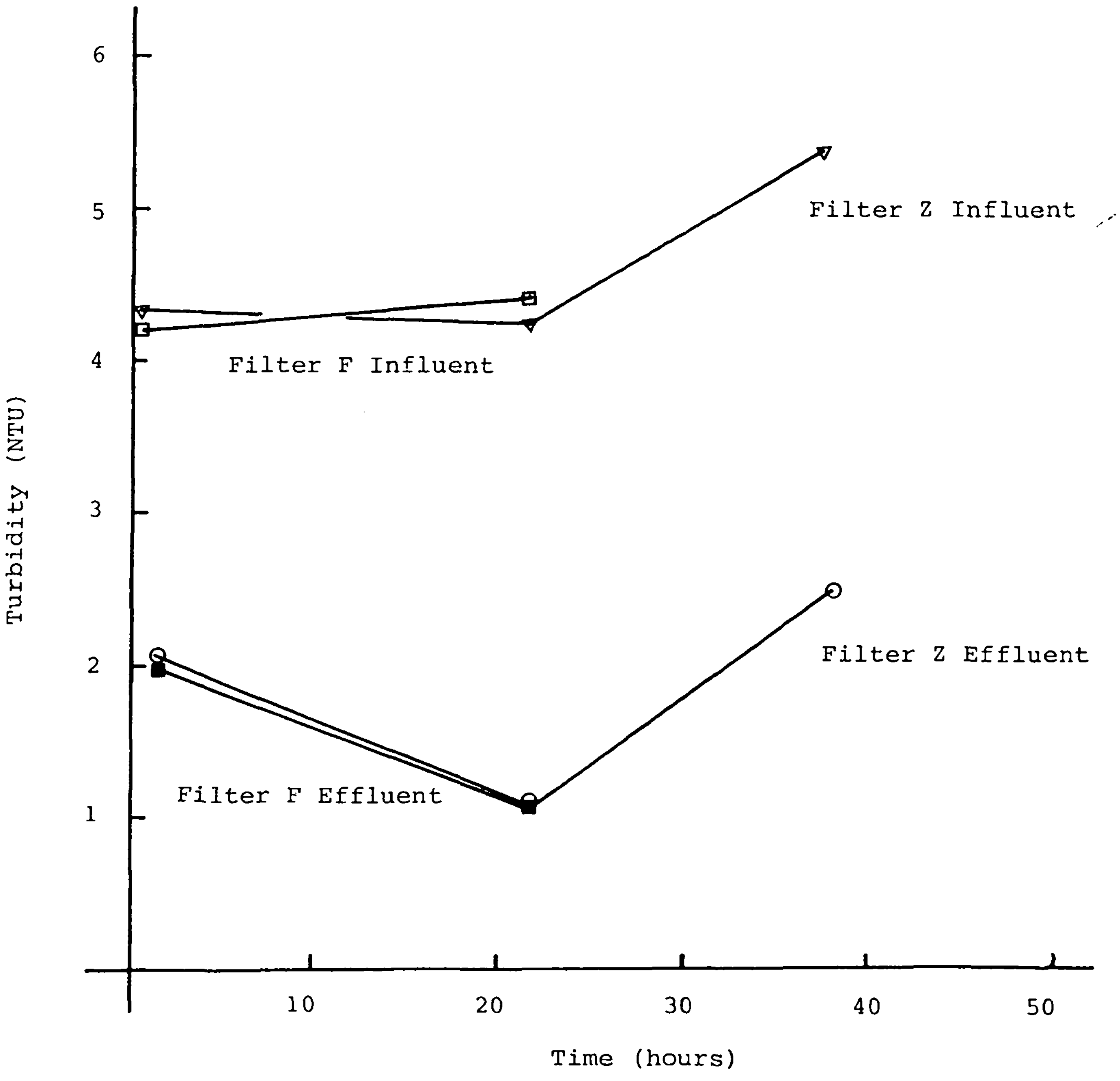


Figure 2 Turbidity Values: Unprotected filters F and Z.

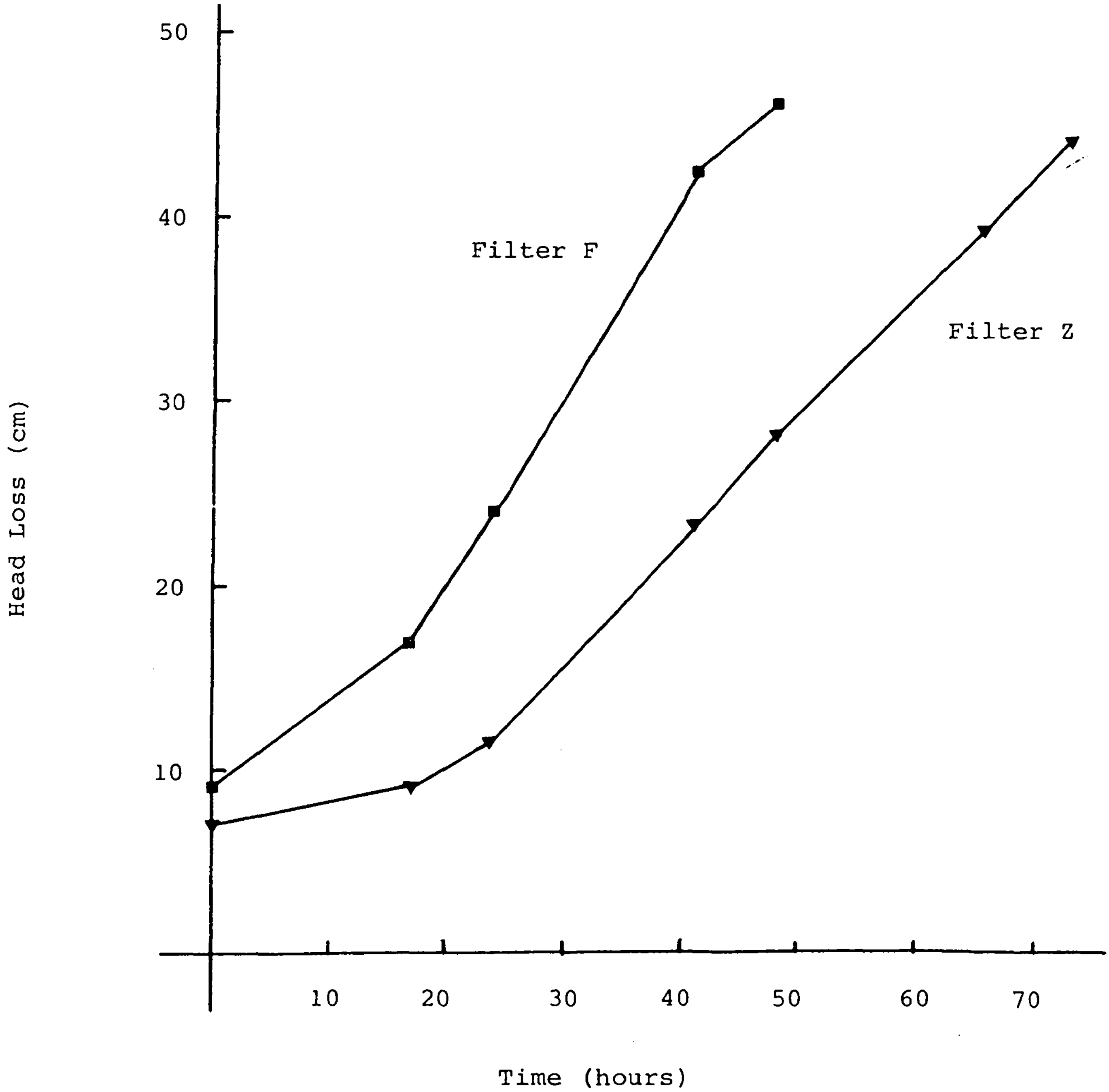


Figure 3 Progress of Filtration Runs:
Comparison of single fabric layer in squares (Filter Z) with no protection (filter F)

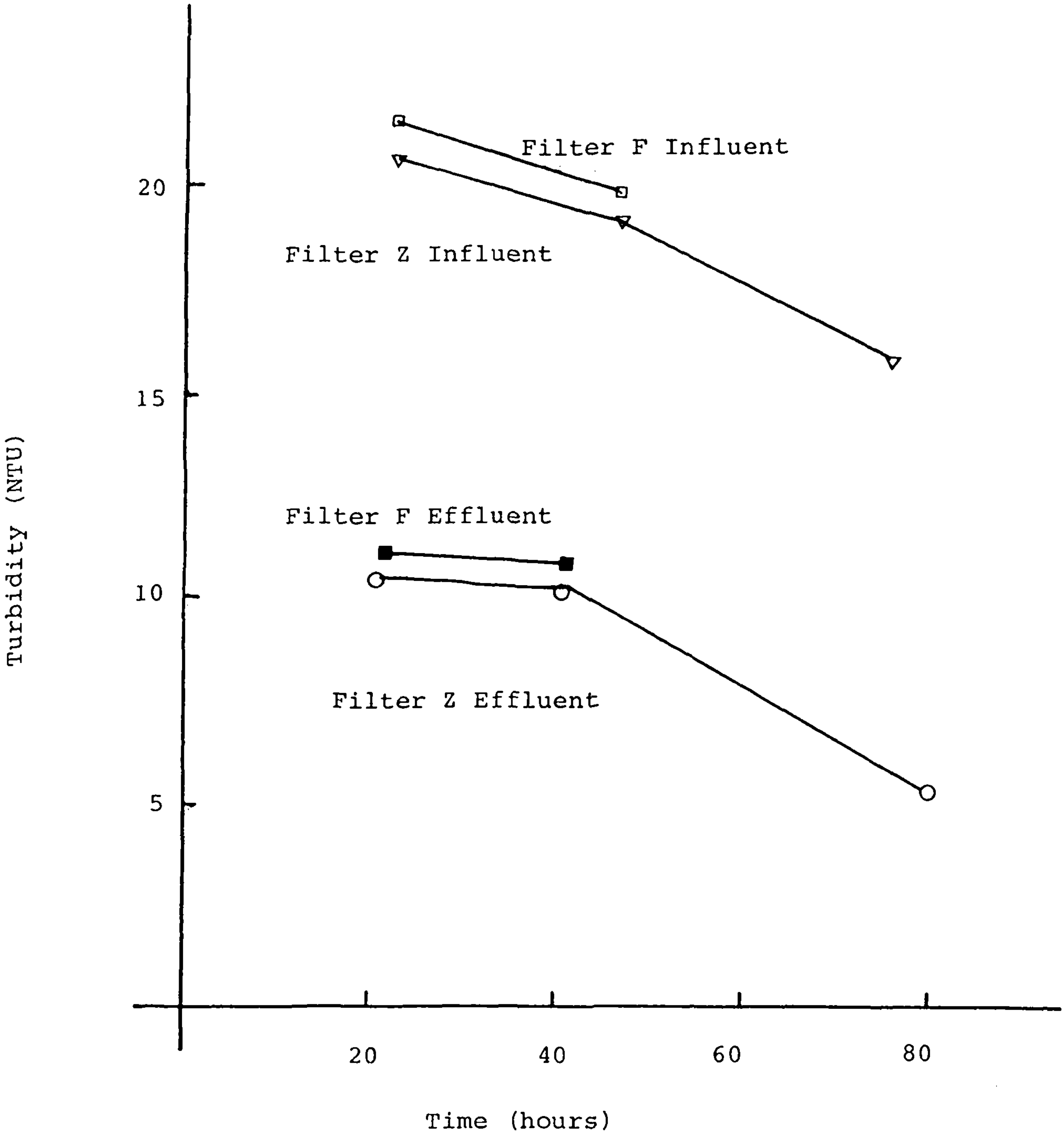


Figure 4 : Turbidity Values: Comparison of single fabric layer in squares (filter Z) with no protection (filter F)

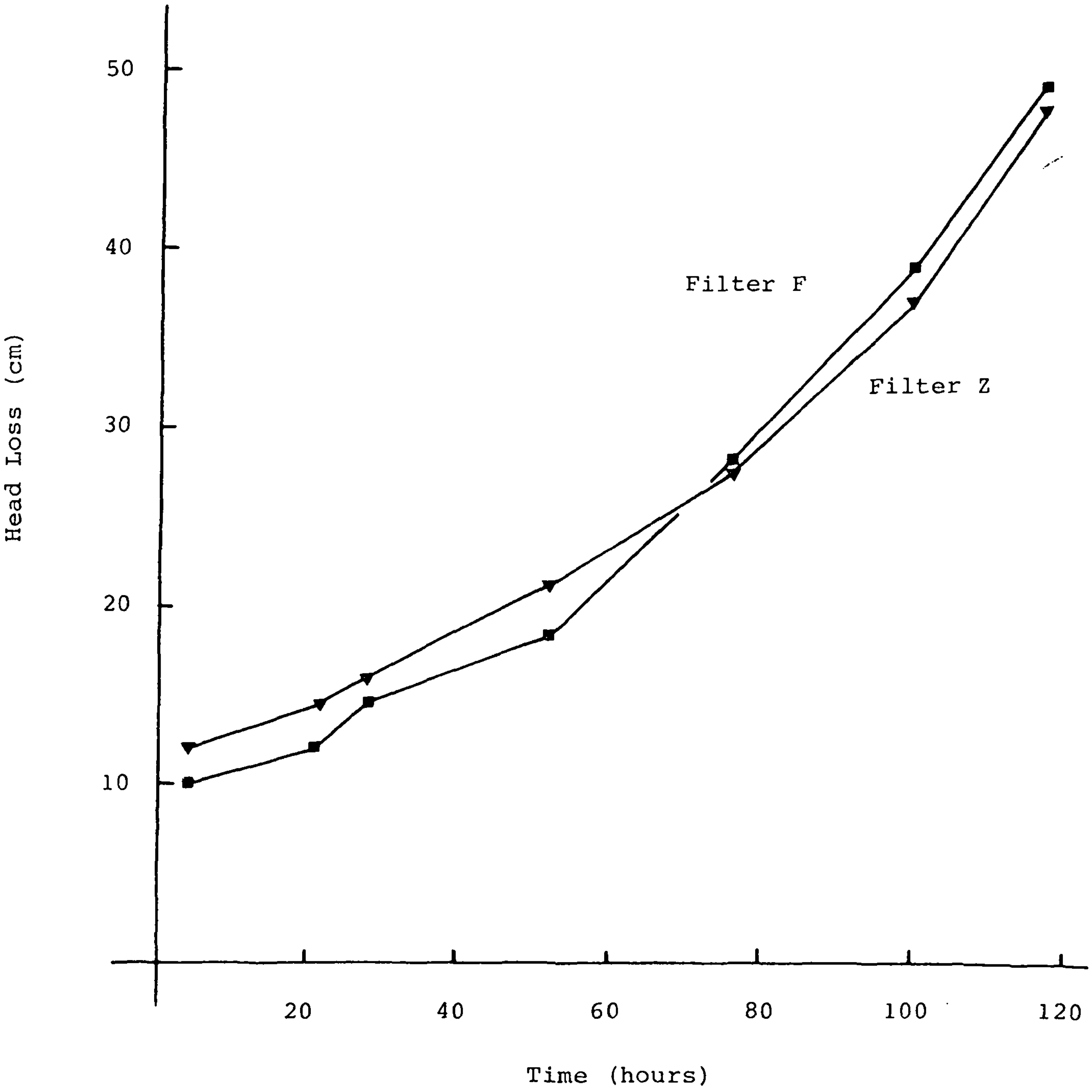


Figure 5 Progress of Filtration Runs:
Comparison of single fabric layer in squares (filter F) with no protection (filter Z).

The two replicate experiments were undertaken with widely different influent raw water types. Mean filterability in the first experiment of the pair (Figure 3) was 39.5 and the percentage inorganic or mineral suspended matter uniformly 0%. The second experiment, depicted in Figure 5, was conducted with a similar filterability index of 37, but it was in a water containing mineral solids in the range 75-100%. Such differences in raw water quality do not invalidate the overall result, but they do not allow a comparison of results between experiments. The very short standard filter run length of 37.4 hours was due in large measure to the absence of any protection in a particularly unfavourable circumstance i.e virtually 100% algal suspended matter in the influent water.

In comparing the efficiency of single fabric layer protection, both entire and in squares (Figures 6 and 7), it is interesting to note that very similar performances were returned for both. This applied to both filter run length and turbidity removal (note: there are no turbidity data to accompany Figure 6). However, in both experiments the standardised run length is marginally better for the entire fabric layer protection compared with protection by an equivalent quantity of fabric in squares. This provides a mean net negative effect of square protection of -7.2.

Figure 9 and 11 demonstrate the effect of the equivalent of two fabric layers in squares compared with no protection. In both replicate experiments, the standardised filter run length for filters with protection was substantially lower than that of the unprotected filters. While this would not have been surprising for the first experiment (Figure 9) where the most efficient filter, Z, received no protection, it was not to be expected where filter Z also received a measure of protection (Figure 11). There is no immediately obvious reason for a discrepancy which implies a lower performance for two fabric layer equivalents in squares than for one. However, it is noticeable that influent turbidities were relatively high

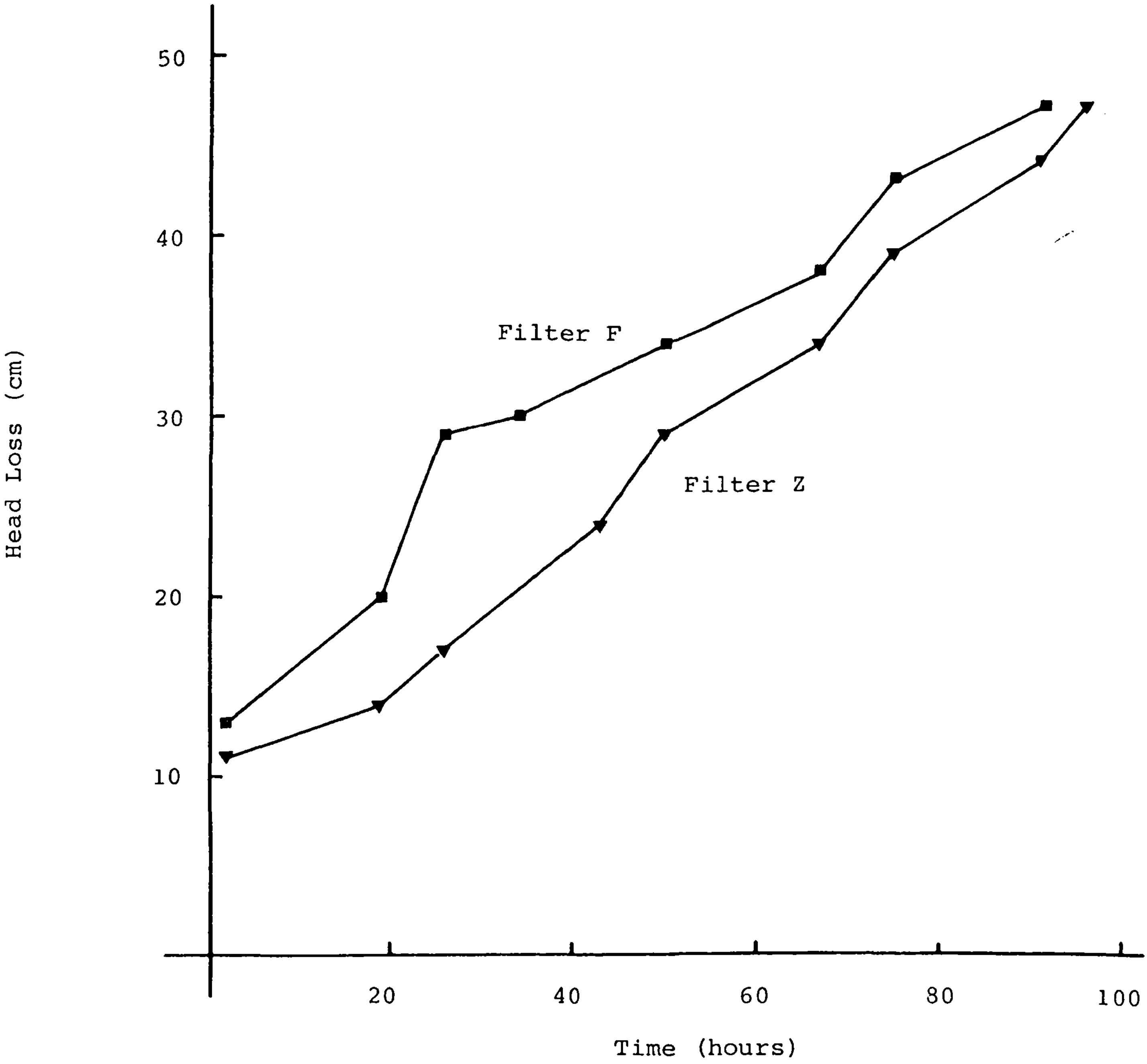


Figure 6 Progress of Filtration Runs: Comparison of single fabric layer in squares (filter Z) with entire single fabric layer (filter F).

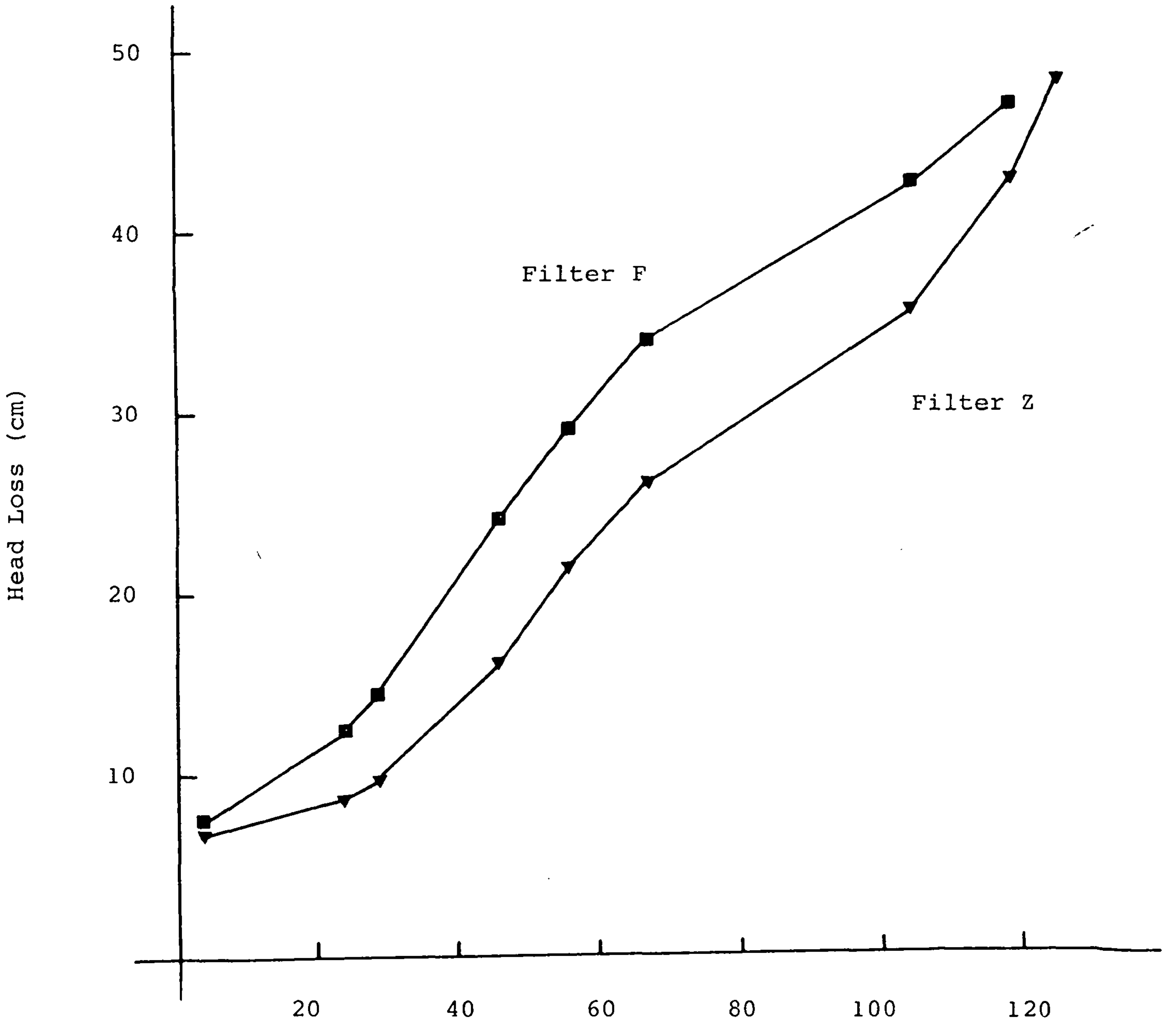


Figure 7 Progress of Filtration Runs: comparison of single fabric layer in squares (filter F) with entire single fabric layer (filter Z)

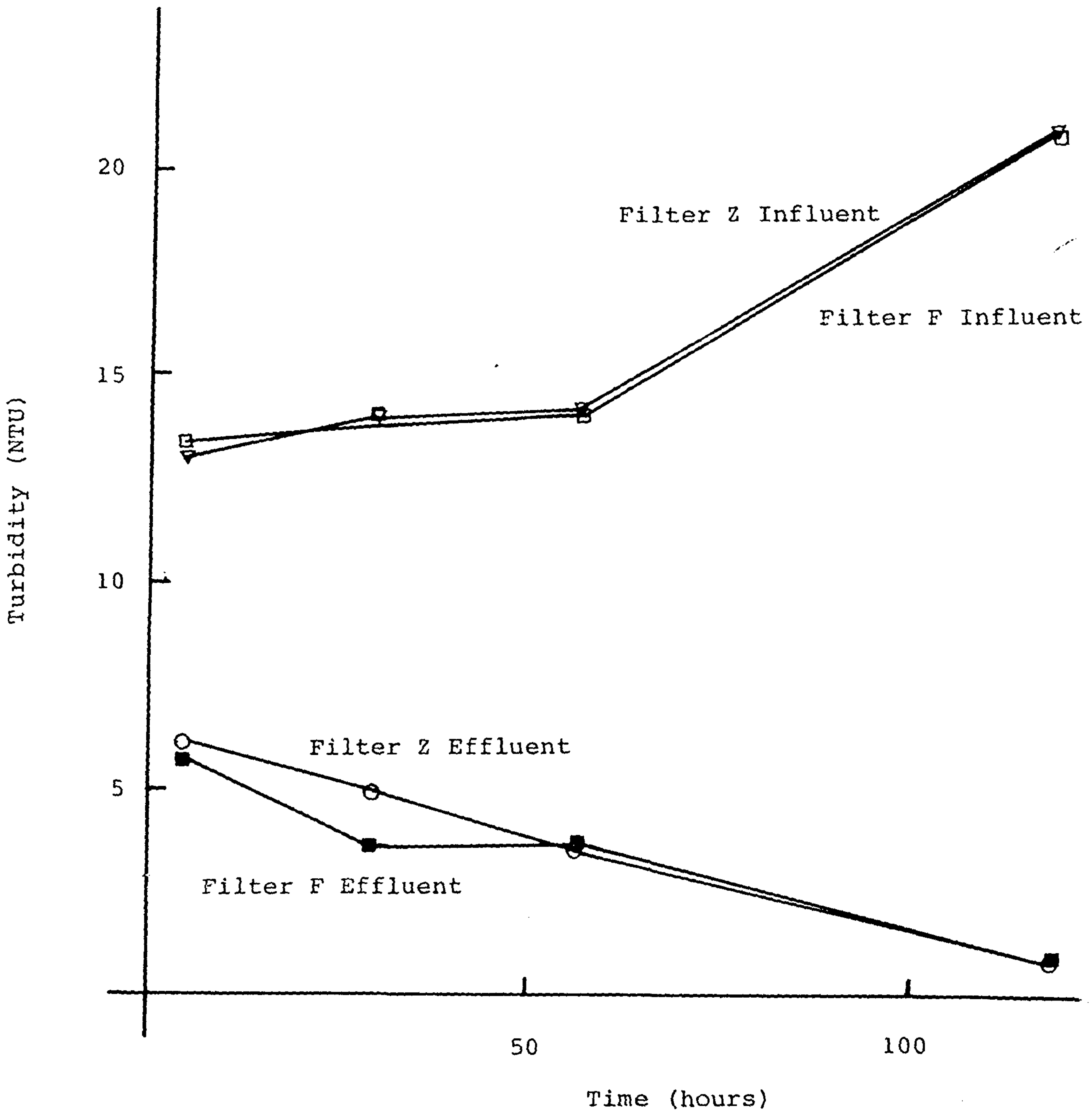


Figure 8 Turbidity Values: Comparison of single fabric layer squares (filter F) with entire single fabric layer

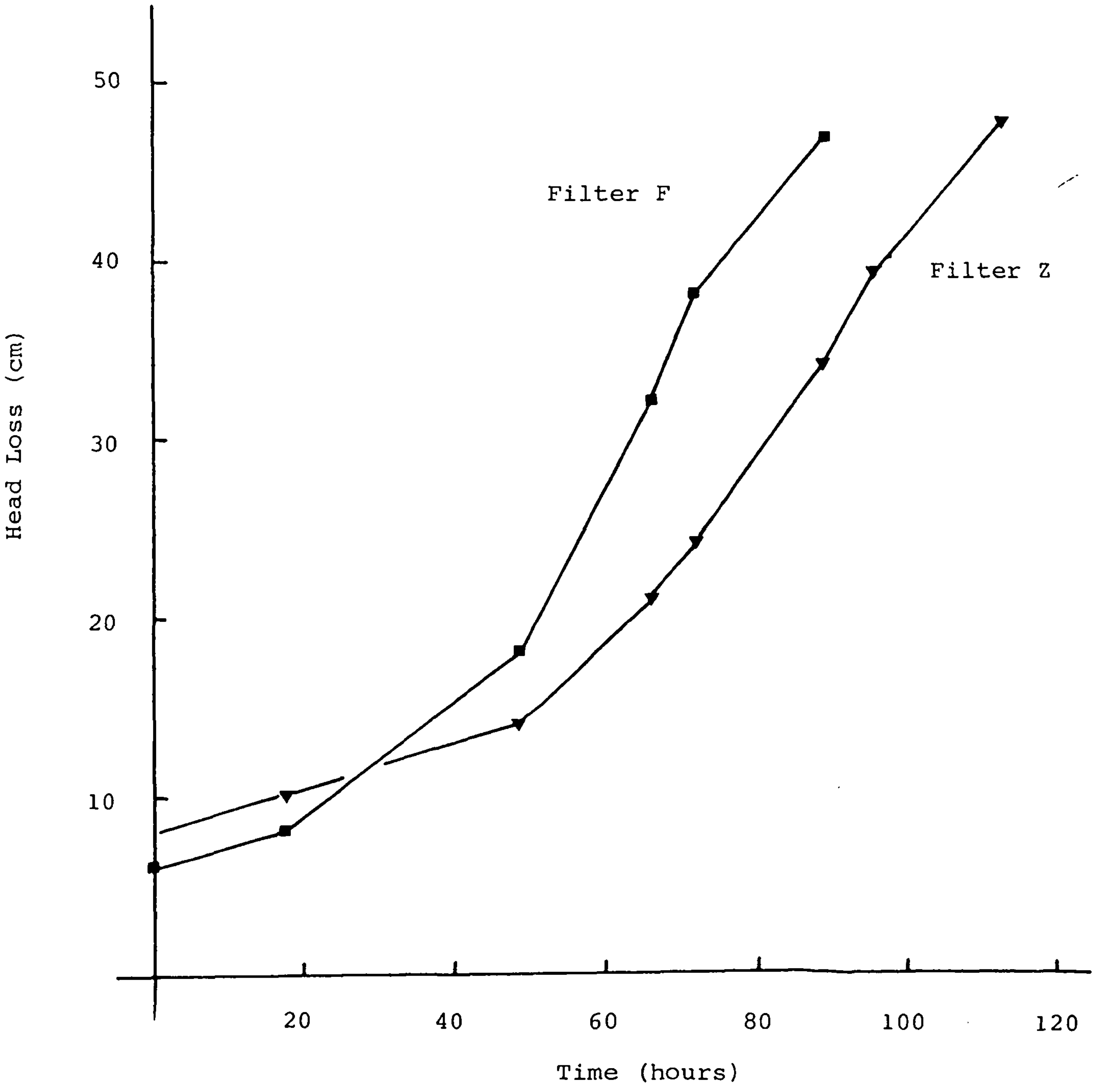


Figure 9 Progress of Filtration Runs: Comparison of double fabric layer in squares (filter F) with no protection (filter Z)

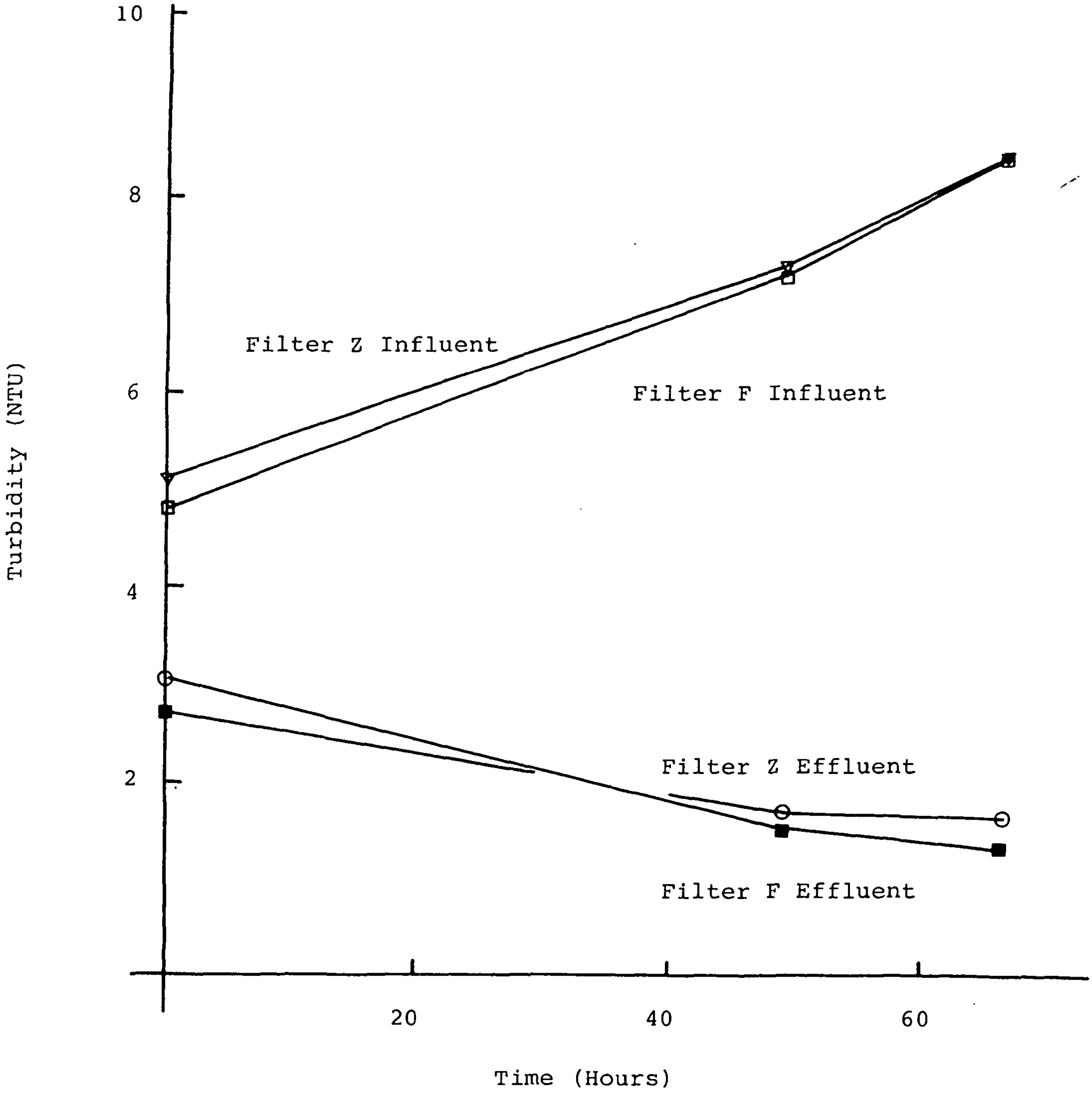


Figure 10 Turbidity Values: Comparison of double fabric layer in squares (filter F) with no protection (filter Z)

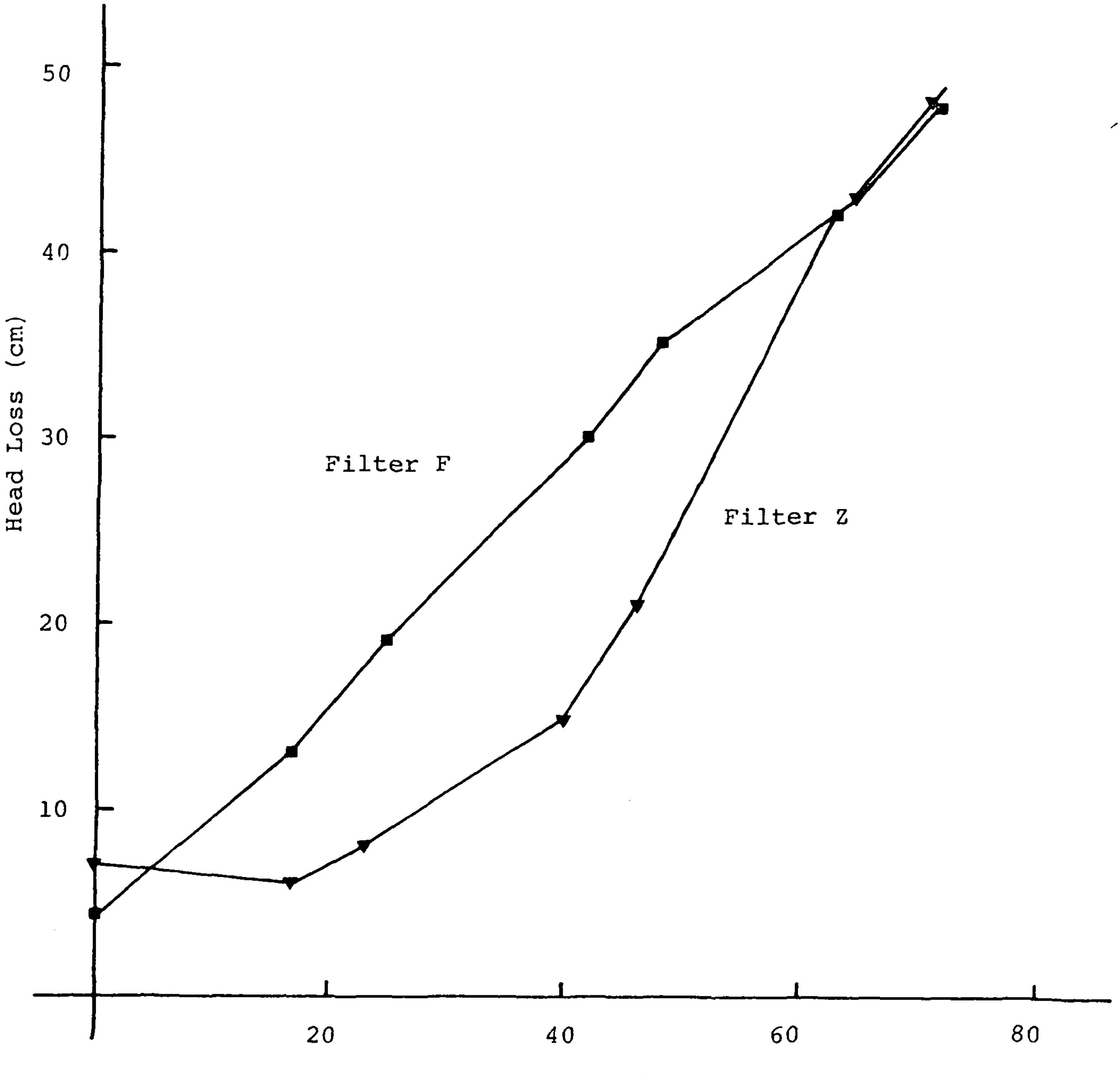


Figure 11 Progress of Filtration Runs: Comparison of double fabric layer in squares (filter Z) with no protection (filter F)

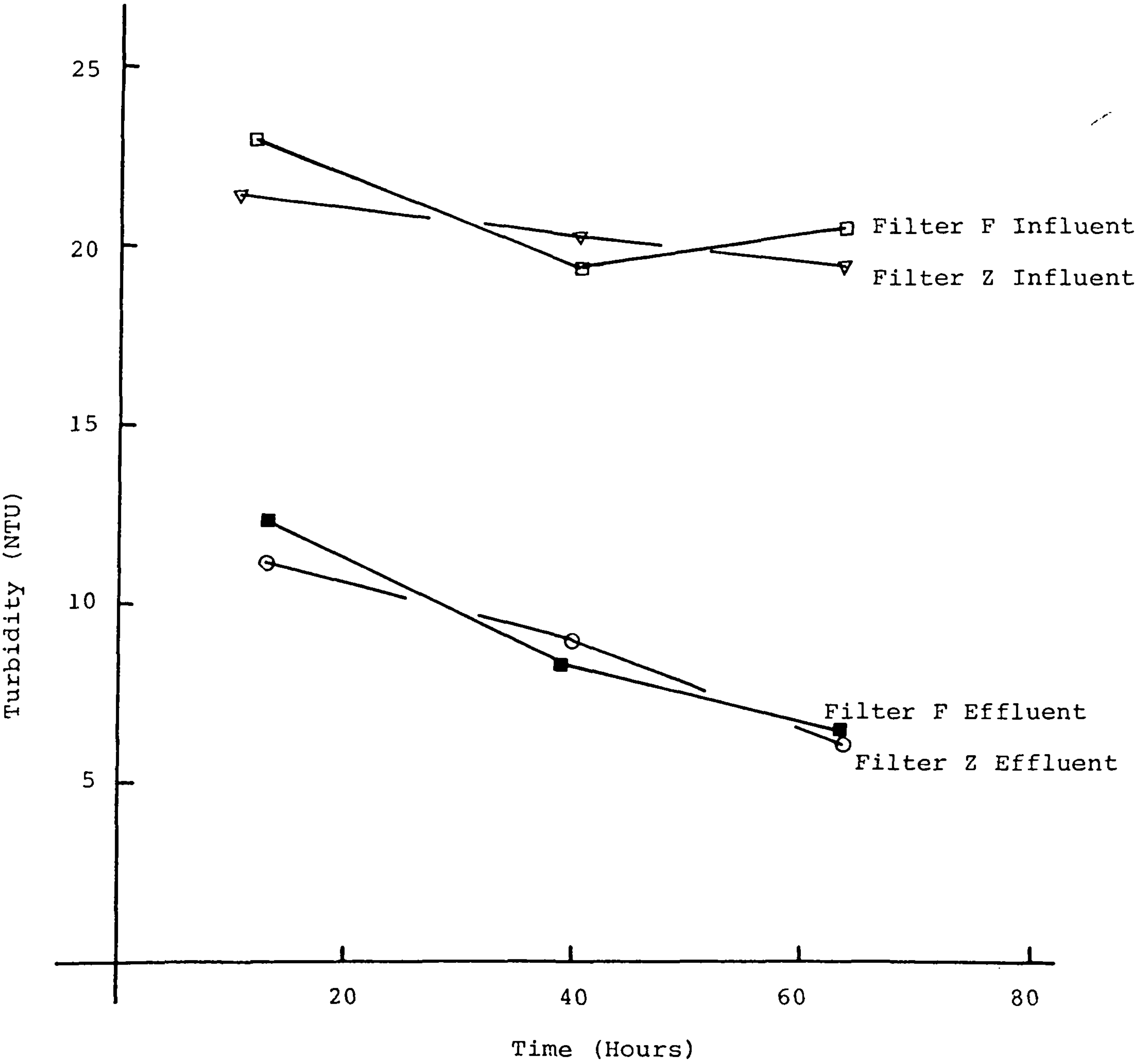


Figure 12 Turbidity Values: Comparison of double fabric layer in squares (filter Z) with no protection (filter F)

during the second experiment, a factor which would tend to accelerate head loss accumulation. It is possible that in this circumstance, filter Z simply had a bad run. Turbidity removals were very similar for protected and unprotected filters in both experiments (Figures 10 and 12).

Figures 13 and 15 compare the efficiency of entire double fabric protection with its equivalent in squares. Not surprisingly, entire double fabric layer protection out-performs fabric square protection substantially when it is placed on the more efficient filter Z (Figure 13). However, this is masked in Table 2 because by taking the standard run length to represent only that time in hours for head loss to increase from 10 cm to 40 cm, the first 100 hours filter run for Z are excluded on that occasion. In the reverse experiment where filter Z was protected by fabric squares, a positive effect of +42.4% was noted. Thus the net positive effect of fabric squares becomes +20.3%. Clearly this observation should be treated with some caution in view of the arbitrary nature of the run length criterion. Nevertheless, fabric square protection clearly does not always suffer in comparison with complete layer protection. Once again, turbidity removals are remarkably similar on parallel filters (Figures 14 and 16).

Figures 17 and 19 provide further mixed evidence, suggesting that the equivalent of three fabric layers in squares provides little or no protection to slow sand filtration. The standardised filtration runs were in all cases very similar. While there are no turbidity data available for the second experiment, Figure 18 shows the familiar similarity in turbidimetric results for both filters regardless of protection.

In the final experiments of their kind, Figures 20 and 22 illustrate the substantial improvement in filtration run performance of entire fabric layers compared with their equivalent in squares. In this case, three layers of fabric were used and the overall difference in performance was approximately 18%. Naturally, the effect is most marked in the superior filter (Figure 20), but is still apparent when circumstances were reversed (Figure 22). Turbidity results followed the previously noted form (Figures 21 and 23).

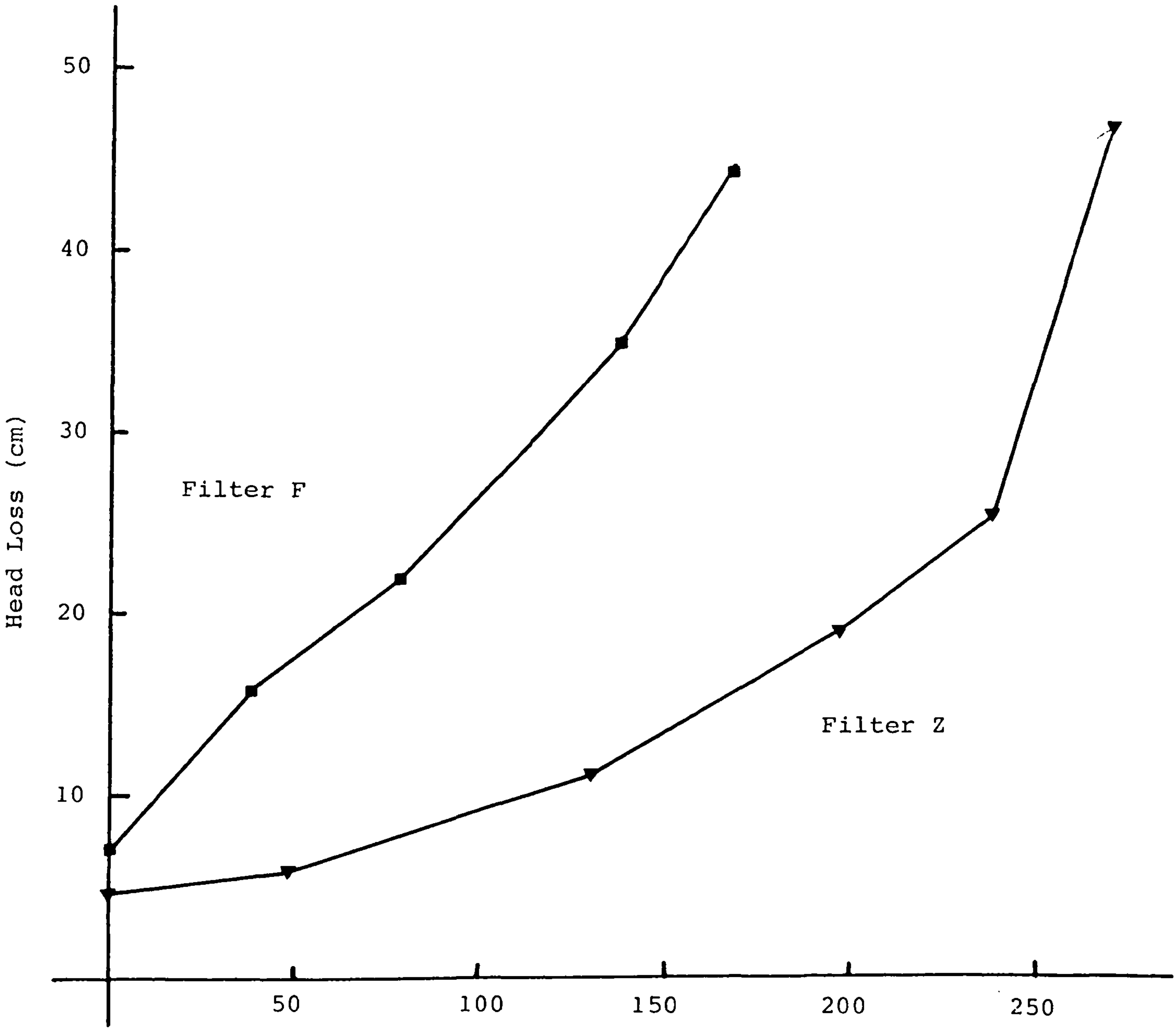


Figure 13 Progress of Filtration Runs: Comparison of double fabric layer in squares (filter F) with entire double fabric layer (filter Z)

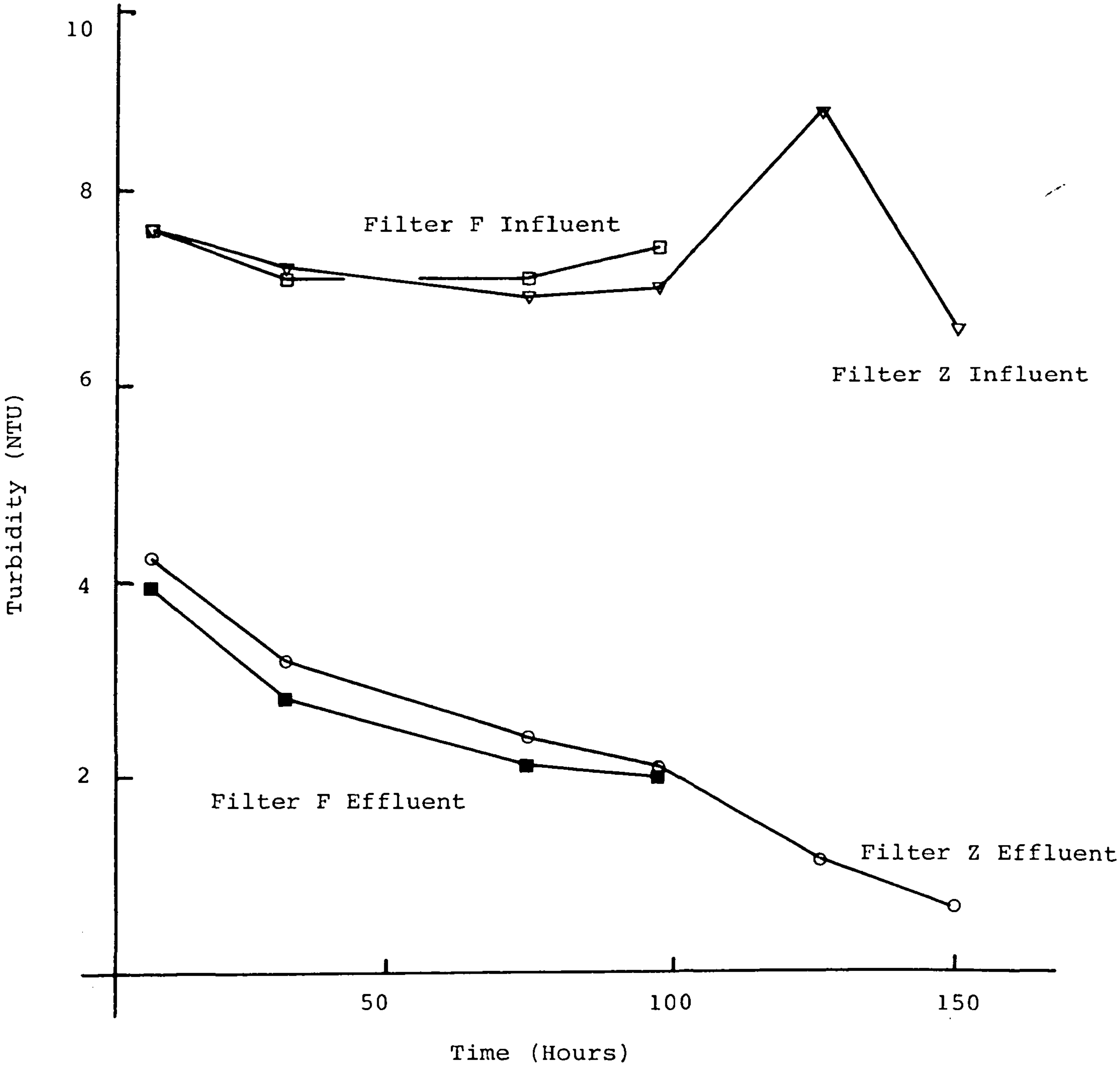


Figure 14 Turbidity Values: Comparison of double fabric layer in squares (filter F) with entire double fabric layer.

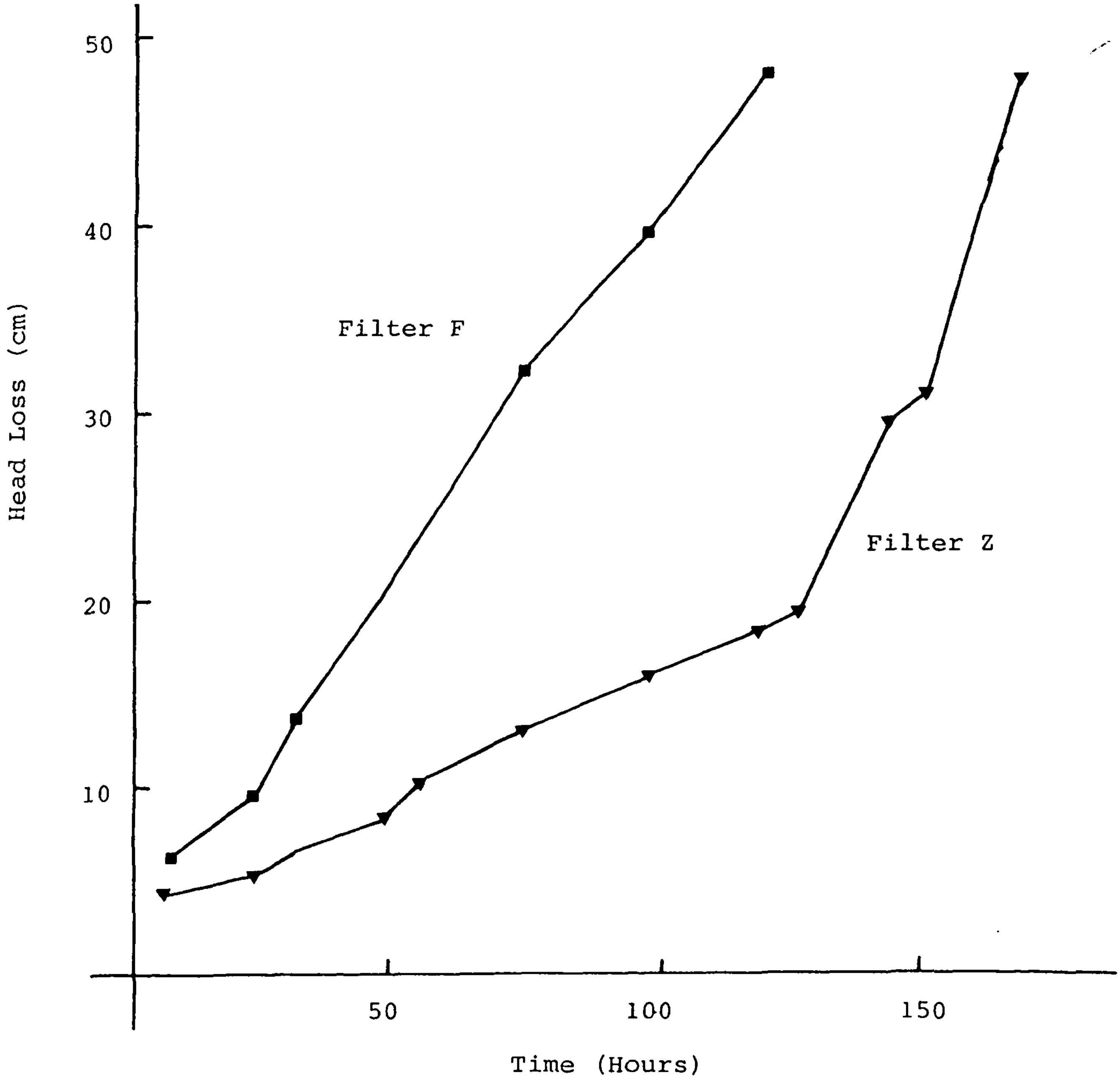


Figure 15 Progress of Filtration Runs: Comparison of double fabric layer in squares (filter Z) with entire double fabric layer (filter F)

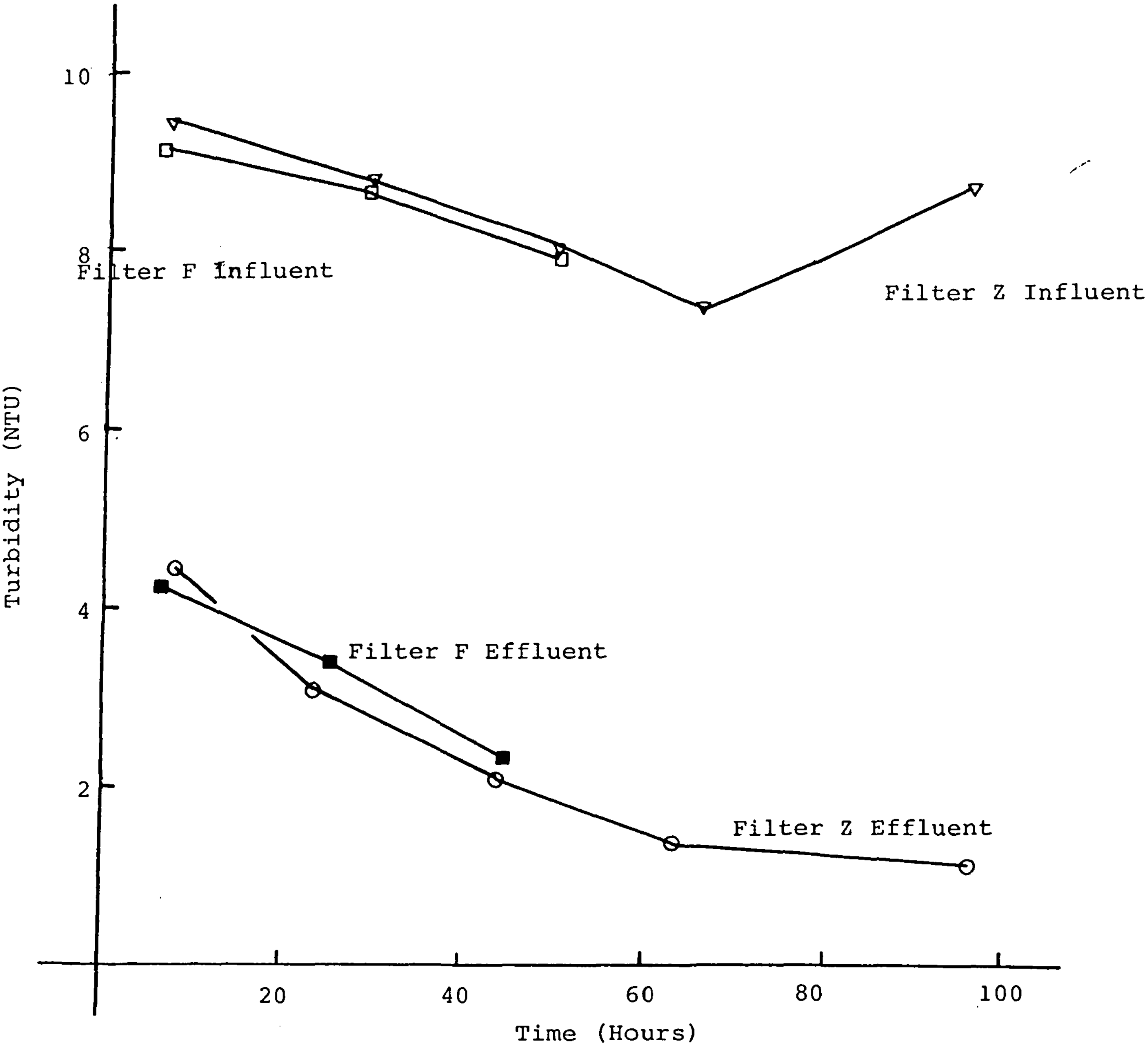


Figure 16 Turbidity Values: Comparison of double fabric layer in squares (filter Z) with entire double layer (filter F)

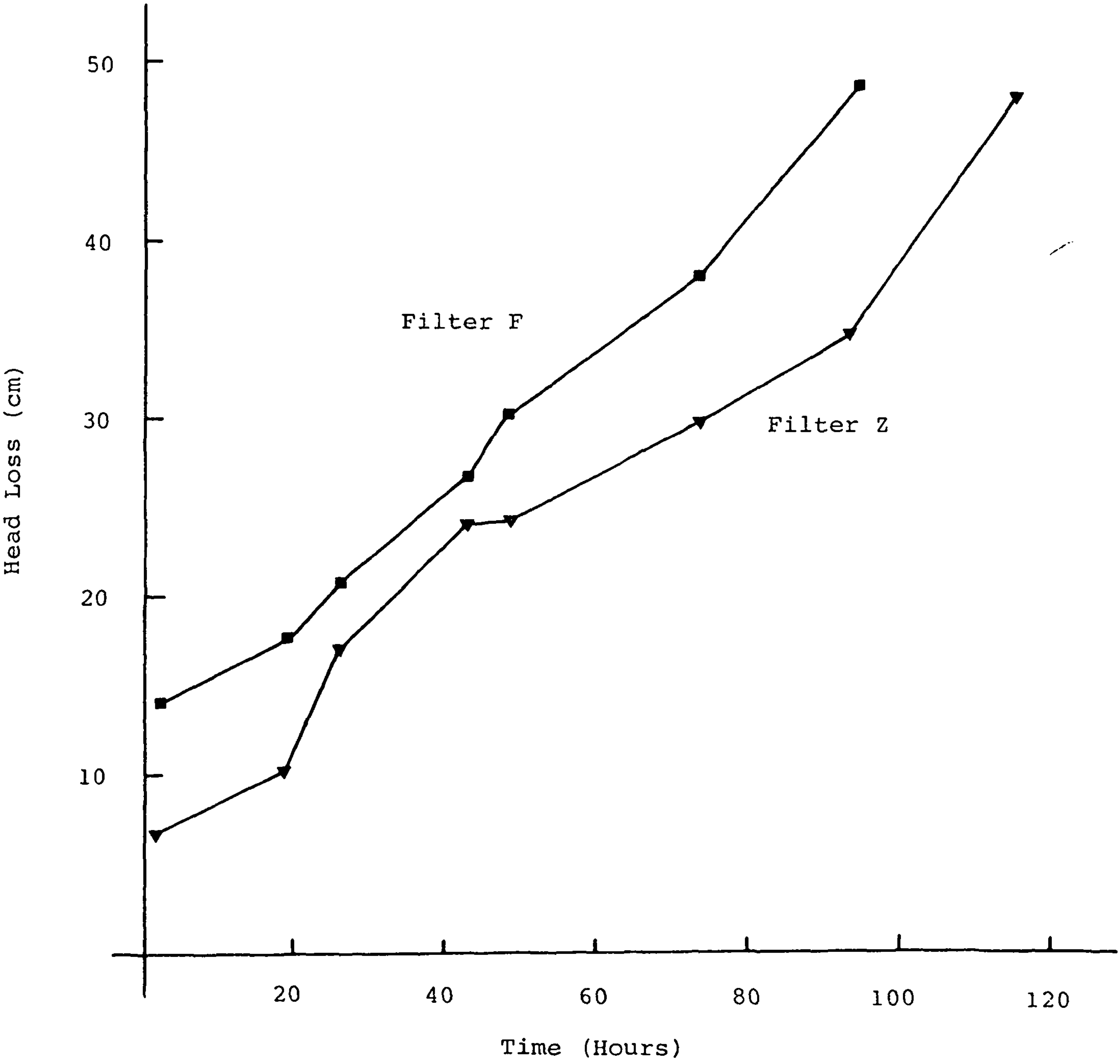


Figure 17 Progress of Filtration Runs: Comparison of treble fabric layer in squares (filter F) with no protection (filter Z)

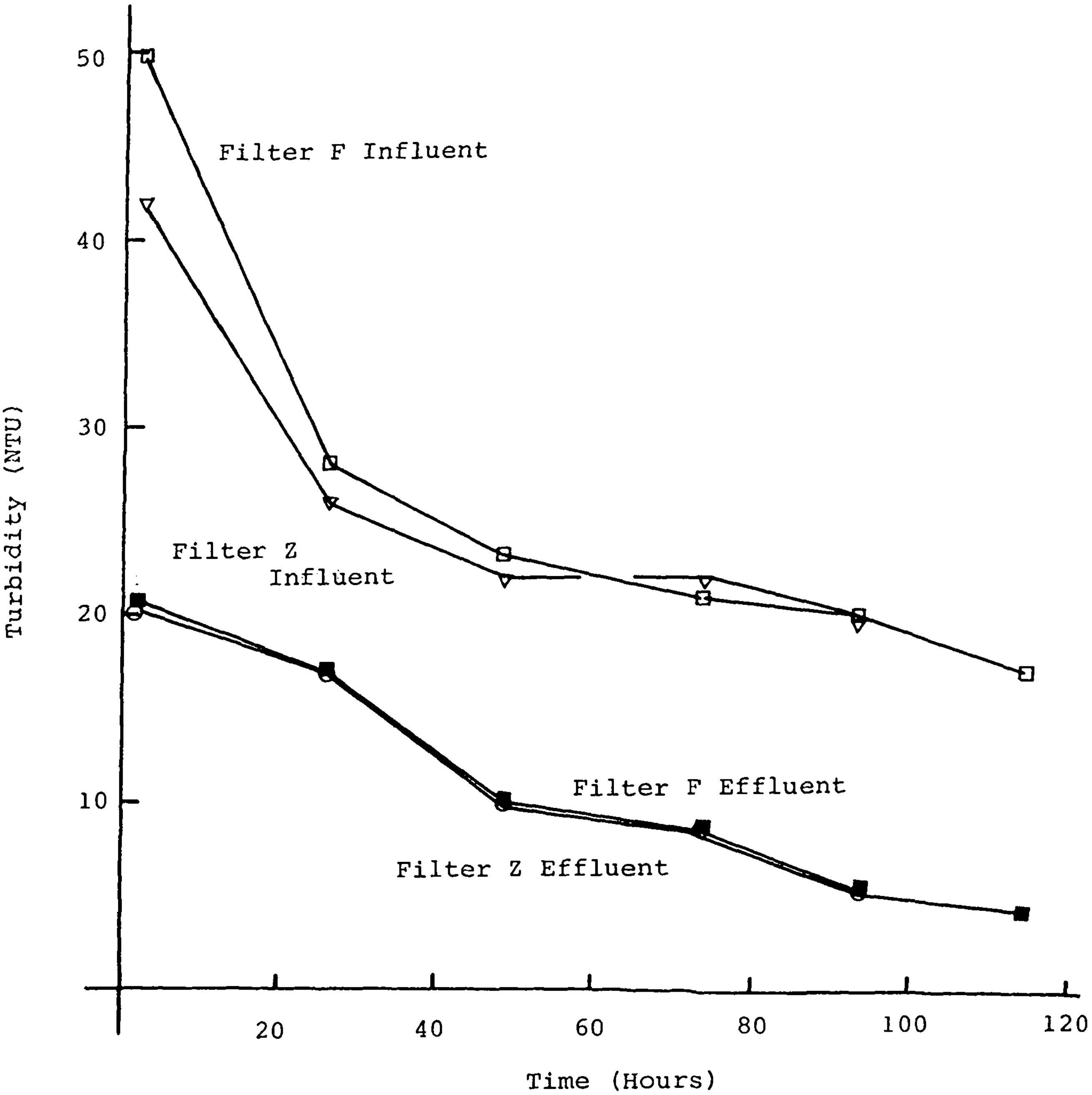


Figure 18 Turbidity Values: Comparison of treble fabric layer in squares (filter F) with no protection (filter Z).

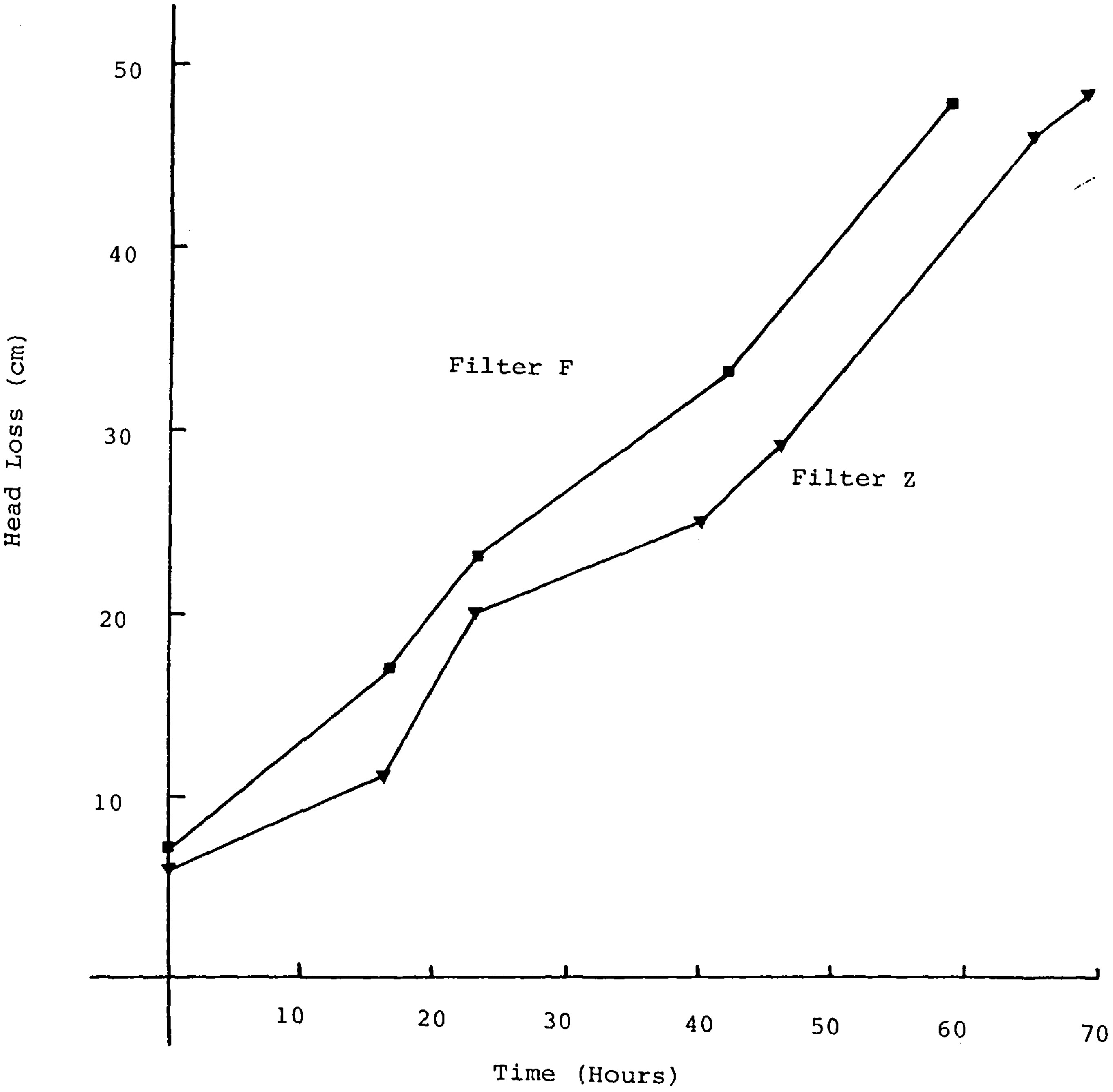


Figure 19 Progress of Filtration Runs: Comparison of treble fabric layer in squares (filter Z) with no protection (filter F)

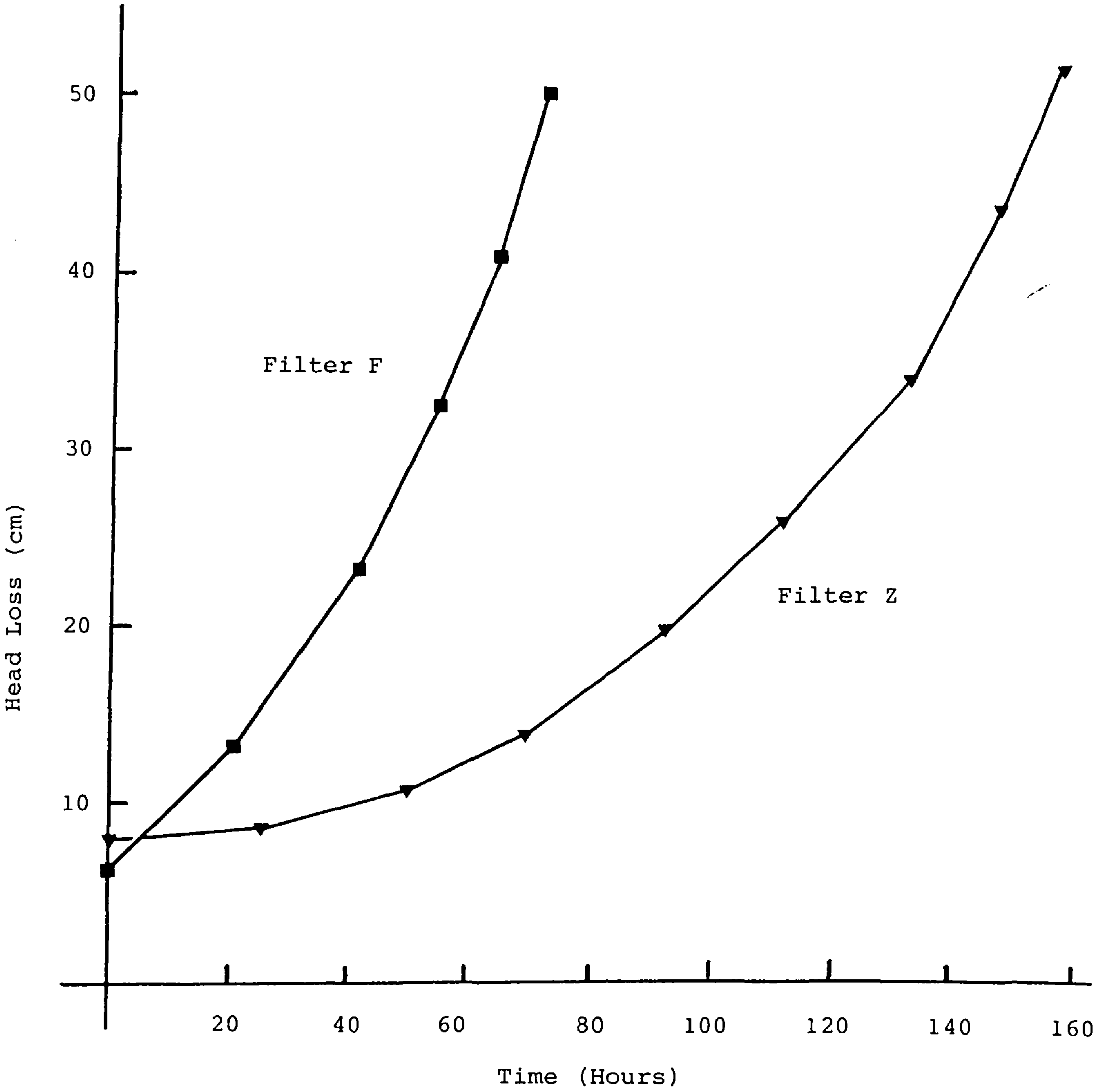


Figure 20 Progress of Filtration Runs: Comparison of treble fabric layer in squares (filter F) with entire treble fabric layer (filter Z)

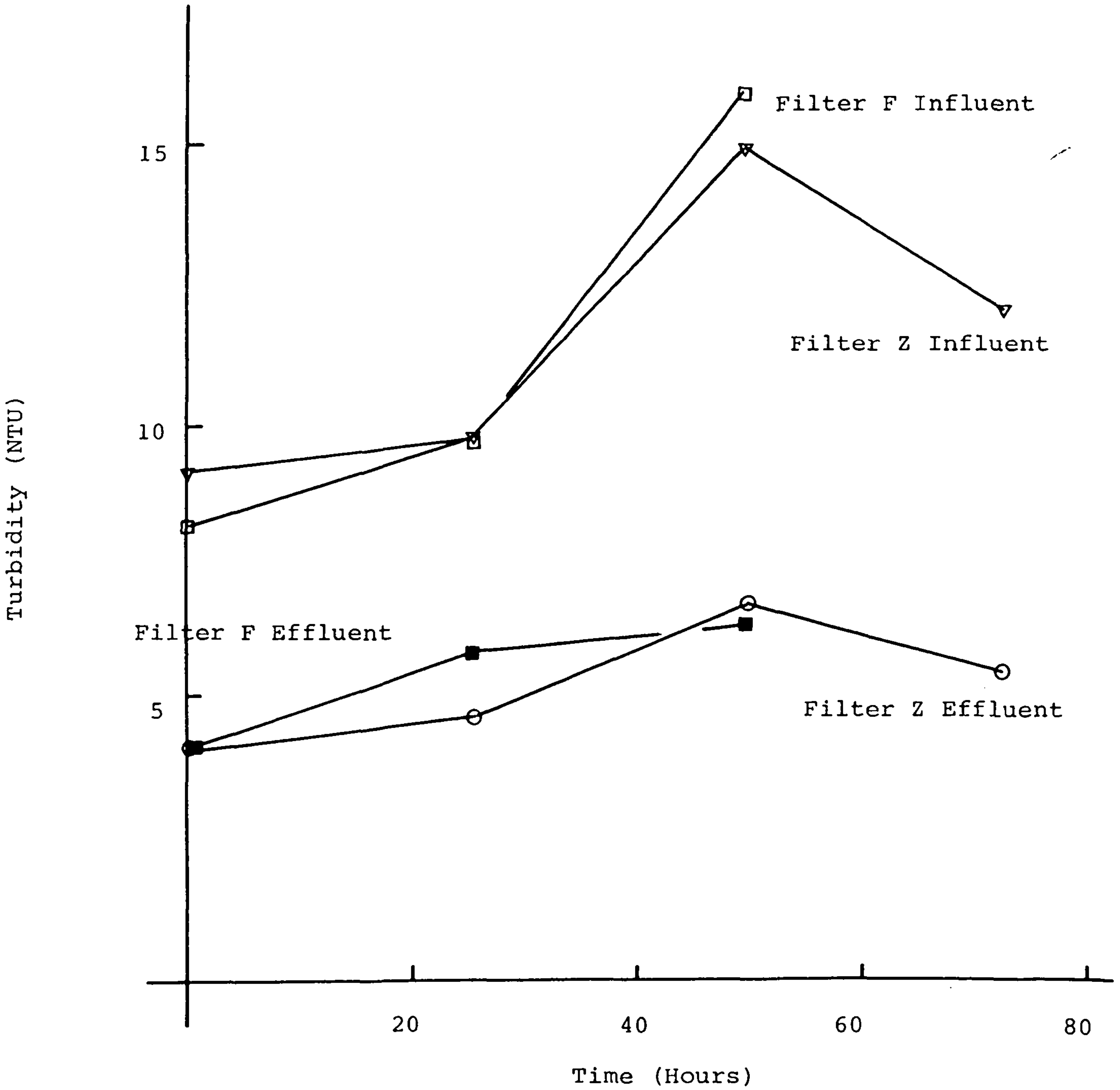


Figure 21 Turbidity Values: Comparison of treble fabric layer in squares (filter F) with entire treble fabric layer (filter Z)

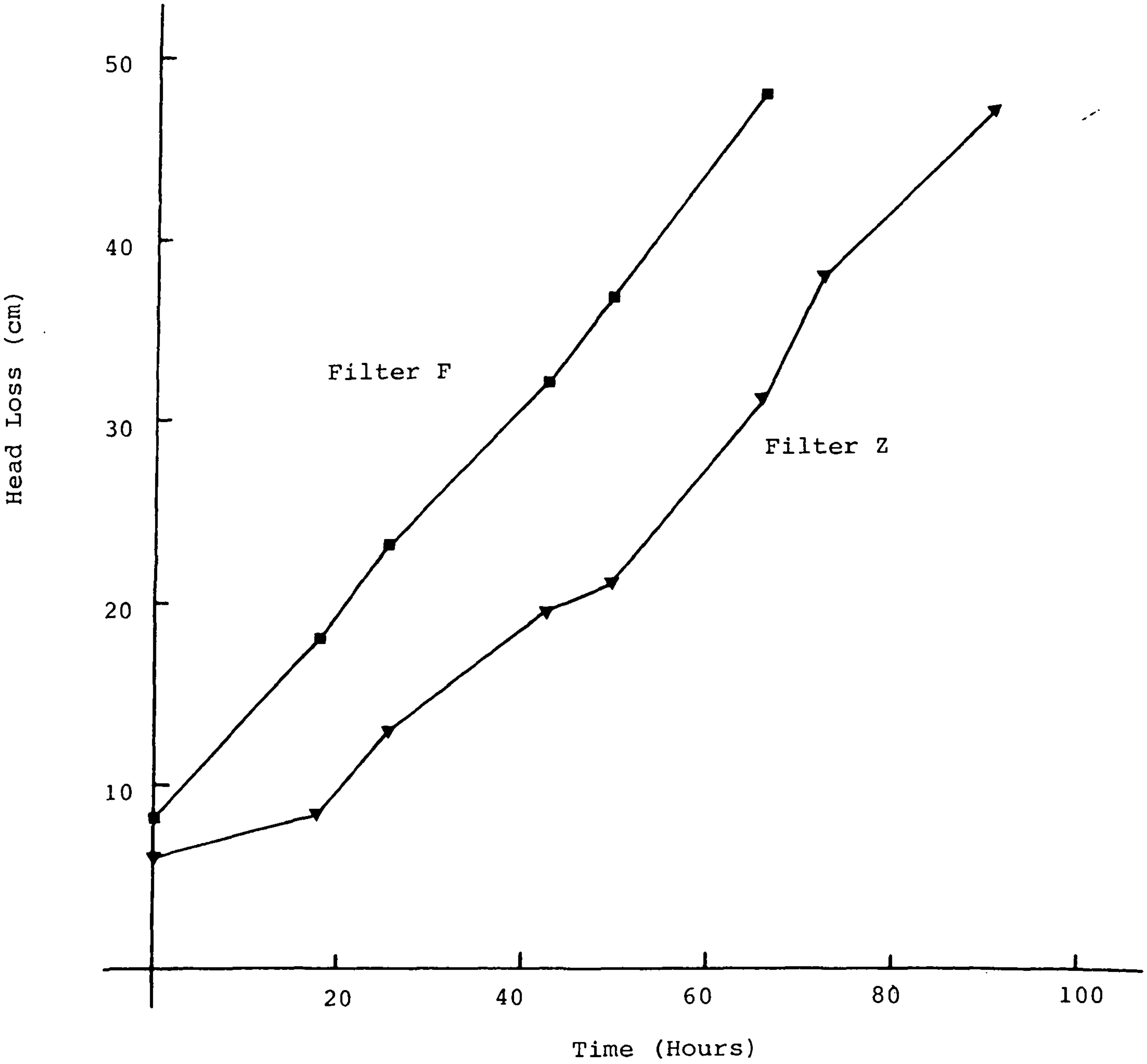


Figure 22 Progress of Filtration Runs: Comparison of treble fabric layer in squares (filter Z) with entire treble fabric layer (filter F)

# SECTION II

## IIi THE APPLICATION OF COARSE MEDIUM ROUGHING FILTRATION IN THE TREATMENT OF TURBID SURFACE WATERS.

A brief review of the available literature concerning horizontal and vertical gravel filtration was provided in an earlier report (10). Since the production of that review, more information has become available, and thanks to the International Reference Centre for Wastes Disposal (IRCWD) there now exists a focus for international research and collaboration on this topic.

A more recent, if informal appraisal of developments in the field is provided in Appendix I, and an excellent general account of progress in horizontal flow roughing filtration was circulated widely in late 1984 (11). We are also aware of research conducted in Finland and Ethiopia which specifically addressed direct and horizontal coarse medium filtration and was completed in 1984 (12, 13).

It is not intended here to offer a more complete review or to describe the detailed mathematical concepts involved in gravel filtration. However, a summary of definitions is provided (Appendix IV) and brief consideration is given here to some of the theories and parameters appertaining to this form of water treatment. The results of field trials in the UK and Peru are presented with a discussion of their joint relevance.

## IIii THEORETICAL CONSIDERATIONS

The theoretical basis of porous medium filtration was investigated in this study, to incorporate the relationships between medium type, flow rate, head loss, filter length, Reynolds number and friction factor.

We were aware of the mass of empirical evidence which has accumulated to suggest that filtration rates should be restricted to 0.5-2.0 m/h in order to optimise performance and reduce maintenance commitments (11) and that

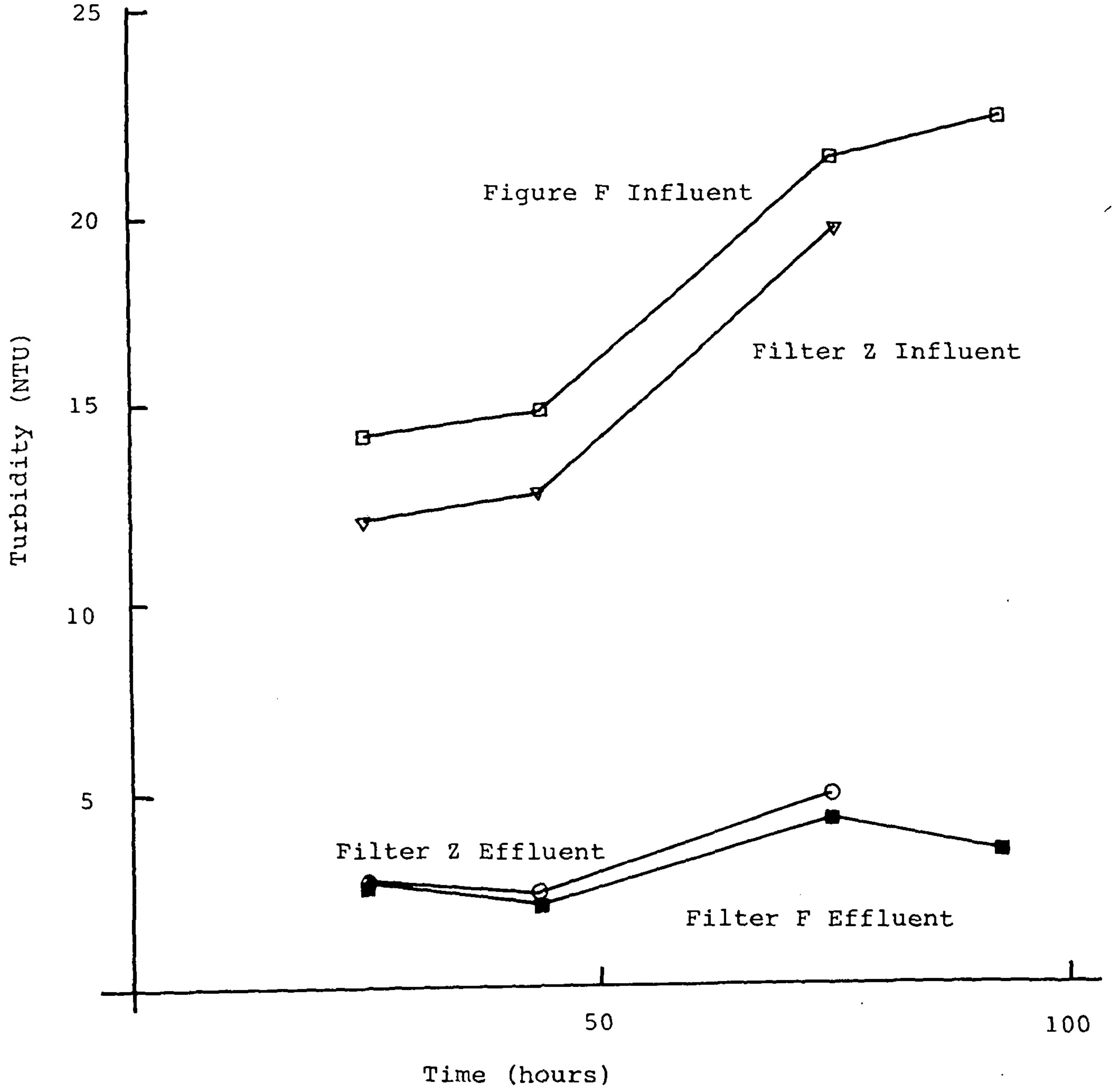


Figure 23 Turbidity Values: Comparison of treble fabric layer in squares (filter Z) with entire treble fabric layer (filter F)

efficiency is directly related to Reynolds Number (13). However, we were also aware of some practical and experimental evidence which suggested that efficiency is high in the transitional zone between laminar and turbulent flow. This occurs when the Reynolds Number exceeds 5 (14). It has also been reported that at the onset of turbulence, total solids removal may be even greater due to the increased chances of contact between particles and grain surfaces. For a grain size of 18-32 mm, for example, this can mean a Reynolds Number as high as 38 (13). Thus, actual velocities of 5-20 m/h have been applied in Europe (15, 16).

Scarlet attempted to characterise the relevance of porous and particulate systems to filtration technology (17). Ives summarised developments in filtration theory and incorporated them into a mathematical analysis involving a filter coefficient to assess the effectiveness of a filter as a clarifyer for uniform and non-uniform flow (18). Reviews by Dullien (19), and Tien and Payatakes (20) reflected continuing interest in porous medium filtration. Using the assumption that a filter reaches its head loss limit simultaneously with the limit of filtrate concentration, Sembi and Ives (21) mathematically modelled various permutations of media size and filter length. They predicted that two combinations of gravel were as effective as multi-layer systems, considering the technical and economic constraints which would be encountered. Although the majority of theoretical filtration analysis has been concentrated on deep bed filtration it has been judged reasonable to predict that horizontal filters should function in a similar manner with regard to physical performance

Thus it is conceivable that whereas high flow rates promote efficiency in both vertical and horizontal filters with minerally turbid waters, in the former they may induce premature blockage thereby increasing maintenance requirements. Conversely, Wegelin has demonstrated that with horizontal filters there is a sequential blockage which may be likened to a downward, diagonal cascading of particles and aggregates from upper to lower horizons in the bed (11). Thus the filter blocks from the bottom upwards while the top portion regenerates permeability. This process could be enhanced and maintenance substantially reduced by allowing for underdrainage of the filter on a periodic basis. Then, total blockage becomes a function of filter length, and with very long filters, total overhaul may be very infrequent indeed. Maintenance schedules measured in years rather than months have been quoted for filters operated in Germany and Switzerland (13).

It was with a view to helping resolve the apparent contradictions in recommended flow rates for coarse medium filtation that experiments were conducted both in the UK and Peru. Furthermore, the behaviour of gravel filters subject to widely different suspended solids type and loading was investigated in order to provide field operational data relevant to the design of gravel prefilters. Emphasis was also placed on the microbiological performance of the process.

## IIiii METHODS (UK).

Research work at the University of Surrey included investigations of the optimum media size for maximum physico-chemical and bacteriological improvement. Three gravel sizes were selected in this study: 10, 20 and 40 mm in diameter. The three critical physical parameters selected to describe the gravel were porosity, voids ratio and specific gravity.

Experimentally, the parameters were determined by a displacement technique on samples comprising 1L of gravel in a measuring cylinder. The following relationship was employed for porosity:

$$n = 1 - \frac{W_s}{G\,Y_w\,V}$$

where n is porosity;

$Y_w$ is unit weight of water,

G is specific gravity of solids,

V is volume of solids mass; and

$W_s$ is dry weight of solids.

Porosity is related to voids ratio (e) by the following equation

$$n = \frac{e}{1 + e}$$

and thus:

$$e = \frac{G\,Y_w\,V}{W_s} - 1$$

Specific gravity was also calculated simply from the displacement and weight measurements.

Table 3 describes the principle characteristics of the three gravel types incorporated in the UK study.

TABLE 3 PRINCIPLE PHYSICAL CHARACTERISTICS OF GRAVELS USED IN THE STUDY OF HORIZONTAL PREFILTRATION

| Gravel Type | Porosity (n) | Voids ratio (e) | Specific Gravity (G) |
|---|---|---|---|
| 10 mm | 0.45 | 0.73 | 2.56 |
| 20 mm | 0.49 | 0.94 | 2.76 |
| 40 mm | 0.57 | 1.21 | 3.31 |

The Reynolds Numbers ($R_e$) calculated for the gravels and flow rates in this study are illustrated in Table 4. As described in Appendix IV, Reynolds Number is derived from the ratio of inertial to viscous forces.

Since inertial force ($F_i$) is given by the following equations:

Force = Mass x Acceleration

thus: $F_i = p\, L^2\, u^2$

where: p is density;

L is length; and

u is velocity

and viscous force ($F_v$) is derived thus:

$F_v = \mu\, u\, L$

where $\mu$ is viscosity ;

u is velocity; and

L is length,

Reynolds Number is calculated by:

$$R_e = \frac{p\ u\ L}{\mu}$$

The path length component in the above relationship (L) is variable and can be either the diameter of gravel (d) or the square root of permeability ($k^{.50}$). All calculations in this study assume : L = d.

It is assumed that the numerical values of Reynolds Number ($R_e$) define flow conditions in the following manner :

| | | |
|---|---|---|
| 0 - 5 | : | laminar flow, where viscous forces predominate and $R_e$ is more affected by temperature; |
| 5 - 100 | : | transition zone; and |
| > 100 | : | turbulent flow; where inertial forces predominate |

TABLE 4 CALCULATED REYNOLDS NUMBERS ($R_e$) FOR GRAVEL TYPES AND VELOCITIES OF FLOW USED IN THE UK STUDY

| | GRAVEL TYPE | | |
|---|---|---|---|
| Velocity (m/h) | 10mm | 20mm | 40mm |
| 0.5 | 1.23 | 2.46 | 4.92 |
| 1.0 | 2.46 | 4.92 | 9.84 |
| 1.5 | 3.69 | 7.38 | 14.76 |
| 2.0 | 4.92 | 9.84 | 19.68 |
| 5.0 | 12.3 | 24.6 | 49.2 |
| 10.0 | 24.6 | 49.6 | 98.4 |

NB: Kinematic viscosity ($\nu$) = $1.13 \times 10^{-6}$ $m^2/s$ at $50_oF$

As described in the preliminary report (10), three horizontal gravel filters were constructed from marine plywood (Figure 24). The dimensions were 8 x 1 x 1ft and the filters were filled with the 10 mm, 20mm and 40mm graded gravel before operation in parallel and later in series (Figure 25).

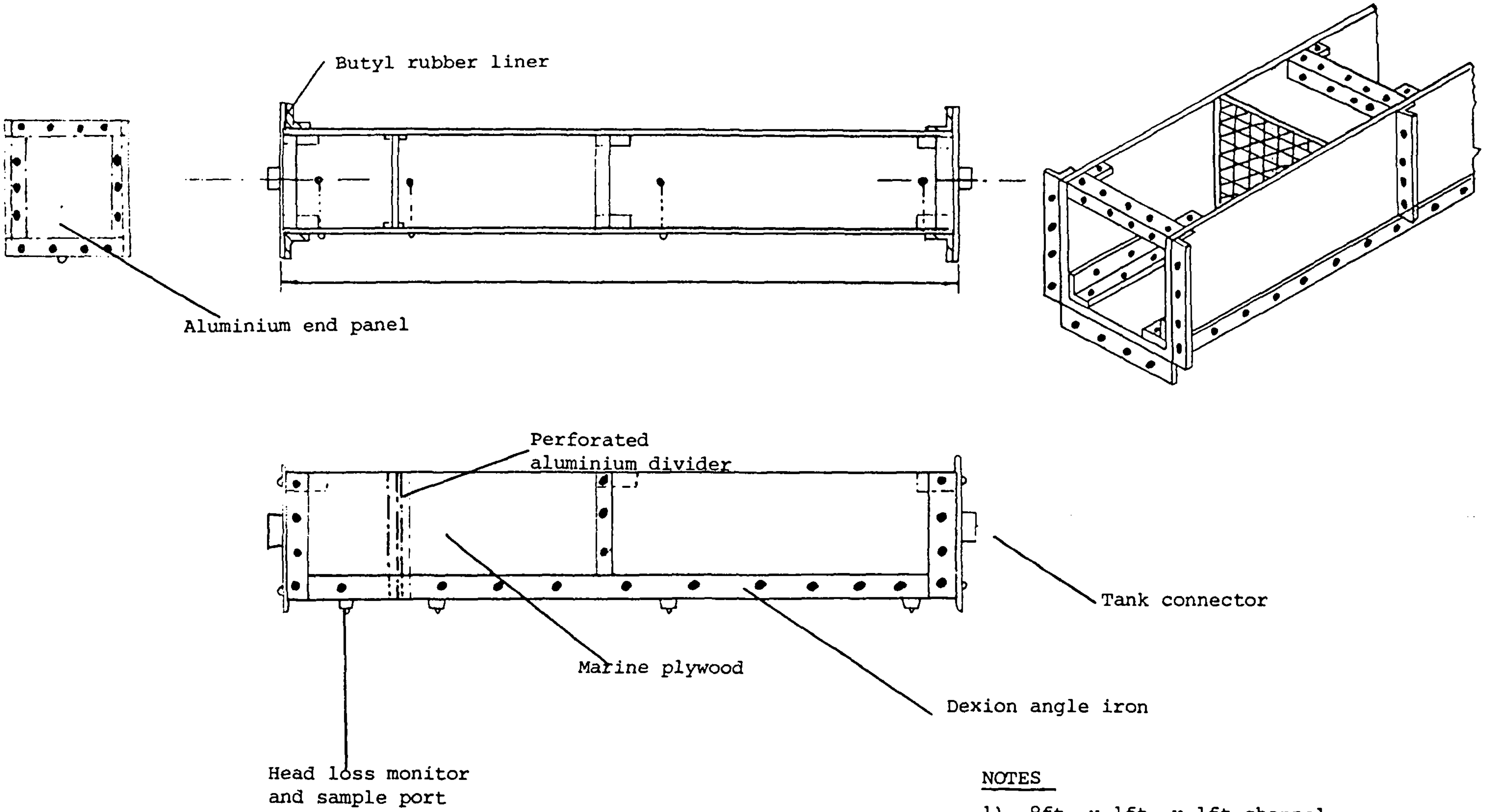
The raw water source was of variable quality being served by run-off and drainage from playing fields and farmland. Influent turbidities ranged between 2 and 100 NTU, suspended solids between 5 and 400 mg/L and faecal coliform densities were almost entirely within the range 1,000 - 10,000 per 100 ml. This water was abstracted directly and pumped to a header tank from which each pilot prefilter was served (see Figure 25).

Filter performance was monitored on a daily basis. Several physico-chemical parameters were analysed including turbidity, suspended solids, filterability and dissolved oxygen. Bacteriological removal in terms of faecal coliform and faecal streptococcus density reductions were assessed. Qualitative suspended solids loading was monitored and head losses measured by piezometers inserted at intervals along the length of the gravel prefilters.

Methods for turbidity, filterability and qualitative suspended solids loading were discussed in Section I. Dissolved oxygen was measured by calibrated probe and meter in the form of percentage saturation which was then converted to DO in mg/L by reference to standard tables. Faecal bacteria were enumerated by standard membrane filtration techniques. Coliforms were recovered on membrane lauryl sulphate broth and streptococci on enterococcus agar using 0.45 µ membrane filters (Gelman GN-6).

## IIiv RESULTS

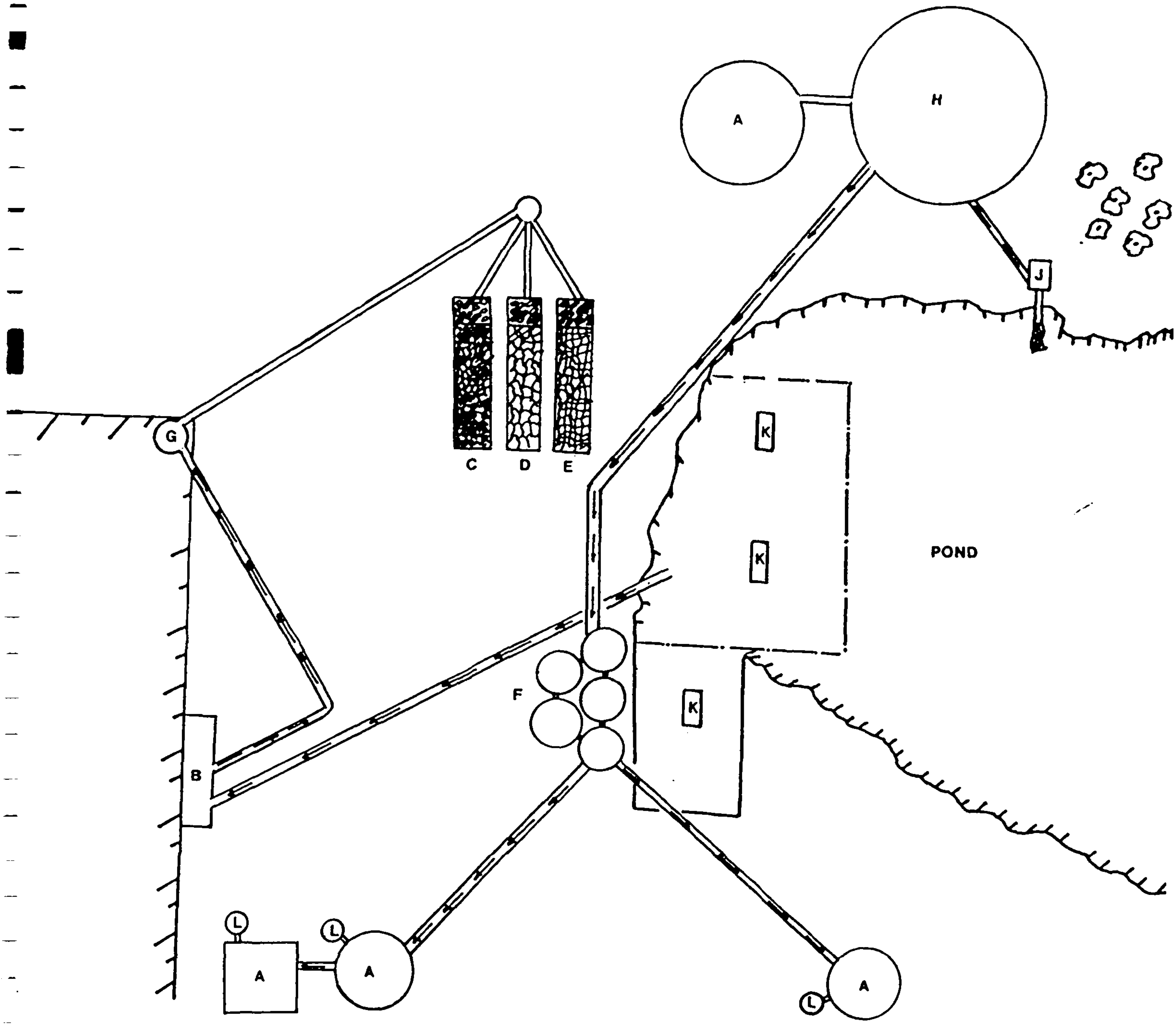
Figures 26-28 describe raw water quality over the total period of experimentation with gravel prefilters. The three major physico-chemical parameters are plotted with the qualitative suspended solids type (four



NOTES

1) 8ft. x 1ft. x 1ft channel
2) Head loss and sampling ports incorporate stainless steel and perspex tubing

Figure 24 Construction of horizontal gravel prefilters



A - Slow sand filters
B - Mono-pumps for sub-sand abstraction
C) -
D) - Gravel pre-filters
E) -
F - Header tank for ODA slow sand filters
G - Header tank for gravel pre-filters
H - OXFAM sedimentation tank
J - Pump for raw water abstraction
K - Cansdale abstraction unit
L - 'Sure-flow' devices

Figure 25 Plan view of field station

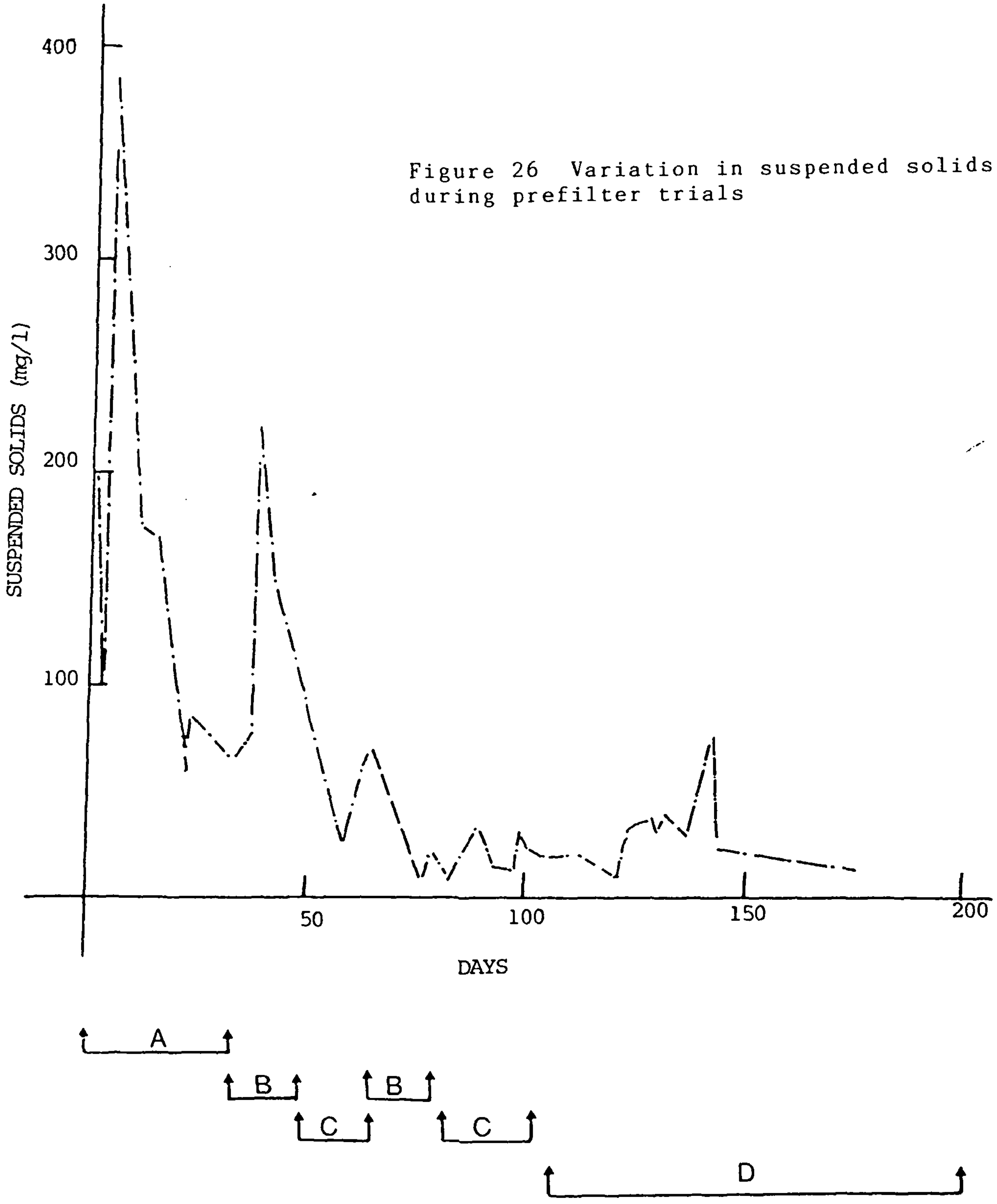


Figure 26 Variation in suspended solids during prefilter trials

WATER QUALITY.

A:- 75 - 100%
B:- 50 - 75%
C:- 25 - 50%
D:- 0 - 25%

Proportion of mineral turbidity

Figure 27 Variation in turbidity of raw water during prefilter trials

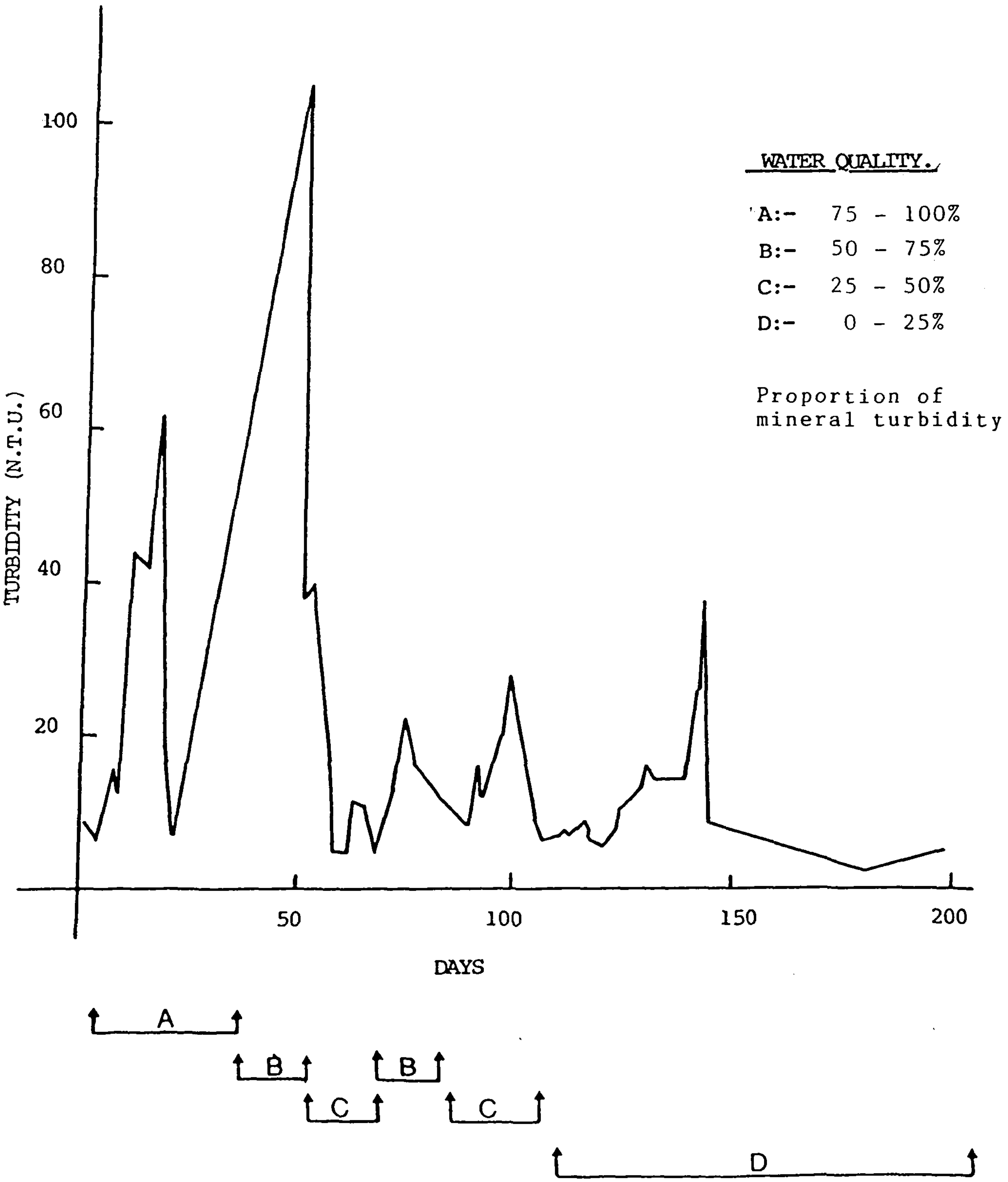
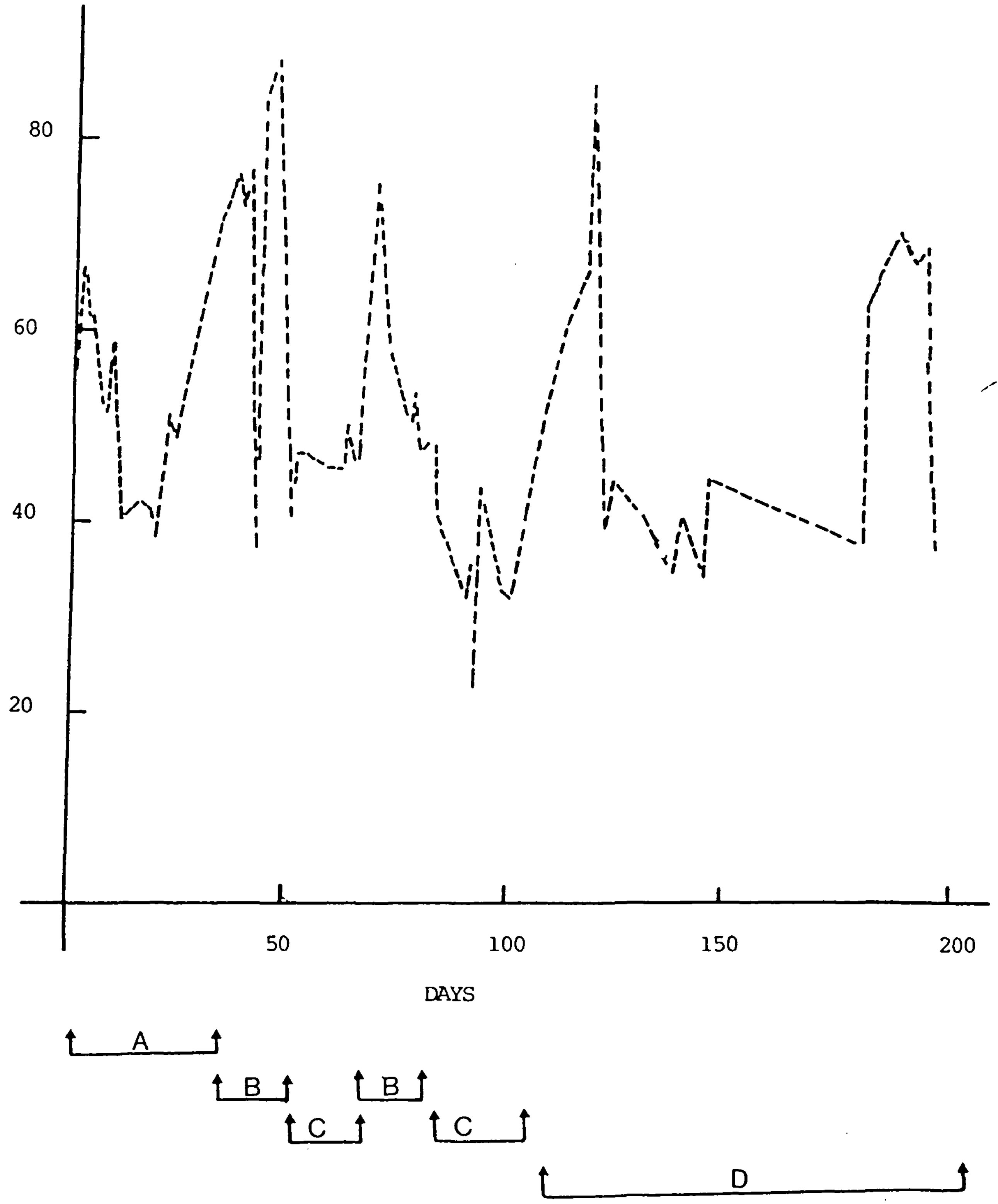


Figure 28 Variation in filterability of raw water during prefilter trials



WATER QUALITY

A:- 75 - 100%
B:- 50 - 75%
C:- 25 - 50%
D:- 0 - 25%

Proportion of mineral turbidity

categories) super-imposed below the lower axis. Regression analyses between all four individual parameters were plotted on a one against one basis. There were no satisfactory individual correlations and time did not permit multivariate analysis. These correlations are not therefore presented here but may become available at a later date as a supplement to this report.

As an early check to establish the flow characteristics through the prefilters, a phage tracer method was employed. Bacteriophage MS2 (coliphage) and Serratia marcescens phage were introduced into the inlet channel of a gravel filter in steady state. Samples were extracted from the effluent channel and analysed for the presence of phage over a four hour period according to standard techniques (22). Results are plotted in Figure 29.

Because the process of gravel filtration was known to provide a degree of microbiological improvement in water quality and therefore to supplement the multiple barrier principle, some attention was directed towards the rate of maturation of filters. Data were generated on several occasions following commissioning of horizontal gravel filters. Representative plots of maturation period are illustrated for both faecal coliform removal and turbidity reduction (Figures 30 and 31). The graphs depict a ten day maturation period for a single horizontal filter containing 10 mm gravel. The filter was operated at a flow rate of 0.5 m/h. Similar logarithmic maturation curves (though with lower overall efficiencies) were obtained for both 20 mm and 40 mm gravel, but are not presented here. Water quality was in the category 75-100% mineral suspended solids and turbidity 10 - 40 NTU.

The majority of data gathered in the gravel filtration study were concerned with the empirical performance of three horizontal filters operated in parallel. The filters were operated at flow rates of 0.5 - 10 m/h for a minimum period of 2 days at each flow rate. Filters were not cleaned between changes in flow rate and thus maturation periods are not relevant. The means of efficiency data with respect to faecal coliform, faecal streptococcus and

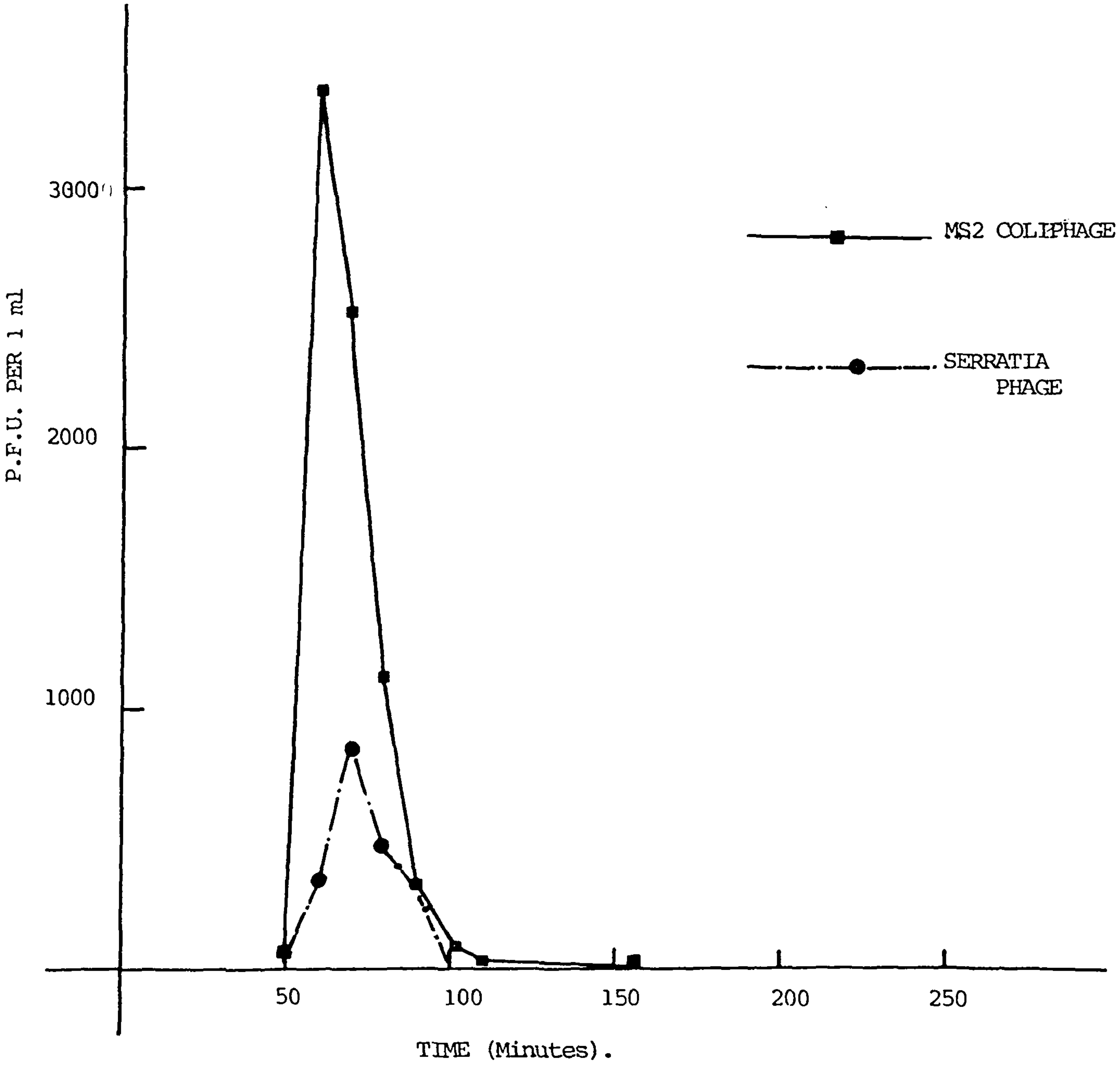


Figure 29 Tracer exercise using bacteriophage in 10mm gravel prefilter operating at 0.5m/h

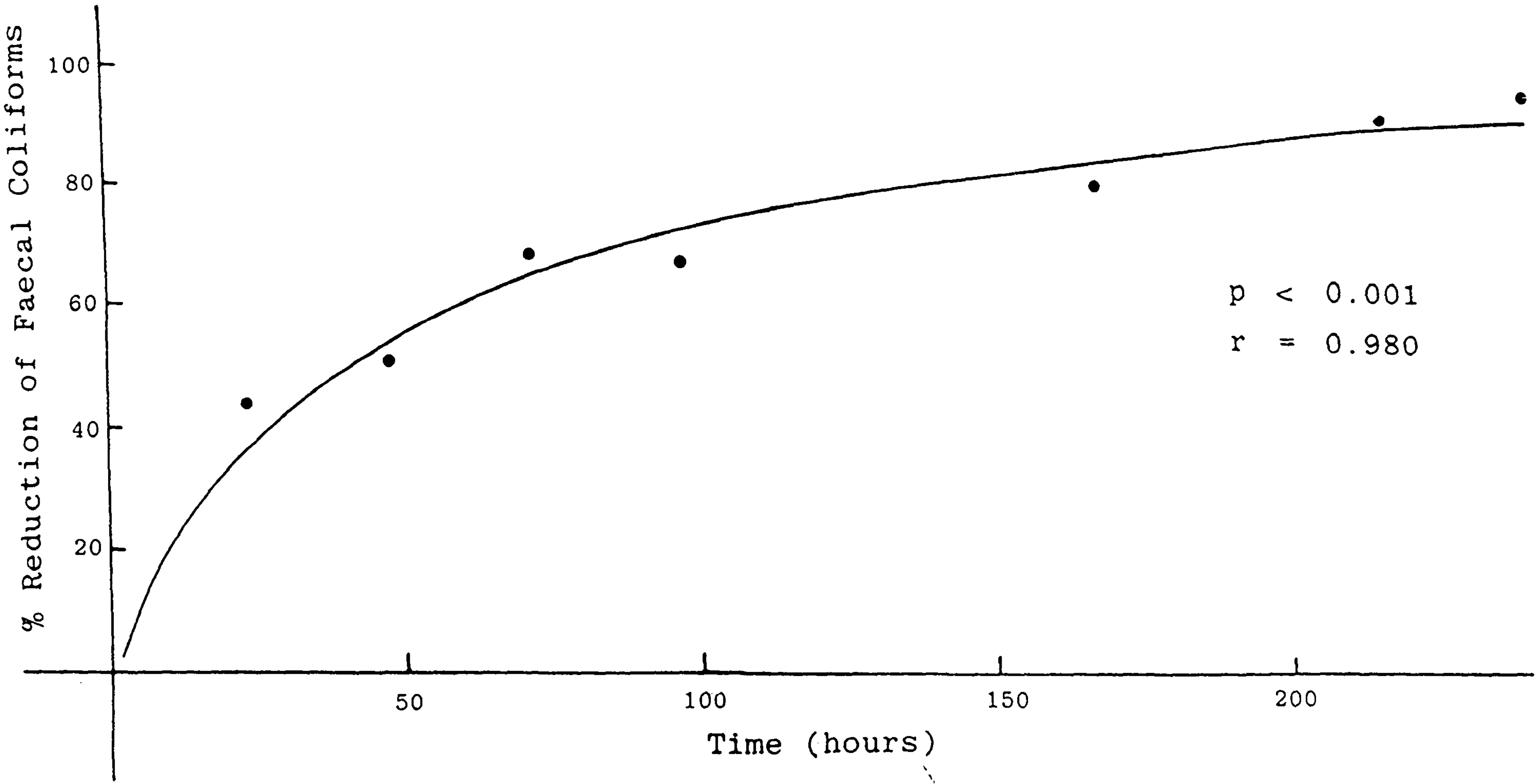


Figure 30 Maturation graph for faecal coliform removal in 10mm gravel prefilter

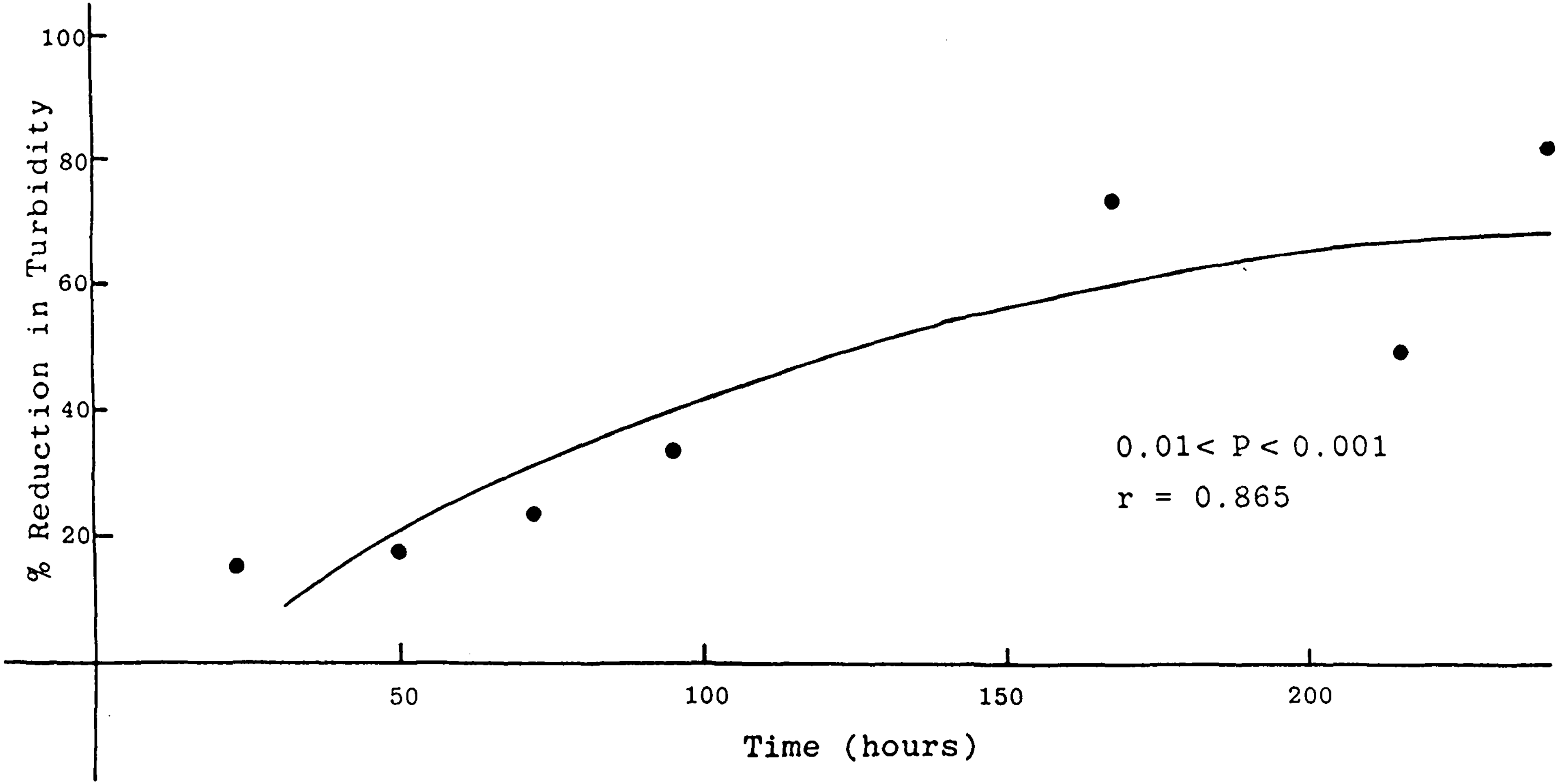


Figure 31 Maturation graph for turbidity removal in 10mm gravel prefilter

turbidity removal are plotted (Figures 32-34). Means were based on a minimum of two separate results. Raw water quality was quite variable. During these experiments faecal coliforms were in the range 100 - 10,000 per 100 ml and faecal streptococci in the range 50 - 5,000 per 100 ml. Turbidity was in the range 5 - 100 NTU, suspended solids 10 - 400 mg/L, and filterability 20-90 (see Figures 26-28).

Subsequent to the comparative trials outlined above, the gravel prefilters were linked in series fashion : 40 mm, 20 mm, and finally 10 mm in order to ascertain total filtration efficiency on an additive basis. Only seven sampling occasions were included in the experiment. Influent turbidity during the period ranged between 2 and 20 NTU. Overall faecal coliform and turbidity reductions over 24ft of gravel medium are described - both Figure 35 and 36 depict the cumulative efficiency of the three media series filter at each stage.

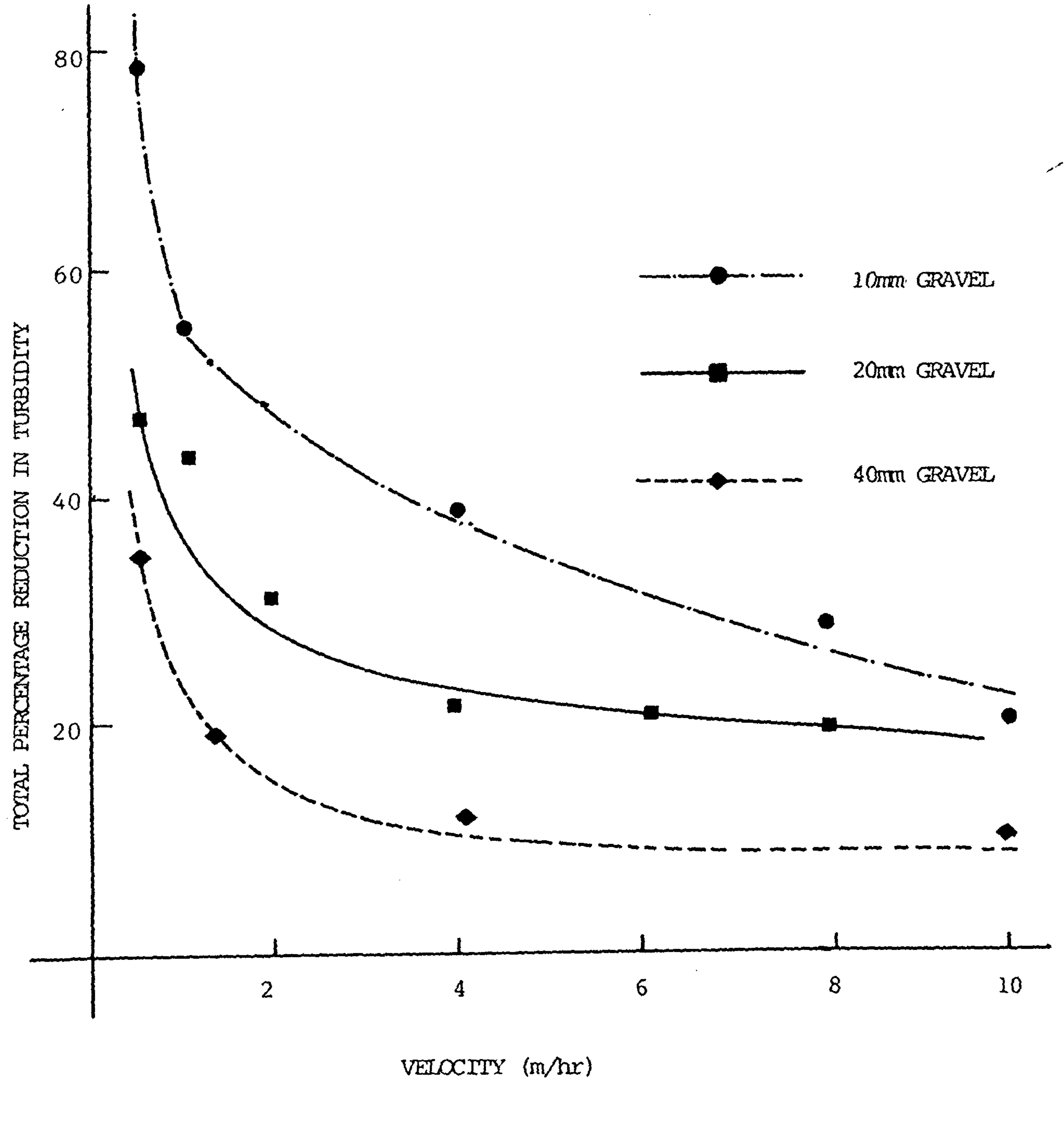


Figure 32 Reduction in turbidity across parallel 8' gravel prefilters (10mm, 20mm and 40mm) at velocities 0.5 - 10 m/h

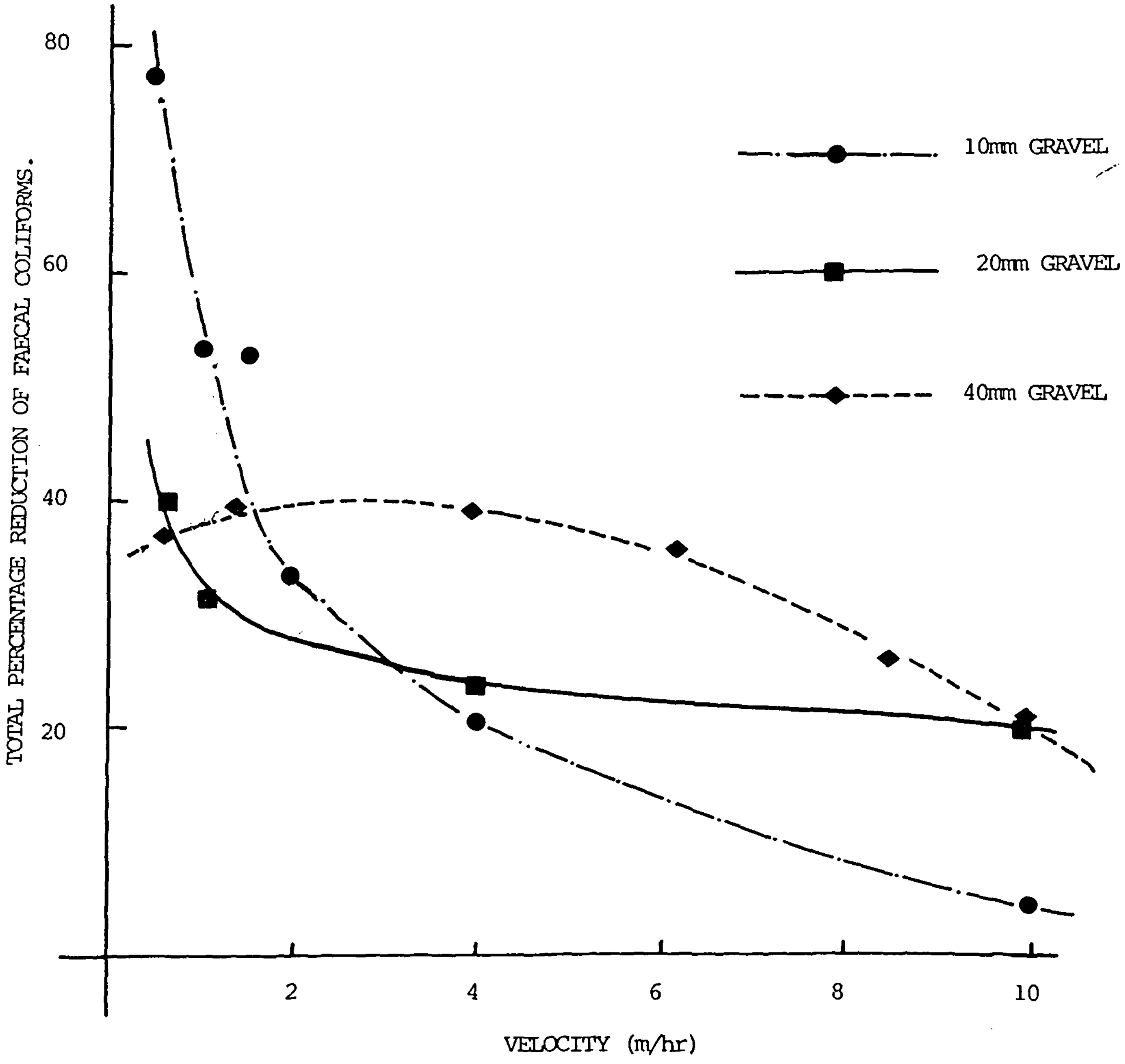


Figure 33 Reduction in faecal coliform densities across parallel 8' gravel prefilters (10mm, 20mm and 40mm) at velocities 0.5 - 10 m/h

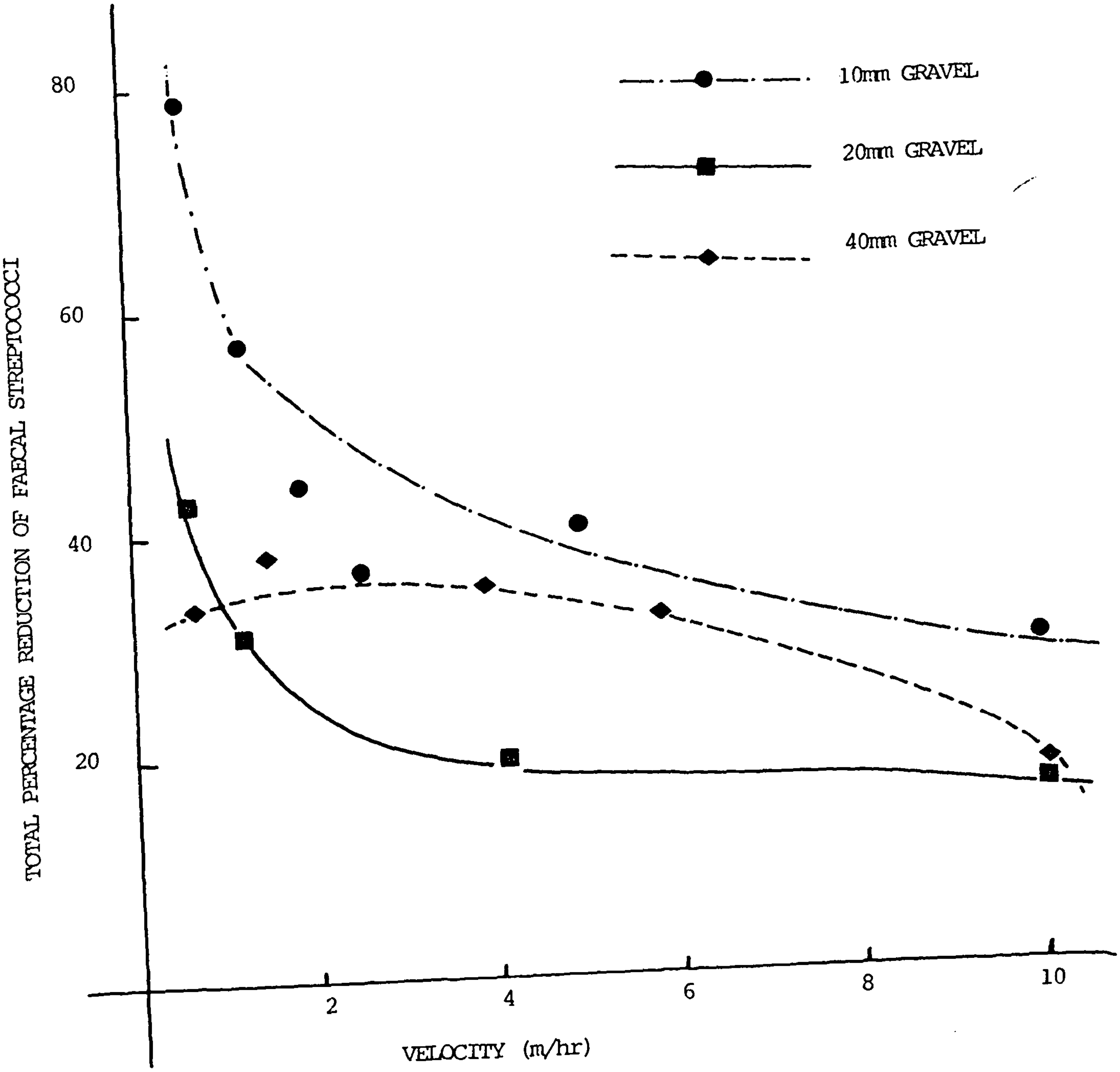
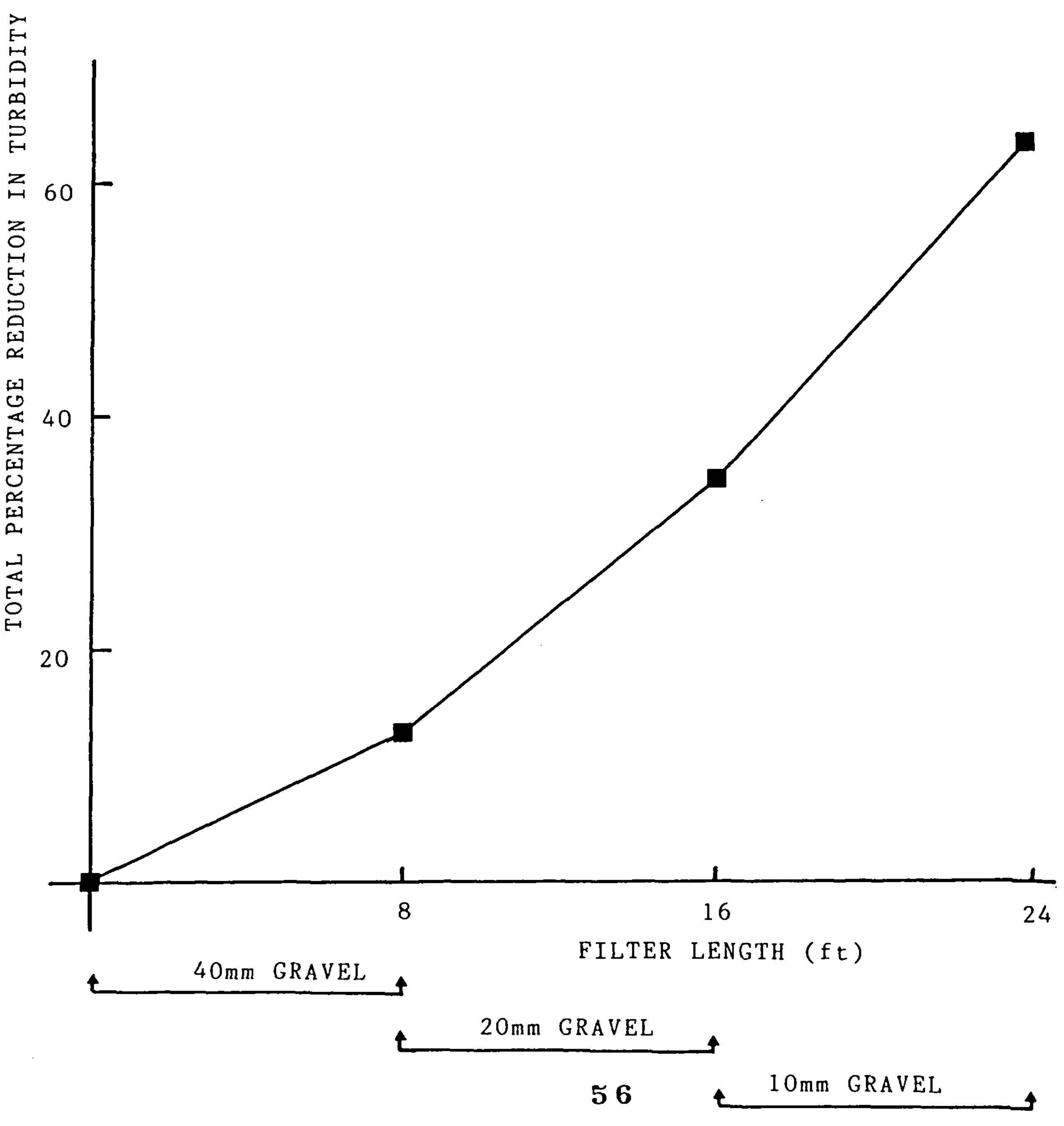


Figure 34 Reduction in faecal streptococcus densities across parallel 8' gravel prefilters (10mm, 20mm and 40mm) at velocities 0.5 - 10 m/h

Figure 35 Cumulative reductions in turbidity across a 3-series horizontal gravel prefilter operated at 0.5m/h (nb Each *point is based on the mean of 7 results*)



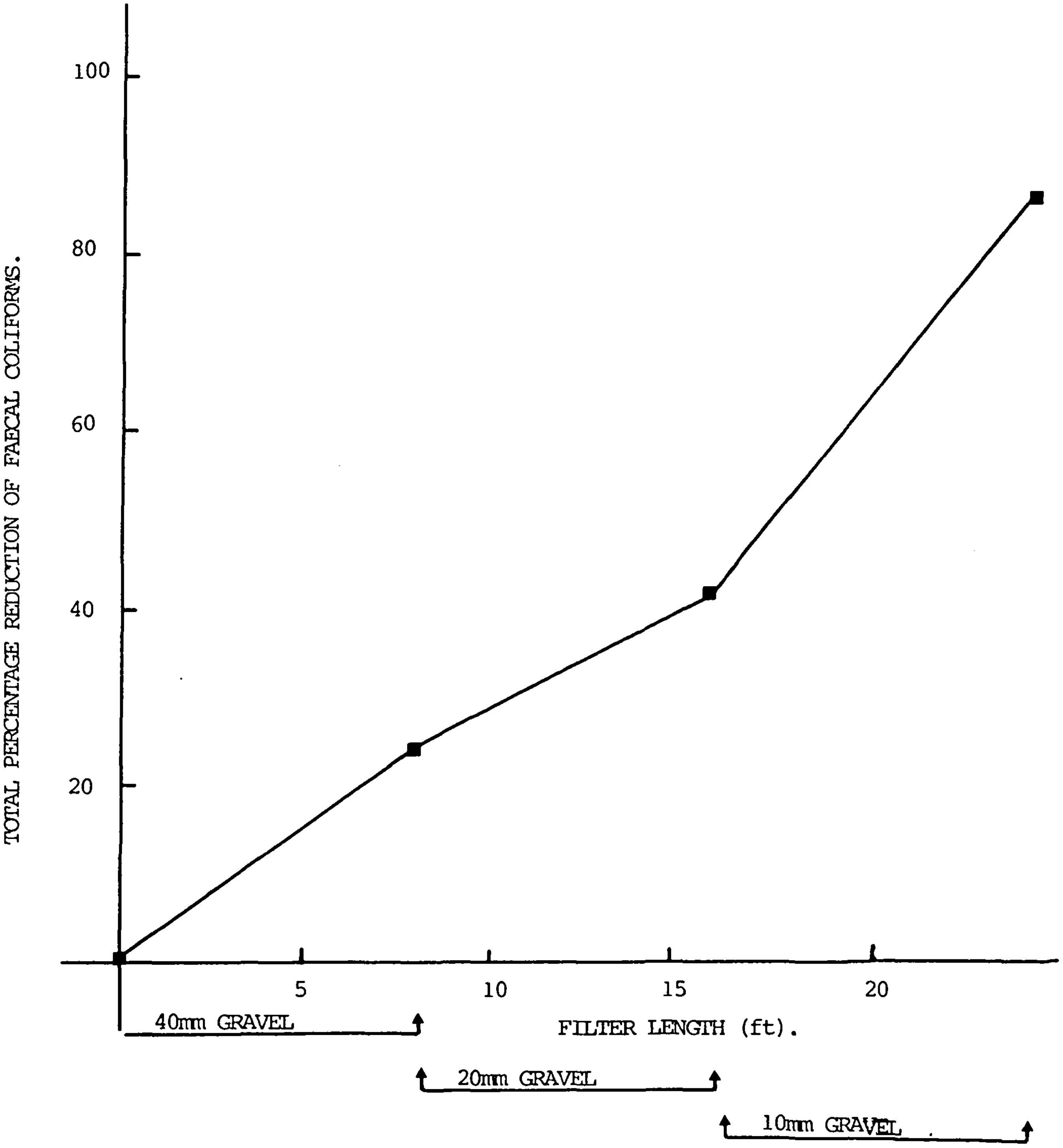


Figure 36 Cumulative reductions in faecal coliform density across a 3-series horizontal gravel prefilter operated at 0.5m/h
(nb Each point is based on the mean of 7 results)

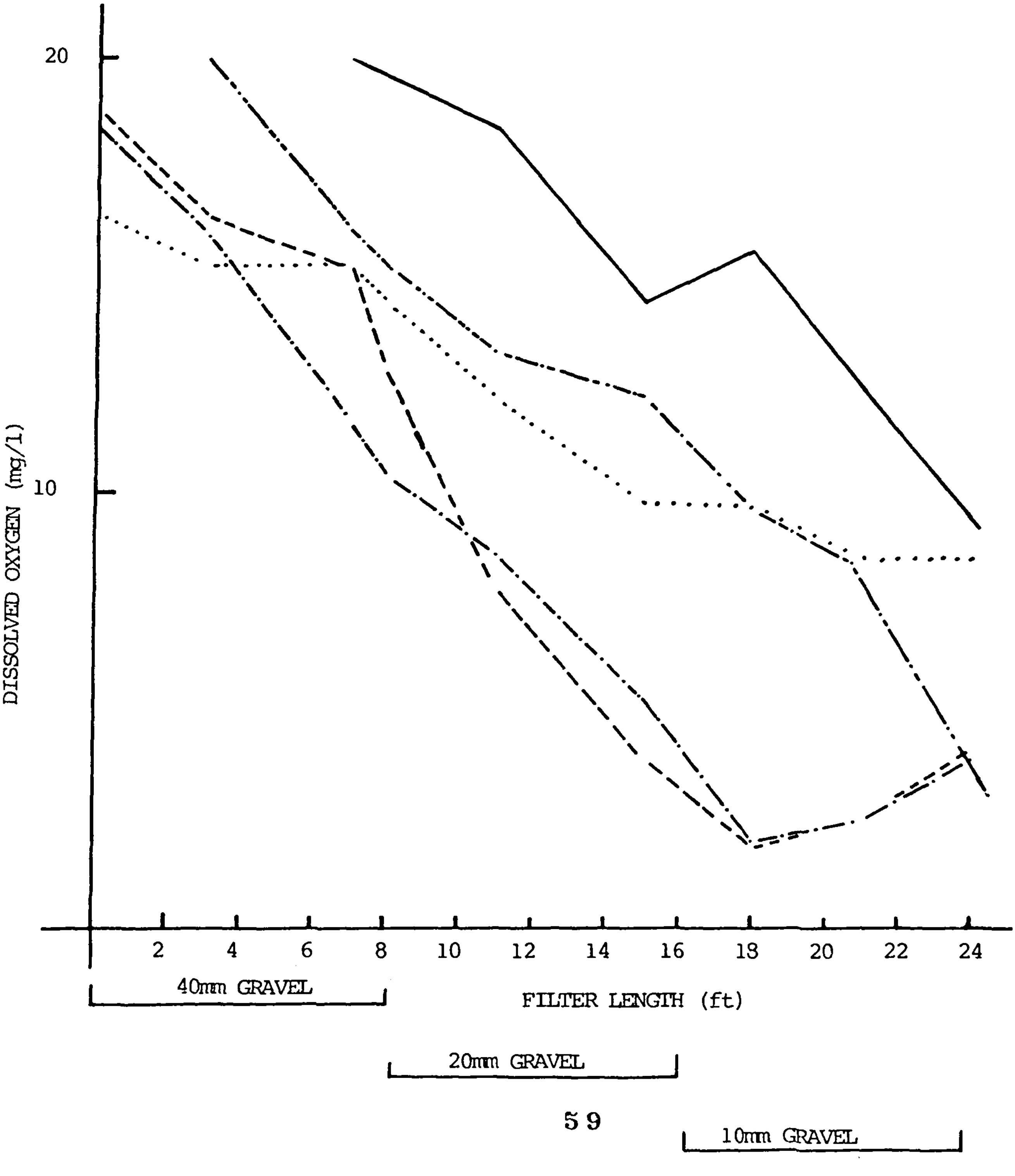
Figure 37 shows the reduction in dissolved oxygen at each point in the series filter. Samples were extracted both within and between the three media in order to detect any re-aeration between individual units. The graphs describe five separate sampling occasions and it is evident that the overall depletion in dissolved oxygen occurs at a roughly comparable rate throughout the filter regardless of medium type. The rate of depletion approximated to 10 mg/L per 12 ft of medium (or approximately 3 mg/L per metre) at a flow rate of 0.5 m/L.

To define the comparative efficiency of horizontal gravel filtration with respect to length, samples were abstracted at intermediate points within filters and analysed for bacteriological and turbidimetric improvement. Table 6 shows the comparative removal efficiency for the first 3ft and the last 5ft of medium for horizontal gravel filters in this study. Figure 38 depicts some of this information graphically.

| | 10mm GRAVEL MEAN REDUCTIONS | | | 40mm GRAVEL MEAN REDUCTIONS | | |
|---|---|---|---|---|---|---|
| | FAECAL COLIF. | FAECAL STREP. | TURBIDITY NTU | FAECAL COLIF. | FAECAL STREP. | TURBIDITY NTU |
| FIRST 3ft | 62 | 54 | 59 | 28 | 29 | 29 |
| LAST 5ft | 19 | 18 | 21 | 10 | 5 | 7 |
| TOTAL | 81 | 72 | 80 | 38 | 34 | 36 |

TABLE 6: COMPARATIVE REMOVAL EFFICIENCY (PER CENT) OF FIRST 3ft AND LAST 5ft OF MEDIUM IN HORIZONTAL GRAVEL FILTRATION

Figure 37 Cumulative reductions in dissolved oxygen across a 3-series horizontal gravel prefilter operated at 0.5m/h (nb Results of five separate sampling occasions are plotted)



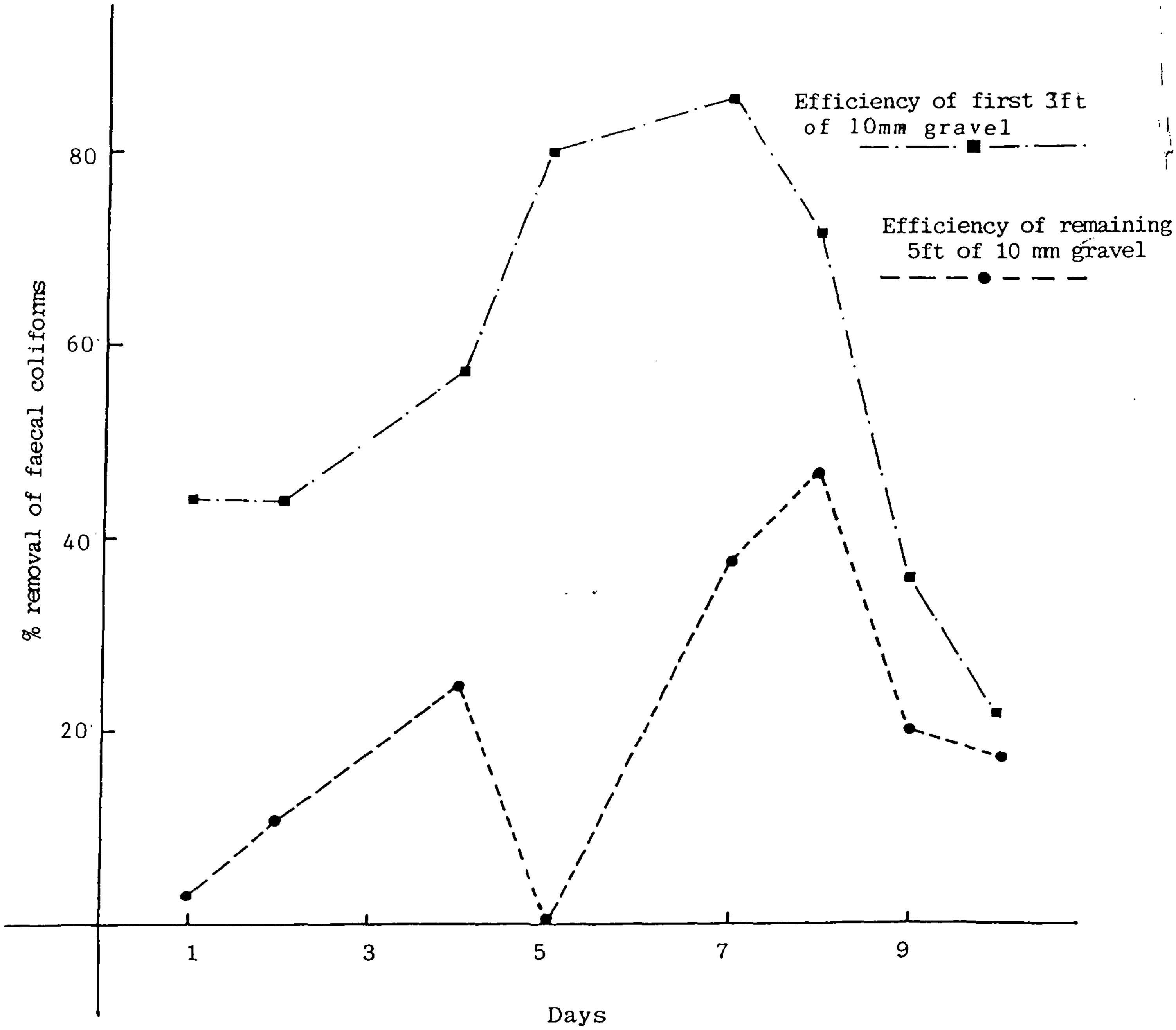


Figure 38 Typical reductions in faecal coliform density after 3ft gravel filtration and after a subsequent 5ft gravel filtration (results taken over 10 day period).

Overall starting head losses for the horizontal gravel prefilters operated in parallel are shown in Figure 39. It is clear that whereas head loss increase is fairly linear with respect to increasing velocity for 10 mm gravel, both 20 mm and 40 mm exhibit noticeable departures from linearity.

## IIv: DISCUSSION

The results of this study confirm the views of other workers with regard to the importance of raw water quality and medium selection in the design of gravel prefiltration systems. It is apparent that certain parameters can be particularly valuable in defining the medium or combination of media most appropriate to each circumstance.

Table 4 demonstrates that for 10 mm, 20 mm and 40 mm gravel, flow rates of 0.5 - 10 m/h encompassed Reynolds Numbers between 1.23 and 98.4. By the definition of laminar flow used in this study, it may be noted that a flow rate of 2.0 m/h would be the maximum rate applicable for 10 mm gravel before water entered the transitional zone between laminar and turbulent flow. The maximum velocities for 20 mm and 40 mm gravel would be 1.0 and 0.5 m/h respectively. Thus if it is intended to restrict a prefiltration system to laminar flow conditions it is relatively simple to arrange the cross-sectional areas of filter to accommodate this.

The advantages of laminar flow systems are several. Firstly, it is apparent from our study that initial head losses may be less predictable in the transition zone, and in any case will be higher with increased Reynolds Number and flow rate (see Figure 39). Secondly, the performance data (Figures 32-34) for removals of faecal bacteria and turbidity nearly all indicate substantially higher overall efficiency in the laminar flow range than in the transition zone. It is conceivable that this is a major reason for the higher performance of 10 mm gravel compared with 20 mm and 40 mm gravel for each water velocity i.e. whereas 10 mm gravel is well inside the laminar flow range at a velocity of 0.5 m/h, 40 mm is only just inside.

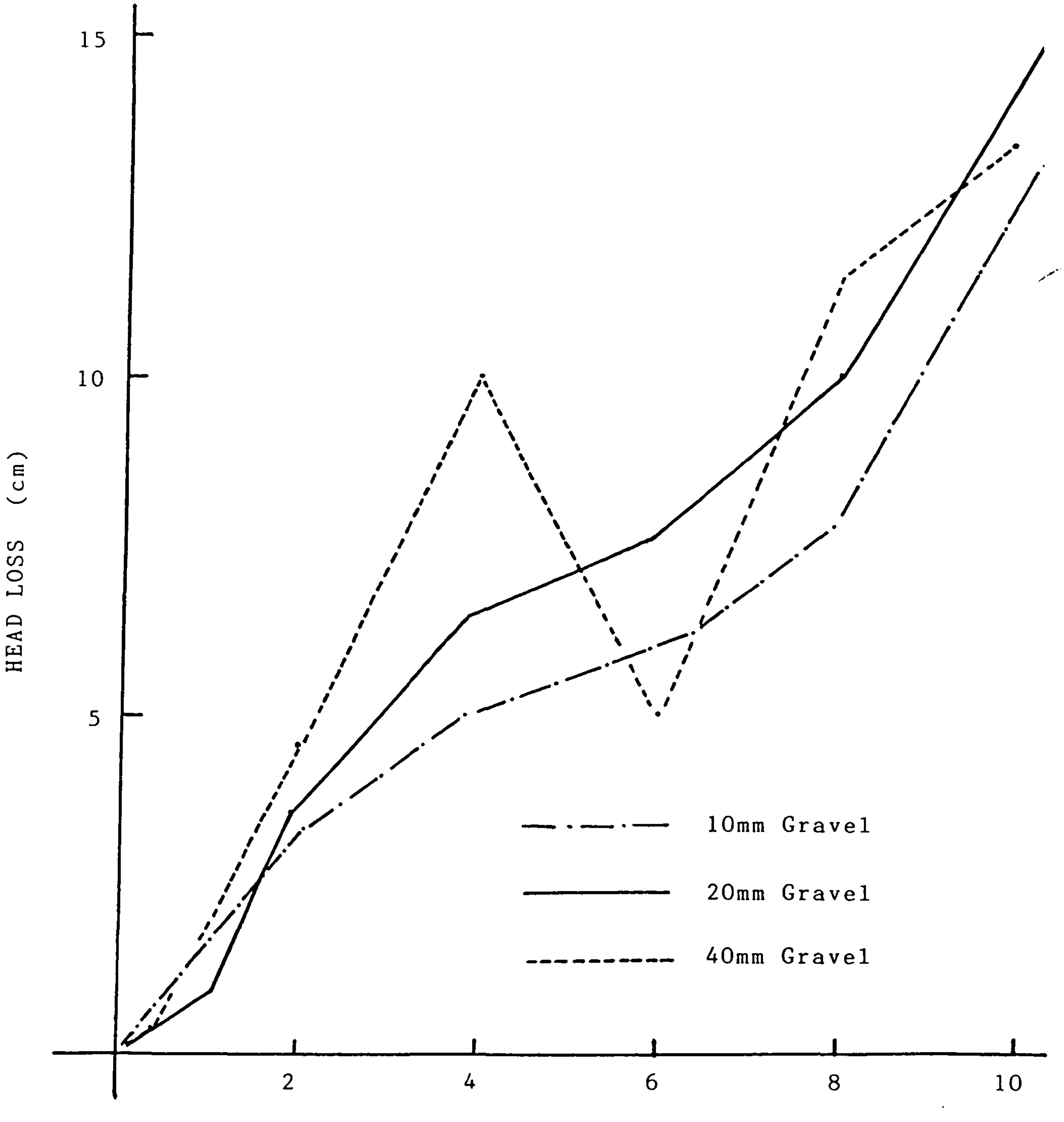


Figure 39 Overall starting head losses for 8ft horizontal gravel prefilters containing different media at velocities 0.5 - 10 m/h

Finally, parallel, streamlined flow encourages those processes of sedimentation and adsorption which are vital for the removal of inert particulate matter.

Conversely, it has been postulated that in the transition zone the chances of contact, aggregation and subsequent sedimentation of less insert particles are increased. Thus, particules which are capable of flocculation may well be most efficiently sedimented at higher flow rates than are suggested by this study. The problem with designing filtration plants with high velocity is that Reynolds Number does not quantify either scale or intensity of turbulence i.e. the size of eddies in the flow. Thus there is no means (other than empirical investigation) of ascertaining the likely efficiency of high rate coarse medium filtration for different influent water quality types.

The water quality in this study was relatively good. Turbidity rarely exceeded 40 NTU and there were long periods towards the end of the study when the majority of suspended solids were not mineral. The commonest cause of premature blockage in slow sand filtration in developing countries is excessive mineral turbidity rather than organic turbidity (eg due to algal productivity in a eutrophic source). Thus the results of this study should be applied with care. However, the water quality was sufficiently variable and exhibited such a large range in suspended solids type, that it is worth commenting on the overall consistency and efficiency of the different gravels subjected to different water velocities.

Table 7 describes the approximate ranges of efficiency obtained for each gravel at a flow rate of 0.5 m/h for each of the four categories of water quality. There are no data for mature 20 mm gravel filters in two of the ranges. However, it is apparent that for all water quality categories, for both faecal coliform and turbidity reductions, 10 mm gravel is substantially the most efficient of the three media. The contrast in efficiency is more

| Gravel type mm | % faecal coliform reduction | % turbidity reduction | % inorganic content |
|---|---|---|---|
| 10 | 70-90 | 60-80 | 75-100% |
| 40 | 40-50 | 30-40 | |
| 10 | 80-90+ | 70-90 | 50-75% |
| 20 | Filter maturing | Filter maturing | |
| 40 | 50-60 | 40-50 | |
| 10 | 90+ | 90+ | 25-50% |
| 20 | 40-60 | 40-60 | |
| 40 | 30-40 | 30-40 | |
| 10 | 85-90+ | 85-90+ | 0-25% |
| 20 | 40-50 | 30-50 | |
| 40 | 20-30 | 20-30 | |

TABLE 7: APPROXIMATE REDUCTIONS IN TURBIDITY AND FAECAL COLIFORM DENSITIES FOR THREE GRAVEL TYPES IN 8ft FILTRATION UNITS OPERATED IN PARALLEL AT 0.5m/h IN FOUR CATEGORIES OF WATER QUALITY

marked where suspended solids are mostly organic. This provides further evidence that low velocity, laminar flow filtration is most appropriate for the removal of non-mineral turbidity. This observation does not preclude the possibility that the contrast in efficiency might narrow further at higher flow rates in minerally turbid waters. Thus there may be considerable value in retaining the principle of dual medium filtration in very turbid waters. It should certainly be possible to design a two-stage filter where large grains are subject to flow in the transition zone (high velocity section) followed by smaller grains subject to laminar flow (low velocity section).

The plots of turbidity removal versus water velocity (Figure 32) demonstrate the superiority of 10 mm gravel over 20 mm and 40 mm gravel for all water types. The narrowing of disparity in performance with increasing velocity probably reflects the shift of flow characteristics from laminar to transitional mode. In contrast to these observations, the graphs of faecal coliform and streptococcus removal (Figures 33 and 34) demonstrate slightly elevated performance in the velocity range 1-4 m/h for 20 mm gravel. Such an elevation is not observed for 40 mm gravel over the entire velocity range (0.5 - 10 m/h) used in this study. However, at no time did maximum removal efficiency for 20 mm gravel exceed that obtainable with low rate filtration using 10 mm gravel.

Thus, it must be concluded that for the range of water quality encountered in the UK trials described in this report, the most efficient single medium was 10 mm gravel operated at a flow rate of less than 1.0 m/h. Where flow rates exceeded 2.0 m/h it was clear that efficiency of 8ft of filter medium declined to an unacceptable level. Although the removal per unit volume of water treated may have been more encouraging, an overall efficiency of less than 50% in 8ft for each parameter is unlikely to provide a worthwile basis for designing small scale high rate coarse medium filters.

At low velocities, head losses were negligible at the commencement of filter runs for all three media. Owing to the relatively shallow form of the horizontal filters, and the maximum permissible head loss of 15 cm, it was difficult to provide much information on likely maintenance requirements for horizontal flow filters. Nevertheless, a filtration run length (to 15 cm head loss) required 10 weeks operation at 0.5 m/h to block a filter containing 10 mm gravel.

Naturally, the rate of head loss increase is a function of efficiency, and the above circumstances : 10 mm gravel with a flow rate of 0.5 m/h, represented good conditions for suspended solids removal. At higher flow rates, efficiency declined and increases in head losses were even less apparent. Where velocities exceeded 4 m/h there were negligible increases in head loss with respect to time, and in fact head loss readings for all piezometers returned erratic and variable data owing to the flow characteristics of the transitional zone. Clearly, a balance needs to be struck between efficiency head loss increase and ease of cleaning. In this context, the construction of increasingly long horizontal gravel filters may be obviated by the kind of regenerative filter designs suggested by Wegelin (11).

In his review of the treatability of water, Ives (23) described methods of physical water testing including turbidity, suspended solids, and colour analysis. However, when assessing the relevance of physical methods for describing the interactive relationship between suspended solids and filtration medium, Ives expressed the view that filterability tests using filter material other than that used in practice would give misleading or meaningless results.

In this study we have not attempted to correlate any physical measurement with gravel filter run length. However, it is apparent from the filterability data generated, that there is little or no correlation between this parameter and suspended solids loading. This may readily be seen by comparing Figures 27 and 28. Thus if filter blockage is purely a function of head loss increase due to suspended solids removal, a filterability index based on a membrane filtration technique is demonstrably not an appropriate guide to filtration run length. However, there is also little correlation between suspended solids loading and turbidity and yet the latter is the parameter most frequently used as a design criterion for both efficiency and maintenance requirements. Thus we would not only endorse Ives' view that simple field filterability methods may be misleading but would extend the criticism to any single field observation. Clearly there is a major gap in understanding of the interaction between the various physical parameters normally used to describe the filtration process. We have attempted to gain comparative data on the different means of describing the material suspended in raw surface water. That material includes mineral turbidity, organic material, colour and colloids. Each component is reflected more or less exactly by suspended solids, turbidity and filterability but there is also a need for some qualitative measure of solids type in order to facilitate accurate predictions of filtration run length and maintenance commitments.

Without further mathematical analysis, it can only be concluded from this study that there is no simple or direct relationship between any of the physical parameters used to define the efficiency or maintenance requirements of filtration systems.

The plug-flow nature of the pilot horizontal filters was demonstrated by the tracer exercise depicted in Figure 29 The experiment was conducted at only one flow rate : 0.5 m/h, thus it is not possible to compare the nature of flow at different rates. It would be of interest to conduct the tracer exercise at a variety of velocities in both the laminar flow and transitional flow zones in order to detect any reduction in plug flow characteristics which might occur at higher flow rates. However, it was reassuring to show the absence of short circuiting in the experimental filters, at least at low velocities.

The value of microbiological improvements across the gravel filters should not be underestimated. In the absence of reliable disinfection, a consistent 90% reduction in faecal bacterial levels across a prefiltration system could be of great importance to the overall hygienic safety of a rural water treatment plant. For this reason, the biological activity of a gravel filter is of particular interest. With the expected stability and low maintenance requirements of low rate horizontal gravel filtration, the length of maturation period following commissioning or cleaning is not of great concern. However, it is of some interest in reflecting the complex nature of the filtration process when the loading is not considered solely in terms of mineral suspended solids. Logarithmic maturation curves (Figure 30 and 31) were observed both for turbidimetric and bacteriological improvements. Water quality at the time of the ten day period depicted was in fact 75-100% mineral turbidity in the range 10-40 NTU. Thereafter, the 10 mm gravel filter was continuously operated at 0.5 m/h and returned to stable performance of ± 10% the established filter efficiency for 2.5 months. It is worthwhile to note also that even when suspended solids were mostly mineral, there was still a maturation period for turbidity removal.

Further evidence of the potentially active biological nature of the gravel filtration process is provided by Figure 37. The reduction in dissolved oxygen for a three stage 24ft filter was substantial. It demonstrates biological activity compatible with the microbiological improvements which were observed. It is entirely reasonable to liken the mechanisms of microbiological removal in gravel filtration with those mechanisms (i.e. sedimentation, adsorption to organic films and grazing by sedentary and free living organisms) which are recognised in slow sand filtration. The reduction in dissolved oxygen does have implications for design. Clearly there may be circumstances where post-treatment oxygen levels are too low to support biological treatment in downstream plant eg slow sand filtration. In such cases, reaeration within the gravel filter or between prefilter and sand filter would be essential.

Biological activity ie respiration within the filter, will be enhanced in waters with high nutrient loading. Thus in eutrophic sources subject to algal productivity, it is likely that gravel prefilters will exhibit higher levels of biological activity with the build-up of biofilms within the medium and thus provide greater efficiencies of bacterial removal. In such sources, the need for re-aeration would also be greater.

The cumulative efficiency of the triple medium series filter (Figures 35 and 36) was impressive. The filter was operated initially at a velocity of 0.5 m/h and thus each section remained within the laminar flow range ($R_e$ <5.0). Turbidity in the raw water was low (5-10 NTU) and most of the suspended material was organic (only 0-25% mineral turbidity). Clearly, the most efficient section of the triple filter with respect to microbiological improvement was the last containing 10 mm gravel. This is particularly important since most of the material likely to sediment readily would already have been removed in the first two sections containing 40 mm and 20 mm gravel.

Time did not permit detailed investigation of efficiencies at higher flow rates. However, it was noted that when velocity was temporarily altered from 0.5 to 2.0 m/h, the efficiency of the 20 mm gravel with respect to turbidity removal increased from 15 - 20% to 20 - 30%. This was accompanied by a reduction in performance for both 10 mm and 40 mm gravel. Turbidity reductions were generally low in percentage terms due to the very low raw water turbidity (5-10 NTU). However, in comparative terms, it is clear that despite turbidity removal in preceding sections the 10 mm gavel section was the most efficient overall.

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# SECTION III

# SECOND FIELD REPORT

# The development, evaluation and field trials of a small scale multiple filtration system for the treatment of rural water supplies.

## GRAVEL PREFILTRATION

Submission to: OVERSEAS DEVELOPMENT ADMINISTRATION, UK.

For the attention of: ENGINEERING DIVISION

From: BARRY LLOYD, MAURICIO PARDON & DAVID WHEELER
University of Surrey
Department of Microbiology
Guildford, GU2 5XH.

Based at: CEPIS/PAHO/WHO.
Casilla Postal 4337
Lima, Peru

December, 1984

CONTENTS Page

(IMPLEMENTATION)

APPENDICES

## THE DEVELOPMENT AND EVALUATION OF GRAVEL PREFILTERS

ABSTRACT SUMMARY:

High turbidity is a seasonal problem on the Pacific Coast of Peru and an all year round problem in the Amazon and its tributaries. This is a major constraint on the successful operation of surface water treatment plants throughout Peru and in many other developing countries. In preceeding reports we have demonstrated the limitations of subsand abstraction as a pretreatment step for slow sand filtration; it was therefore considered essential to examine and evaluate multistage gravel prefilters as a potentially more effective means of providing a low turbidity water for subsequent slow sand filtration.

The work done in Peru in the period February to December, 1984, to meet the water quality requirement indicated, may be summarised under four headings:

1: Evaluation of existing problems of small scale treatment.

2: Development of pretreatment gravel filtration pilot rigs and evaluation of performance for removal of turbidities.

3: Design of a village scale water supply system involving multiple filtration, and incorporating gravel prefilters and slow sand filters.

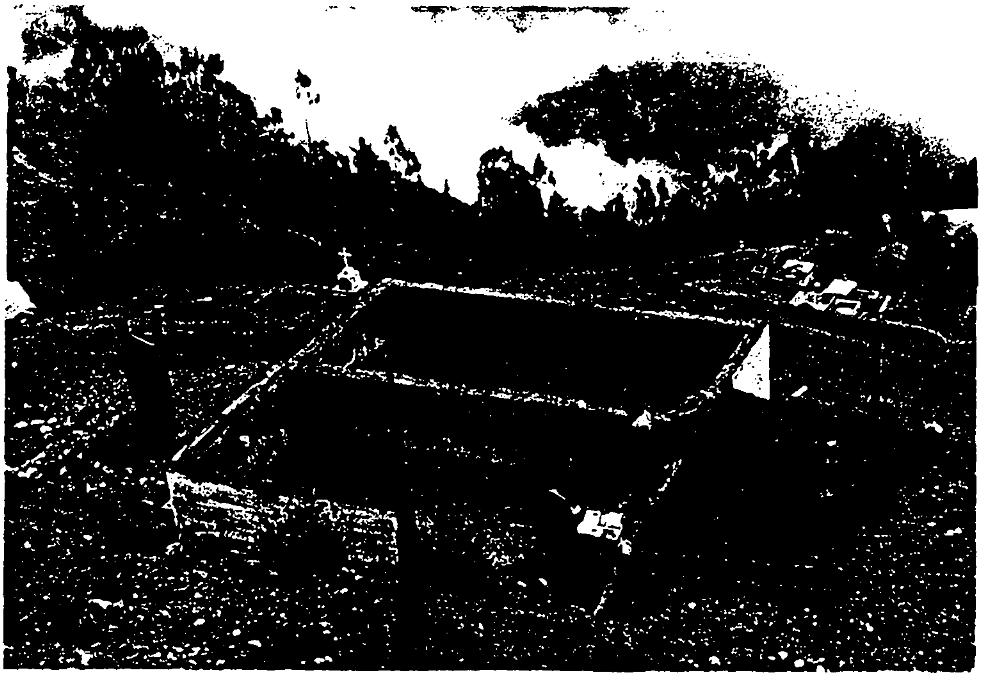
4: Installation of a prototype scheme in Azpitia leading up to commissioning in December.

The above activities led to the Peruvian rural sanitation division (DISAR) organising a seminar to discuss the implications of the project and resulting in an agreement initially to construct 4 similar schemes for comparative performance evaluation.

The period December 1984 to April 1985 will involve the field evaluation of the Azpitian scheme. This is a critical one as it is the period during which the treatment system is placed under maximum turbidity loading.

ACKNOWLEDGEMENTS

The work presented in this report has been carried out under a collaborative scheme between the University of Surrey Research Group financed by the Overseas Development Administration, The Panamerican Centre for Sanitary Engineering and Environmental Sciences (CEPIS) and the Division of Rural Sanitation of the Ministry of Health, Peru. The background discussion has been influenced by work done previously by CEPIS and the final designs of the gravel prefilters presented here were carried out in collaboration with Engineer Jose Perez at CEPIS, Lima. In the current study the day-to-day analysis of samples from pilot filters in Lima has been carried out by Engineer Isaac Lavado of the Division of Rural Sanitation (Ministry of Health); we gratefully acknowledge his assistance.



The figure demonstrates the problem of high turbidity in slow sand filters in the village of Carhua - Department of Lima

## INTRODUCTION

The excessive content of particulate suspended matter in rivers, streams and ponds which are used as sources for water supplies in rural areas present a somewhat neglected aspect of the problem of water treatment in Developing Countries. Hot dry summers, extreme aridity, bad practice in the use of land (abandonment of once productive hillside slopes), herds of goats that consume the sparse vegetation are just some of the factors which contribute to the problem.

When the rainy season begins, the loose, fine soil is washed from the hillsides and give rise to very high loadings of particulate suspended matter in receiving water courses. Under these conditions, water treatment plants can be badly overloaded. The problem is further aggravated due to the fact that excreta will also be washed into the run-of water, raising for a period the bacterial loadings of the source and making the option of by-passing the water treatment system a questionable one because of the health risks involved.

For many years, slow sand filtration has been regarded as an adequate solution to the problem of water treatment in rural areas and is indeed the most widely used system for water treatment in Developing Countries. Its advantages are unquestionable: no other individual unit process improves to such extent the bacteriological and physico-chemical characteristics of water. The construction, operation and maintenance features also point to SSF as a most appropriate treatment system. Nevertheless, experience demonstrates that SSF in rural areas have serious operational problems and are in many cases not functioning due to problems with influent water quality. Wegelin describes the process very clearly (1). High concentrations of particulate matter in water will cause rapid blockage of the filter bed and thus precipitate frequent cleaning. Under these conditions, the biological layer or schmutzdecke does not become properly established and the bacteriological improvement in the quality of the water is reduced. The need for an adequate pre-treatment stage prior to slow sand filtration is therefore evident.

Several research institutes have undertaken projects in the past few years to evaluate the use of horizontal roughing gravel prefiltration. The Asian Institute of Technology (AIT) in Bangkok, Thailand (2) (3), and the University of Dar-es-Salaam (UDSM) in Tanzania (4) and more recently the Swiss Federal Institute for Water Resources and Water Pollution Control (EAWAG)in Duebendorf, Switzerland (1) have contributed to the current state-of-the-art.

# THE EXPERIENCE IN PERU

## GENERAL

The problem of turbid surface water supply in Peru is not significantly different to the scenario suggested in the introduction to this Report. Under these circumstances the development and maintenance of supplies poses an enormous task given the characteristics and distribution of the population throughout the country. The status of rural water supply in Peru was summarised in the Preliminary Field Report of the Project and submitted to ODA in May 1984. (5)

It is apparent that there is a need for a redefinition of the basic criteria applied in the selection and design of processes for the treatment of surface waters in rural communities in developing countries.

## ORGANISATIONAL FRAMEWORK

Since September of 1982 the University of Surrey ODA sponsored group has been executing a research and development project which proposes a multiple barrier approach to treatment of contaminated surface waters for water supply to small communities in rural areas. The emphasis has been given to multiple stages of filtration, including prefiltration in gravel and synthetic matting prior to slow sand filtration. The project entered the field phase in October of 1983 with the installation of treatment systems in rural communities in Peru.

The University of Surrey had previously established collaboration with the Division of Rural Sanitation of the Ministry of Health (DISAR)* and the Panamerican Centre for Sanitary Engineering and Environmental Sciences (CEPIS)** in Peru which dated back to 1981.

*DISAR, an executive branch of the Directory of the Environment of the Ministry of Health has responsibility for providing water and sanitation to communities of less than 2,000 people in Peru.

**CEPIS, a regional centre of the Division of Environmental Health of the Panamerican Health Organisation has a leading role in the dissemination of information regarding technology improvements in the field of sanitation within the region of Latin America and the Caribbean.

DISAR has a grant from the USAID programme for the evaluation of existing water treatment plants and the construction of gravel prefilters.

In January of 1984, an agreement was signed between CEPIS and the German Co-operation Programme (GTZ) to study in detail aspects of prefiltration of highly turbid waters. The Surrey Group was contracted to supervise this project and requested to advise on the DISAR programme.

The objectives of this study are summarised in Table No. 1.

TABLE 1

OBJECTIVES OF THE PREFILTRATION STUDY

1: To develop a simple methodology to analyse and characterise the size of particles which give rise to turbidity in order to establish criteria for the evaluation of efficiency and optimal performance of prefilters.

2: To verify and complete previous studies to establish design criteria for prefiltration units which can cope with a high level of turbidity.

3: To construct and evaluate a prefiltration unit in a rural area preparatory to the implementation of DISAR's construction programme.

Initially the project was intended to be based in Carnua, a community of 800 people located 100 Km N.E. of Lima at an altitude of 3,300 metres above sea level. Carhua has a water supply derived from an irrigation canal which leads to a conventional water treatment plant. It comprises grit settlement, a sedimenter and two slow sand filters. The aim was to analyse and characterise the water source and install pilot gravel prefilters at the plant to generate the data required for the design of a prefilter to be constructed in advance of the slow sand filtration stage in the plant.

The monitoring of the raw water source was conducted over a 7 day period, between the 29th of February and the 6th of March of 1984. Sampling was done on a continuous basis at regular intervals during the day and the night. A total of 115 physico-chemical and 71 bacteriological samples were processed. The results are shown in abstract form in Table 2.

TABLE 2

CHARACTERISTICS OF THE RAW WATER IN THE COMMUNITY OF CARHUA

| Parameter | Min. value | Max. value | Mean value |
|---|---|---|---|
| TURBIDITY (NTU) | 16 | 1,500* | 25 |
| FAECAL COLIFORMS (counts/100ml) | 14 | >2,000 | 115 |
| ALKALINITY (mg $CaCO_3$/L) | 40 | 52 | 48 |
| CONDUCTIVITY (us/cm) | 70 | 105 | 93 |
| pH | 7.2 | 7.3 | 7.2 |
| TEMPERATURE ($^oC$) | 9 | 14 | 11 |

*Earth slip produced the maximum result -lasting 1-2h.

The rainy season had prematurely faded and it can be seen in the Table that the levels of turbidity had already fallen too low to allow for a full scheme of research in the area. The Lima water treatment plant 'La Atarjea' was then proposed and pursued as an alternative for the pilot trials for logistical reasons.

Given the nature of this report, the following discussion will concentrate on the aspects which were most relevant to the ODA-Surrey project at that time, this was the aspect of shallow in series vertical prefiltration (ShiSPF). The broader aspects of the research which included deep bed and horizontal gravel prefiltration with the objectives outlined above, will be published in due course by CEPIS.

## BACKGROUND

In the period 1979-1980, CEPIS undertook a research programme in the Lima Water Treatment Plant of 'La Atarjea' in order to model the efficiency of a pilot sized horizontal gravel prefilter (Perez, J. and Vargas, L. unpublished). A HPF was loaded with a variety of influent turbidities and tested at various velocities using several size grades of gravel.

The data is presented in Figure 1. It demonstrates the high efficiency with respect to the removal of particulate matter that occurs in the first few centimetres of the prefilter irrespective of the loading in the range 100-1,000 NTU. It was deduced that multiple short unit lengths of filtration medium should achieve higher removals of particulate matter than a single deep bed prefilter of the same length. This hypothetical model is shown in Figure 2.

## EXPERIMENTAL WORK IN 1984

In order to test this hypothesis, trials begun in 1984 included a simple set-up of 3 stages of vertical gravel filtration in series. The assembly is shown in Figures 3 and 4. It consisted of:

a) a plastic header tank used both to feed the raw water into the prefilters and to backwash them;

b) three plexiglass prefilter columns of 15 cm, each packed with a filter medium 60 cm deep, containing gravel of 4 to 6 cm, 2 to 3 cm and 1 to 1.5 cm;

Figure No.1 Perfomance of the Horizontal Gravel Prefilter.
"La Atarjea"-Lima,Peru. 1979.

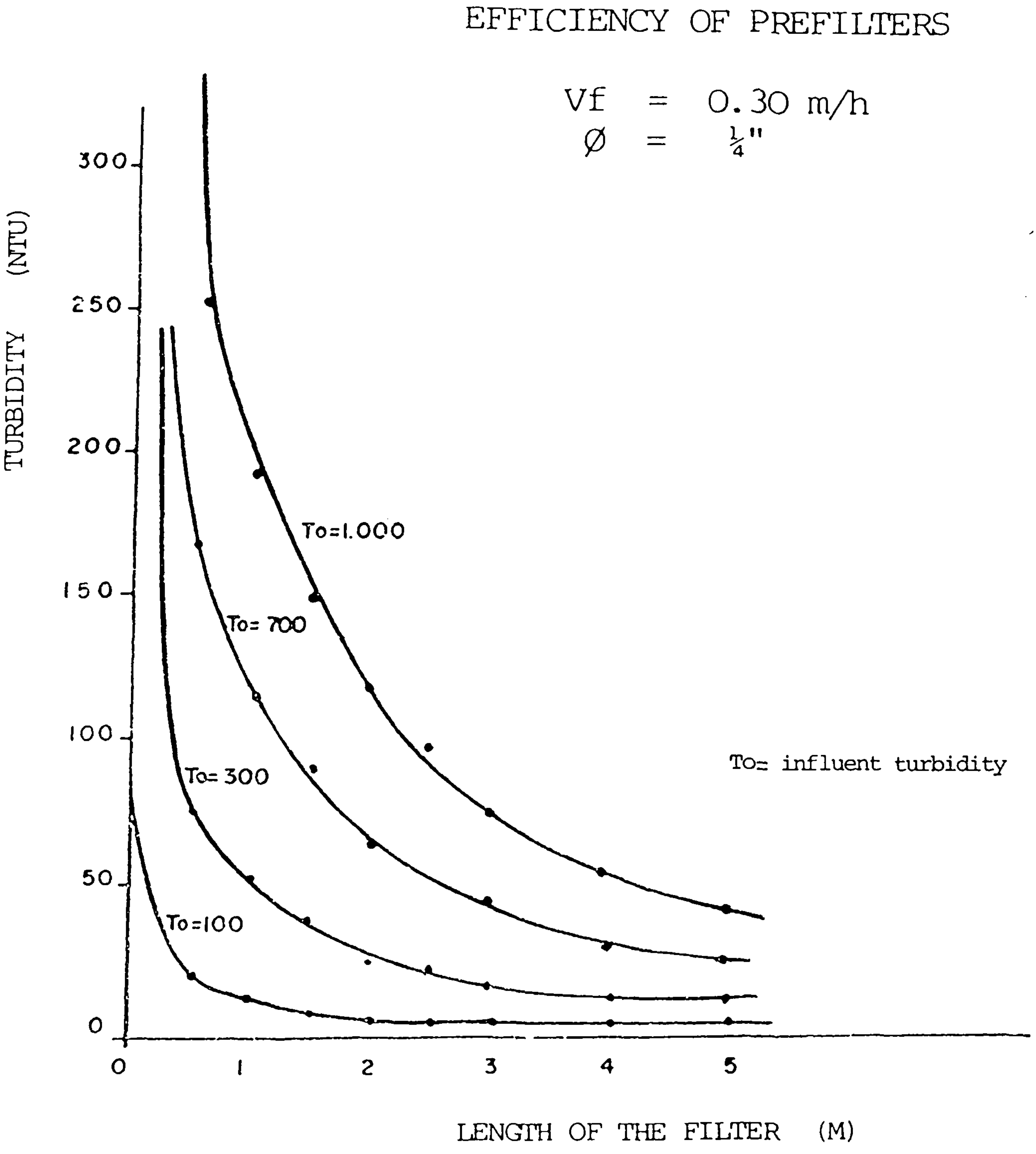
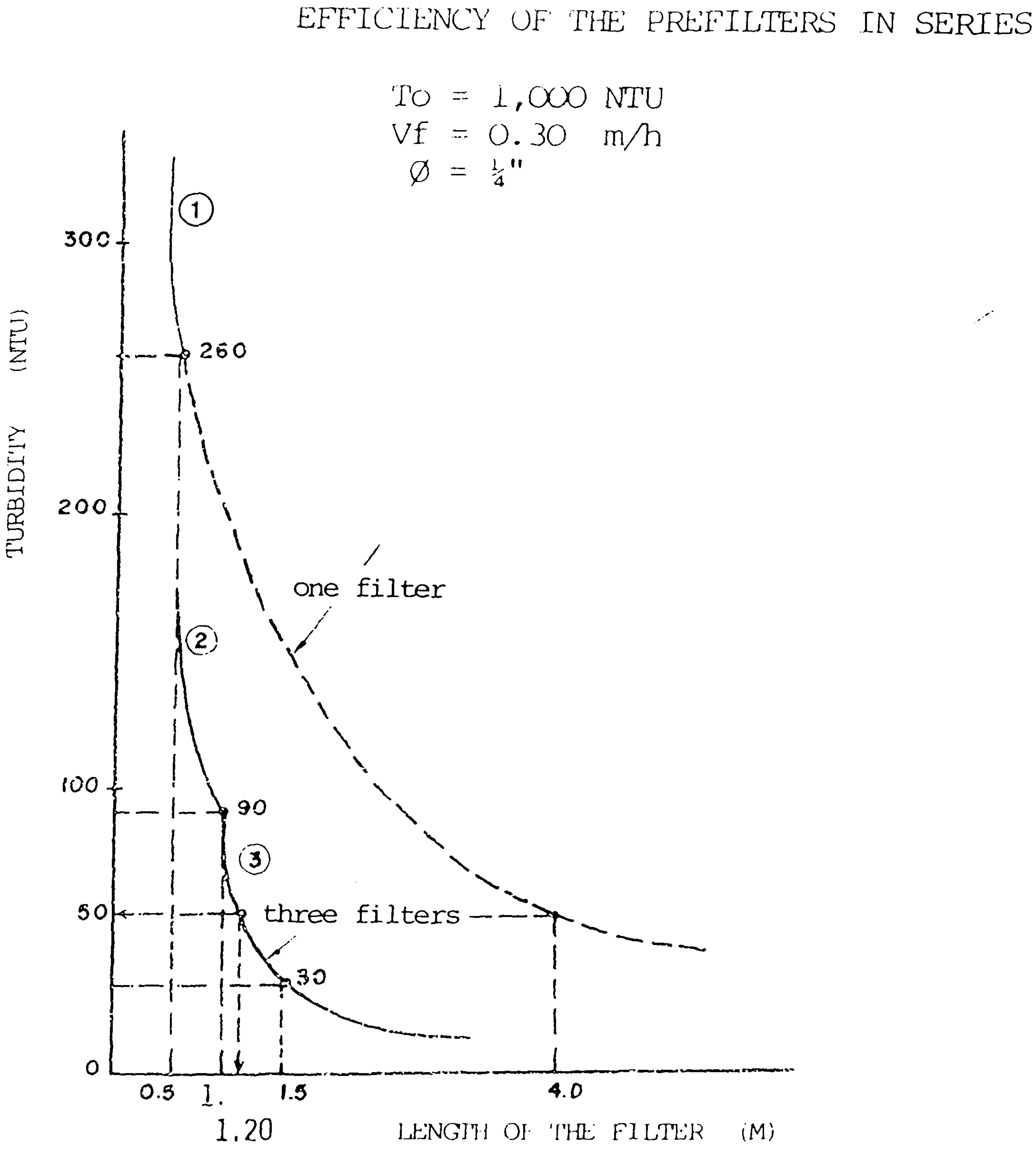


Figure No.2 Hypothetical Performance Model of a Three Stage Shallow in Series Pre-filter.



c) an arrangement of piezometers for head loss measurement;

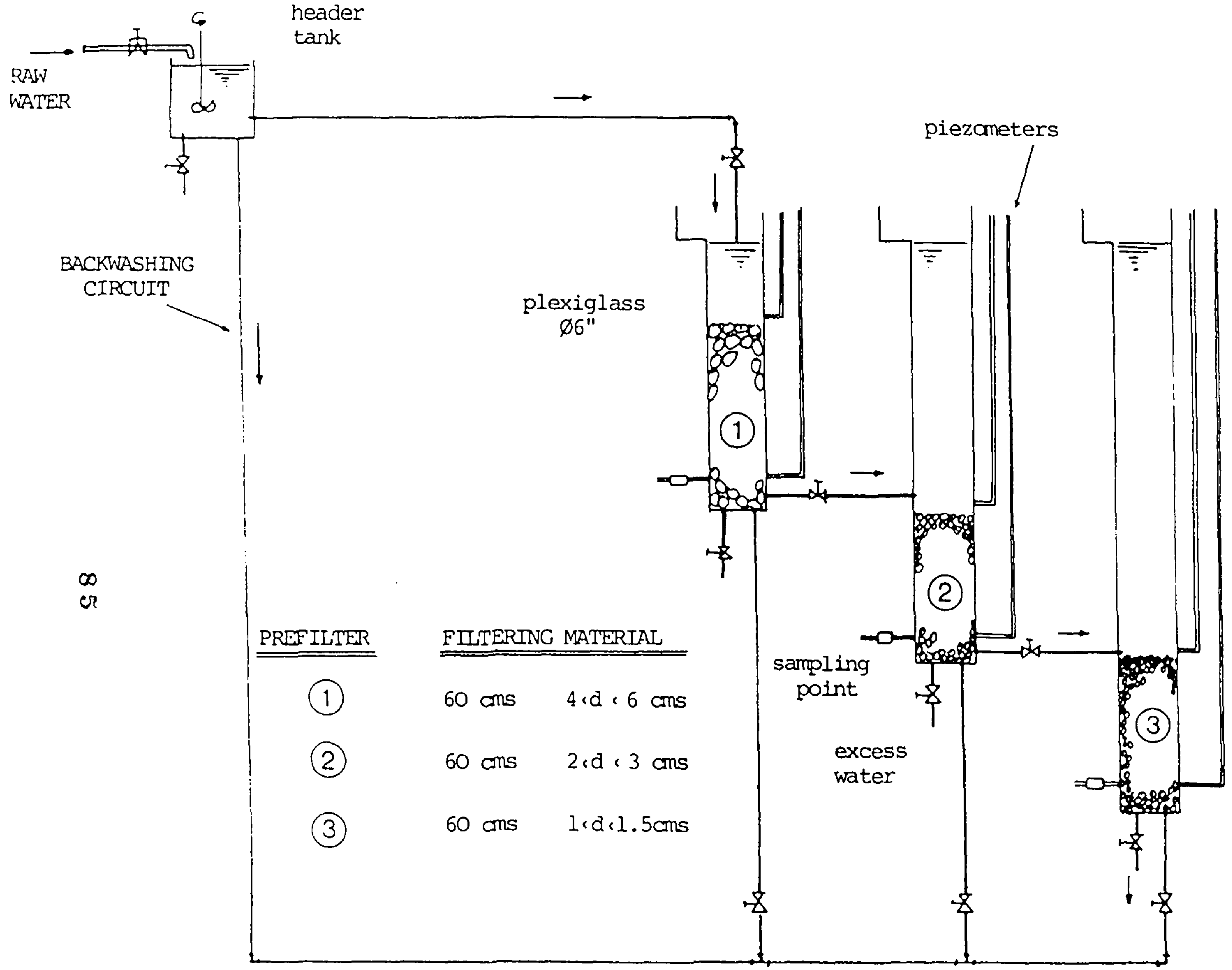
d) outlets designed for taking samples without disturbing the filtration process; and

e) excess water outlets to allow for calibration of filtration velocities at each individual stage.

By the time that the test rig had been installed the levels of turbidity in the Rimac river had already fallen below 100 NTU. The trials demanded a broader range of turbidities, thus for loadings above 50 NTU the turbidity was artificially raised by resuspending a very fine silt which was collected from the same river basin. Settleability tests were carried out on a daily basis, to confirm that characteristics of the resuspended particles were suitable for the study.

The system was tested at 4 different ranges of turbidity:less than 50, 100-200, 250-350 and 600-800 NTU; as well as at 4 different filtration velocities : 0.10, 0.20, 0.40 and 0.80 m/h. Each experiment lasted a week and was followed by a backwashing process to assess flow velocities required in the prefilters to achieve efficient cleaning. The total period of this phase of the study lasted from the 7th April to the 31st August of 1984.

The characteristics of the raw water used in the pilot scheme is presented chronologically for the whole period of study in Table 3.



| PREFILTER | FILTERING MATERIAL | |
|---|---|---|
| ① | 60 cms | 4<d<6 cms |
| ② | 60 cms | 2<d<3 cms |
| ③ | 60 cms | 1<d<1.5cms |

PILOT PLANT
SHALLOW IN SERIES
PRE-FILTER (ShiSPF)
LIMA-PERU

Figure No.3 Diagramatic Lay-out of the Triple Stage Pilot Pre-filter.

Figure No.4 Gravel Prefiltration Study Test Rig.
"La Atarjea"-Lima,Peru. April 1984.

## TABLE 3

## CHARACTERISTICS OF THE WATER USED IN THE PILOT SCHEME AT THE WATER TREATMENT PLANT OF 'LA ATARJEA'[1]

| Period of Study | Turbidity (NTU) | Feacal Coliforms (counts/100 ml) | Conductivity (µs/cm) | Alkalinity ($mgCaCO_3/L$) | Temp (°C) | pH |
|---|---|---|---|---|---|---|
| 7-14th April | 38 | 65 | 533 | 115 | 20 | 8.1 |
| 28th April-5th July | 100-200[2] | 35 | 514 | 115 | 20 | 8.1 |
| 9th July-7th August | 250-300[2] | 27[3] | 494[3] | 110 | 19 | 8.0 |
| 9th - 31st August | 600-800[2] | - | - | 117 | 19 | 7.8 |

NOTES:

1: The mean of daily values on the periods considered are reported.

2: Turbidities were artificially raised to the levels indicated.

3: Analysis done only on the first four days of the period indicated.

Throughout the trials, the water presented a combined residual chlorine concentration of up to 0.1 mg/L due to a prechlorination step used in the plant. Thus biomass accumulation on the filter medium may have been somewhat reduced.

## THE RESULTS

As discussed in the introduction to this report, gravel filtration is considered, in the majority of cases, as a pretreatment stage; a <u>protection</u> step prior to slow sand filtration. Thus, greatest emphasis must be given to the effluent water and its levels of turbidity and suspended particulate matter. Under the design conditions, the water leaving the prefiltration stage should not have a turbidity level of more than 10-20 NTU as our experience has shown that higher levels require unacceptably frequent filter cleaning (6).

Figure 5 shows the total efficiency of the 3 stage ShiSPF plotted against influent turbidity levels for the four filtration velocities tested. The system presents a maximum percentage removal efficiency when influent turbidities in the range 100-300 NTU irrespective of the filtration velocity used. This range overlaps with a fifth theoretical curve, which following the principle stated above, represents the efficiency in removal required from the prefilters in order to achieve an acceptable effluent turbidity of less than 20 NTU. Thus, the limit of performance can be defined as follows: the optimal operational range of the ShiSPF has an upper limit of 300 NTU influent turbidity, for a filtration velocity of not more than 0.30 m/h.

Also, in support of the previous discussion, figures 6,7, and 8 show the level of removal of turbidity for each individual stage of filtration. Results are presented for the low range of influent turbidities (less than 50 NTU); medium range (100 to 200 NTU); and high range (250 to 350 NTU). Filtration velocities of 0.10, 0.20 and 0.40 m/h were employed for each of the 3 ranges.

The points presented in the graphs represent the mean result for a 7-day period in each case. Considering the fact that the evaluations were undertaken within the maturation processes of the prefilters (less than 7 days from the disruption of the process due to cleaning and in the occasional presence of a trace of combined chlorine residual), the results

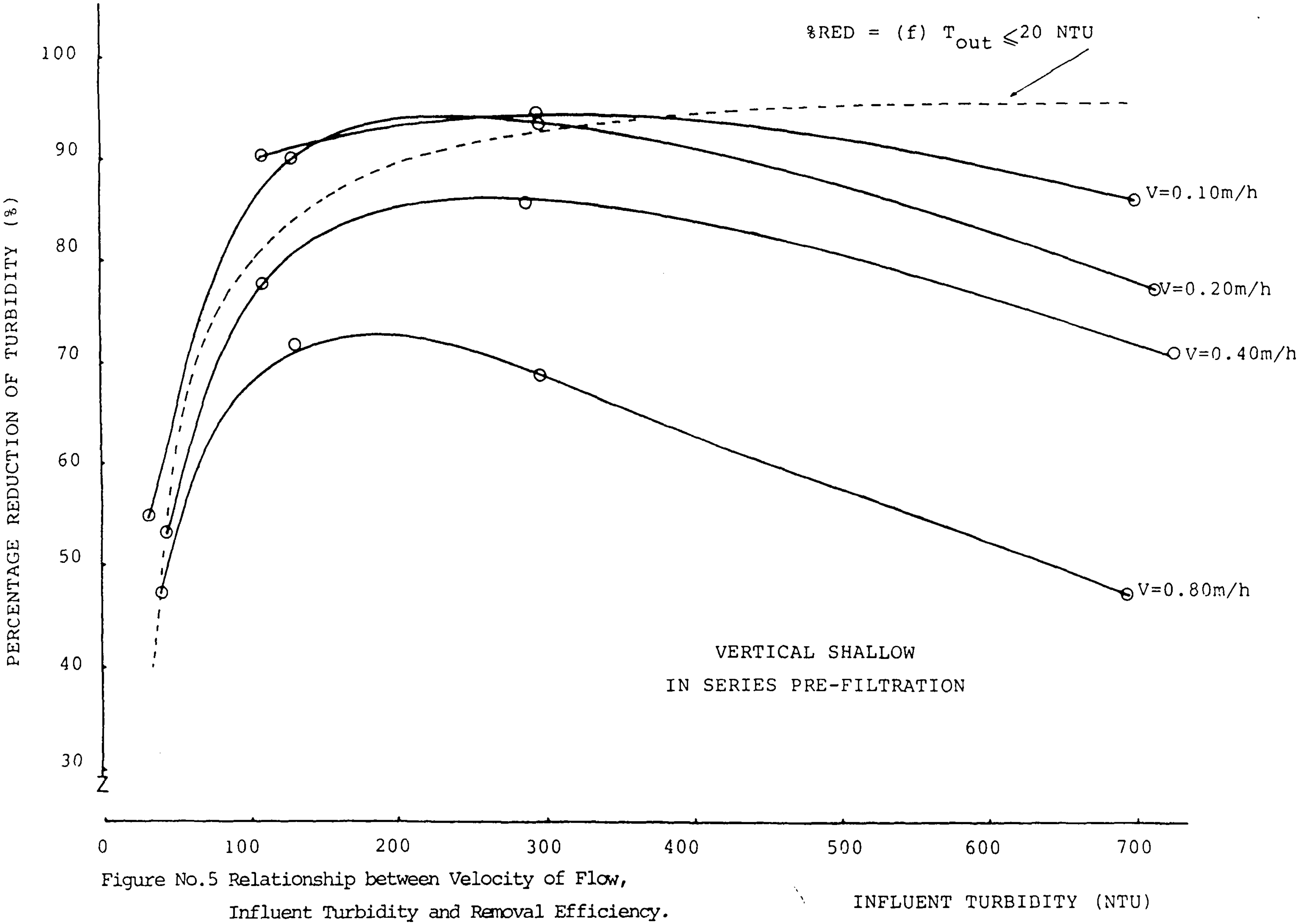


Figure No.5 Relationship between Velocity of Flow, Influent Turbidity and Removal Efficiency.

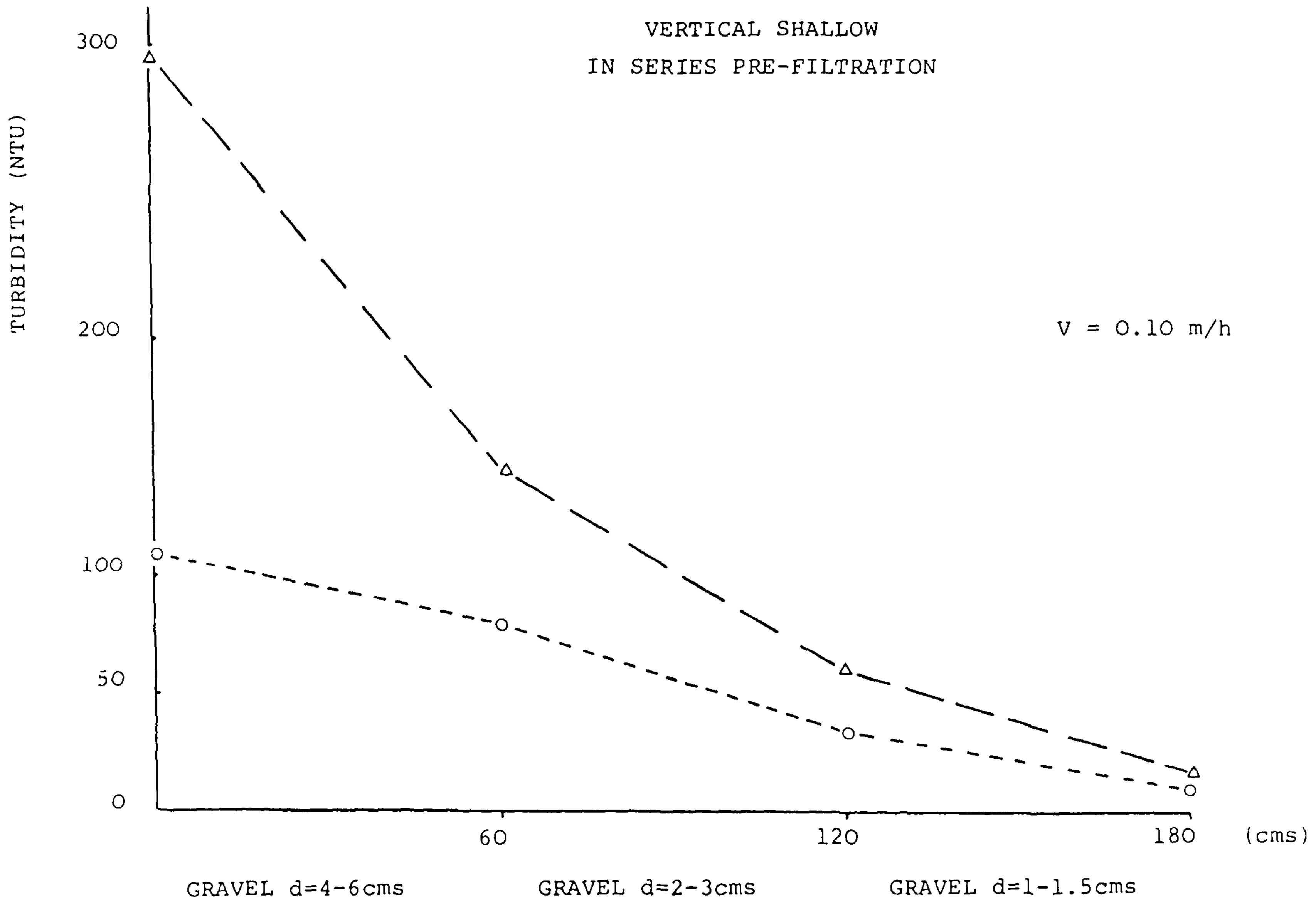


Figure No.6 Level of Removal of Turbidity for each Individual Stage of Filtration.

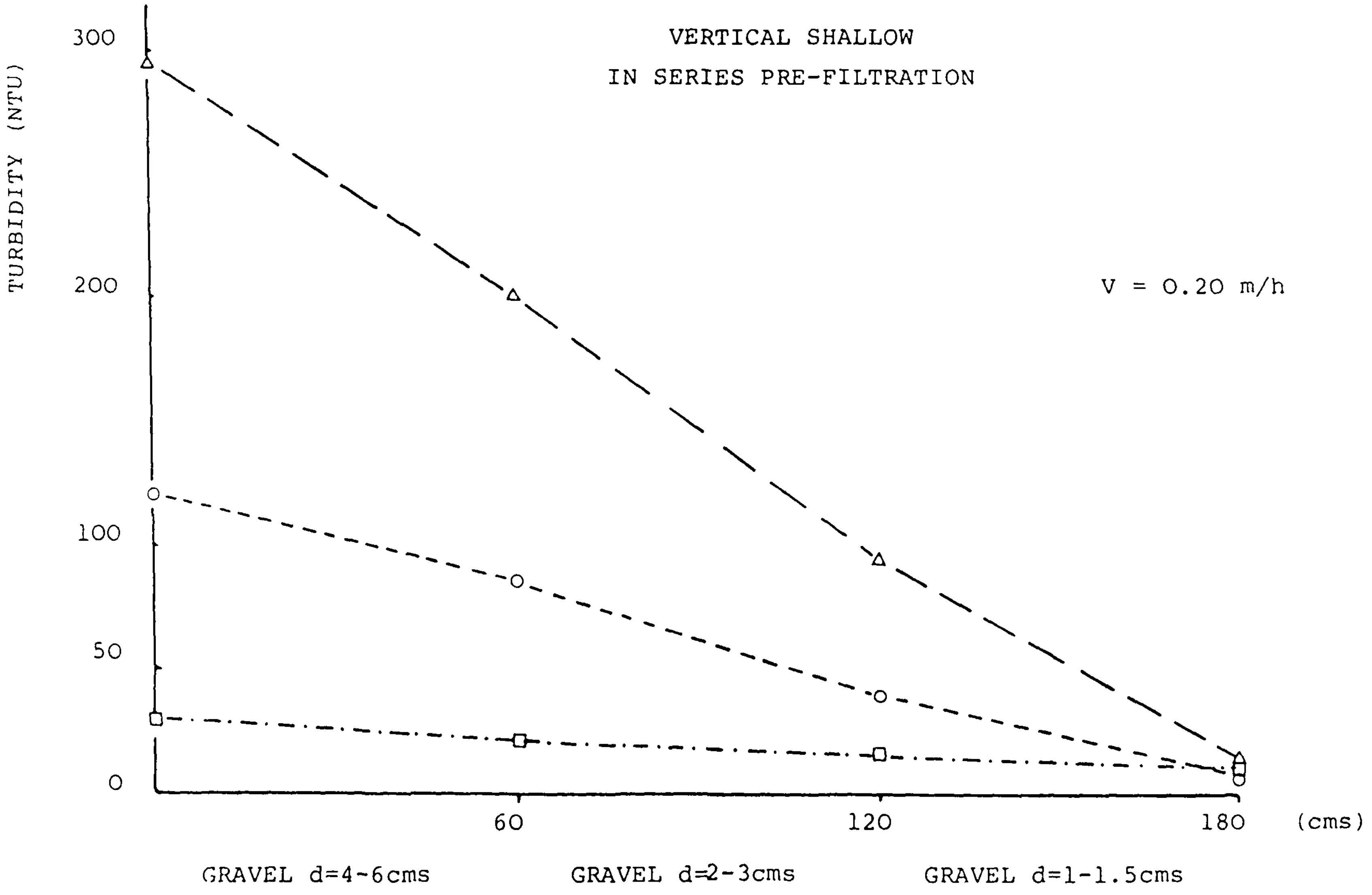


Figure No.7 Level of Removal of Turbidity for Each Individual Stage of Filtration.

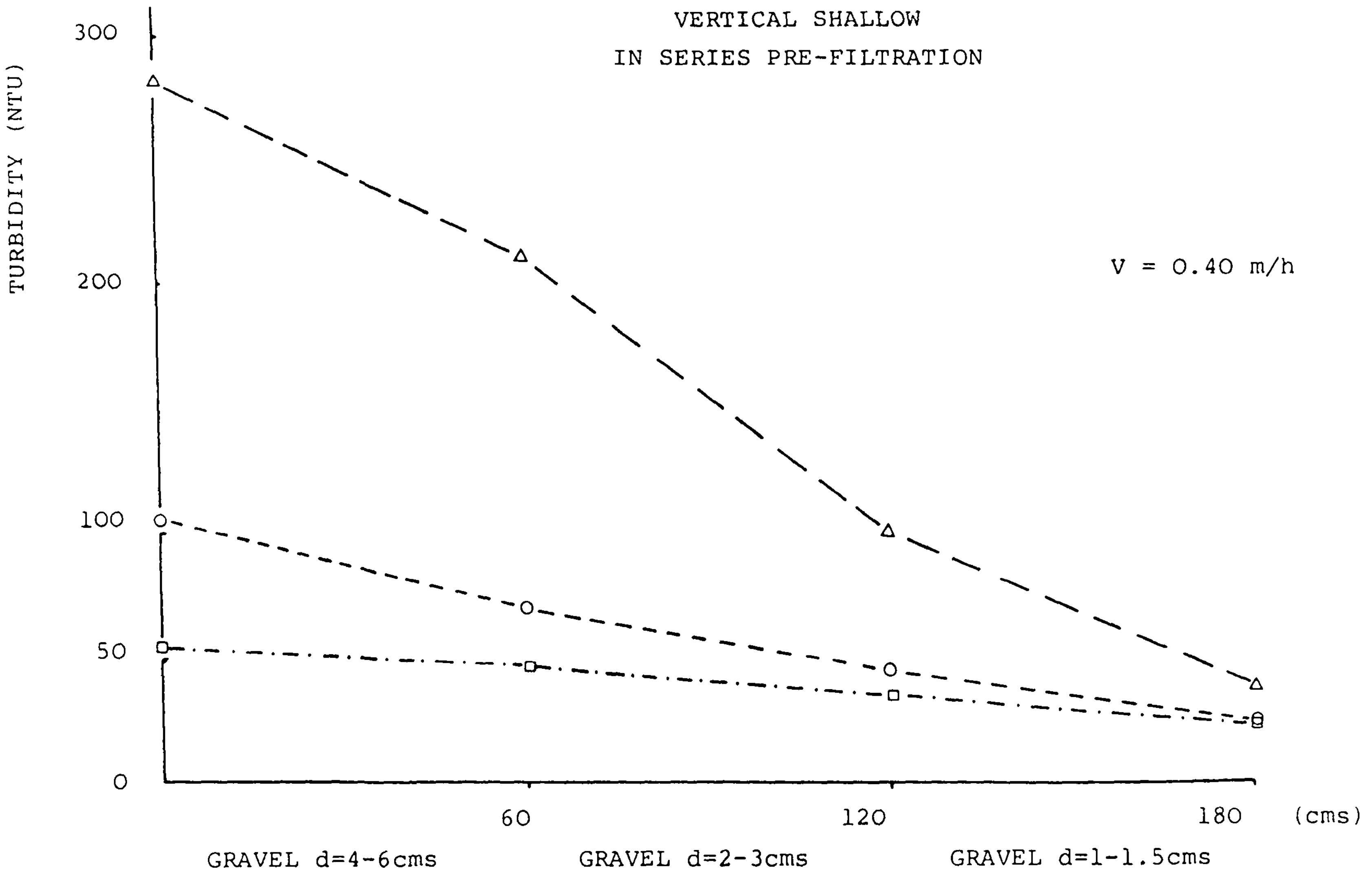


Figure No.8 Level of Removal of Turbidity for Each Individual Stage of Filtration.

can be considered to be of a conservative nature. The experimental work also demonstrated that a velocity of water of at least 1.5 m/min had to be achieved in order to clean the silt deposited on the gravel beds to an acceptable level.

PROTOTYPE TRIALS

San Vicente de Azpitia is a community of around 600 habitants that lies on the coastal plain of Peru 80 Km to the south of Lima. Parallel to the Gravel Prefiltration Research programme, a project to supply the community of Azpitia with treated water derived from an irrigation canal was undertaken.

Frequent samples were taken to assess the quality of the water in the canal. During the rainy season (January-March), levels of turbidity of 1,200 NTU were recorded; during the dry season (April-December), the level of turbidity fell to 10 NTU whilst faecal coliform counts of 1,500 per 100 ml were recorded.

A water supply scheme was designed as shown in Figure No.9. Two of the main features are the protected slow sand filters (discussed widely in References 6, 7, and 8), and the three stage vertical shallow in series prefilters. The other components are a presettler with 2 hour detention time, a 32 mm 0 PVC conduction-distribution line and a multiple scheme of storage tanks and stand posts distributed throughout the community.

The three stage vertical gravel prefilter is presented in Figure 10. It consists of 3 gravel filter beds, each 2.50 m long and 2.15 m wide. The effective filtration depth is 57.5 cms with different gravel sites for each stage : 1st prefilter d-25mm, 2nd prefilter d=13mm and 3rd prefilter d-6mm. Because of the dimensions involved, the system is constructed entirely from brick. The inlet-outlet structures are designed to allow for a cascading effect in order to provide a degree of aeration at each stage. Each

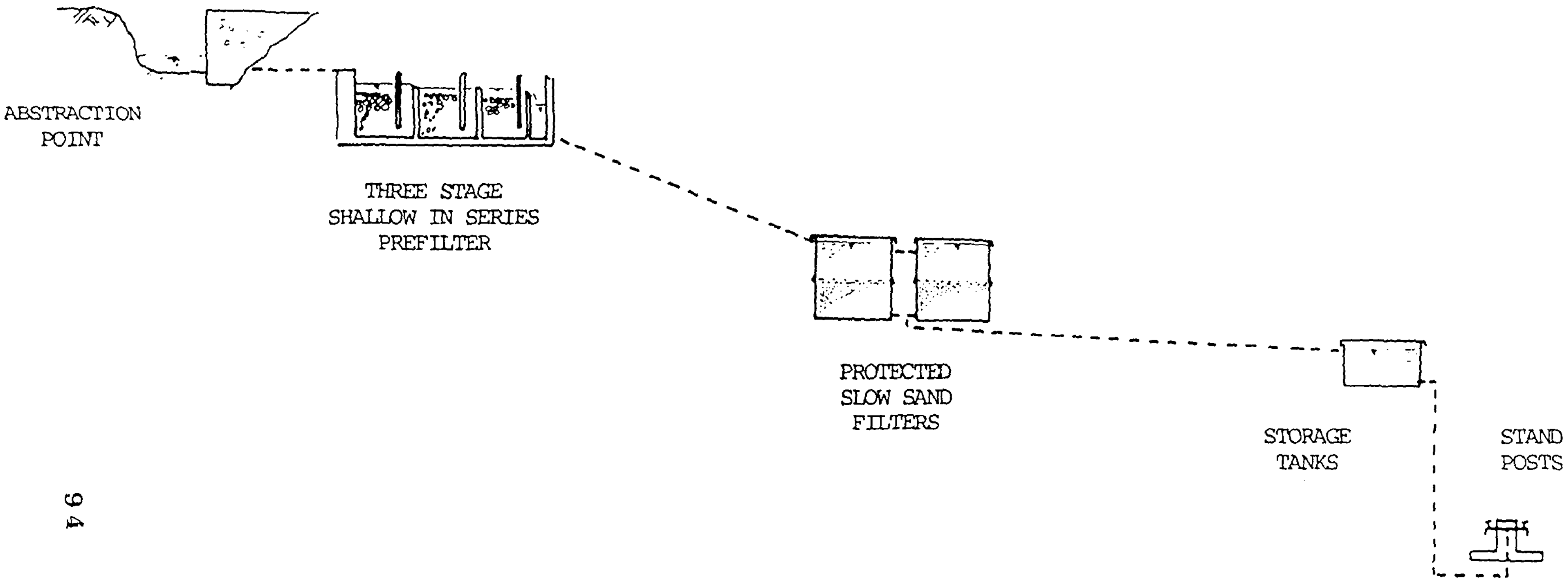
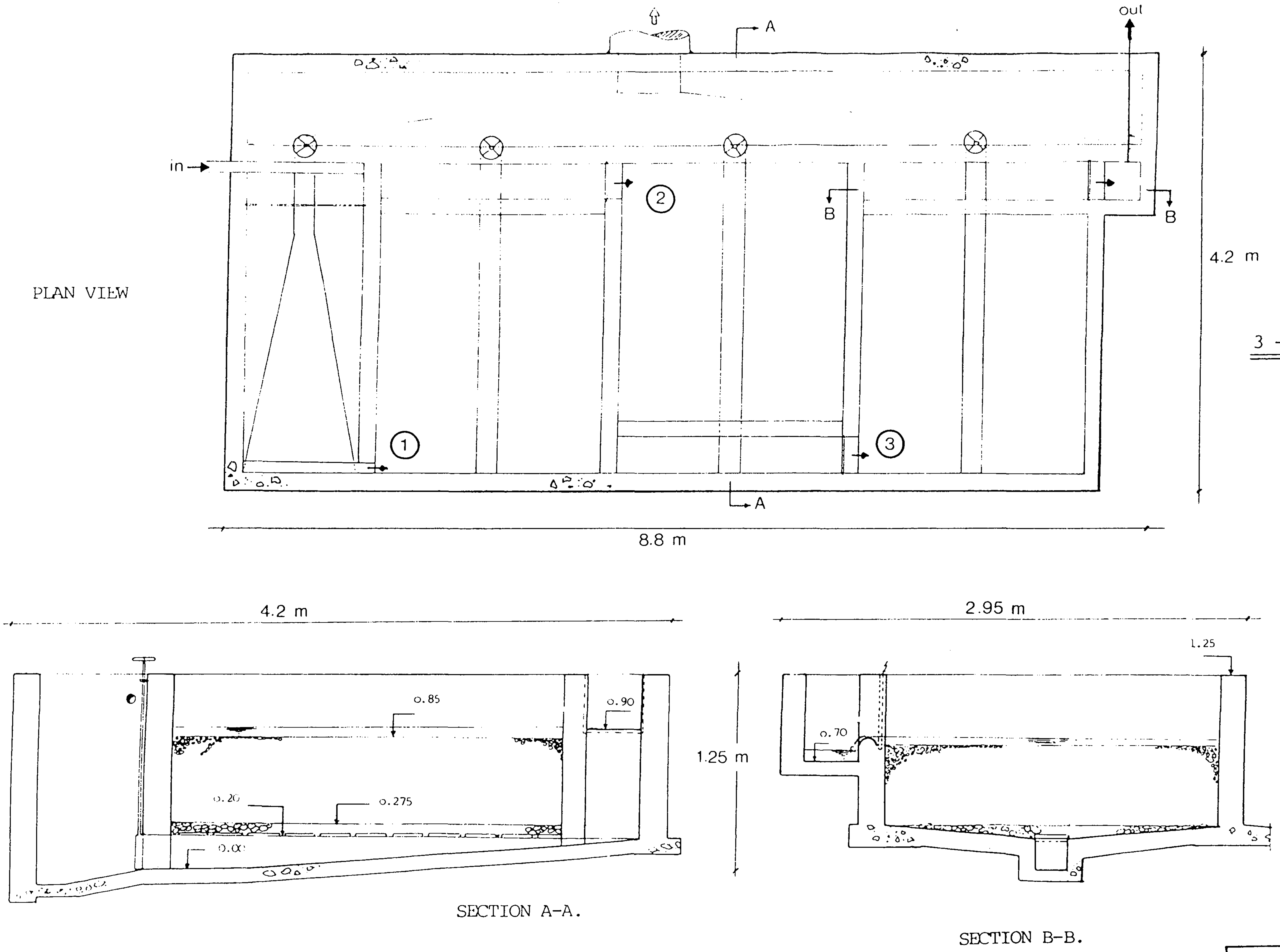


Figure No.9 General Scheme of the Water Supply System of San Vicente de Azpitia-Lima,Peru.

Abastecimiento de Agua Potable a
Pequeñas Comunidades
U.Surrey-ODA/M.Salud-DISAR/CEPIS

PROJECT: San Vicente
de Azpitia

July 84



PLAN VIEW

SECTION A-A.

SECTION B-B.

3 - STAGE GRAVEL PREFILTER

| | | |
|---|---|---|
| ① | GRAVEL ⌀ | 1" |
| ② | GRAVEL ⌀ | ½" |
| ③ | GRAVEL ⌀ | ¼" |

PLANT CAPACITY :- 35 m3/d
POPULATION SERVED :- 750 hab.(50 lppd)
FILTRATION RATE :- 0.30 m/h

Figure No.10 Diagram of the Three Stage Vertical Shallow in Series Pre-filter.

Abastecimiento de Agua Potable a
Pequeñas Comunidades
U.Surrey-ODA/M.Salud-DISAR/CEPIS

PROYECTO:
San Vicente de Azpitia
Lima - Peru

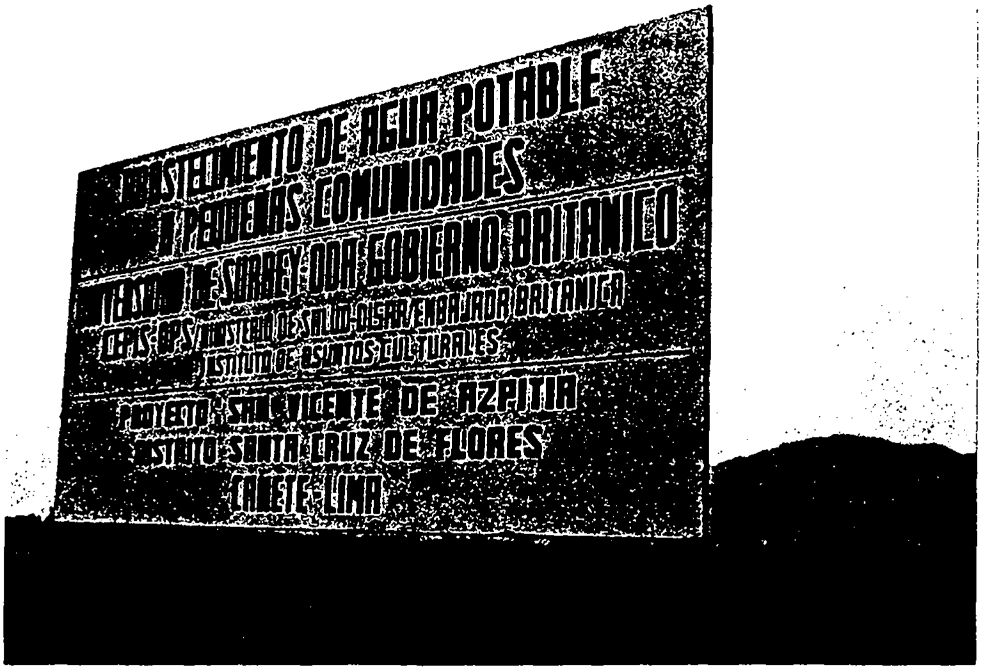


Figure No.11 Building Notice of the Azpitia Project. Sept.'84

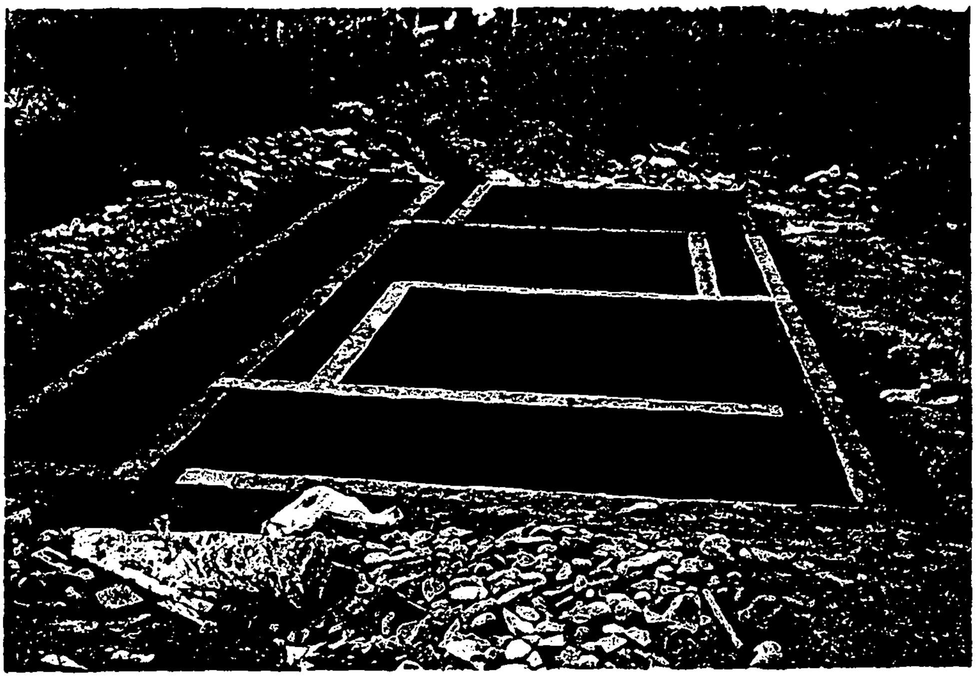


Figure No.12 The 3 Stage Gravel Pre-filter under Construction. Sept.'84

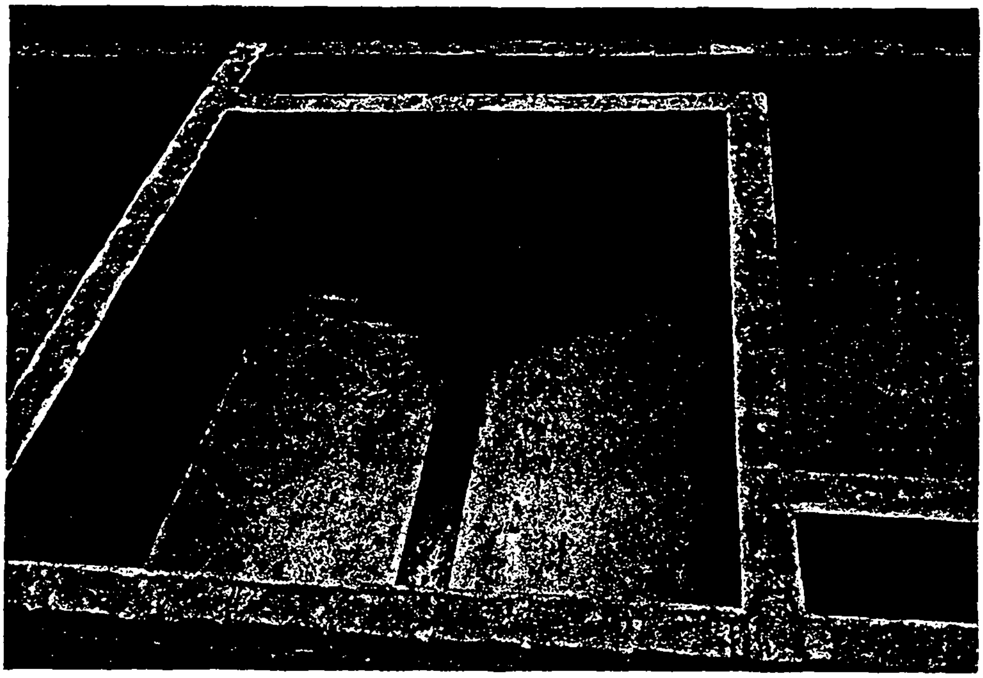


Figure No.13 Detail of the Underdrainage of the 3 Stage Gravel Pre-filter. Sept.'84

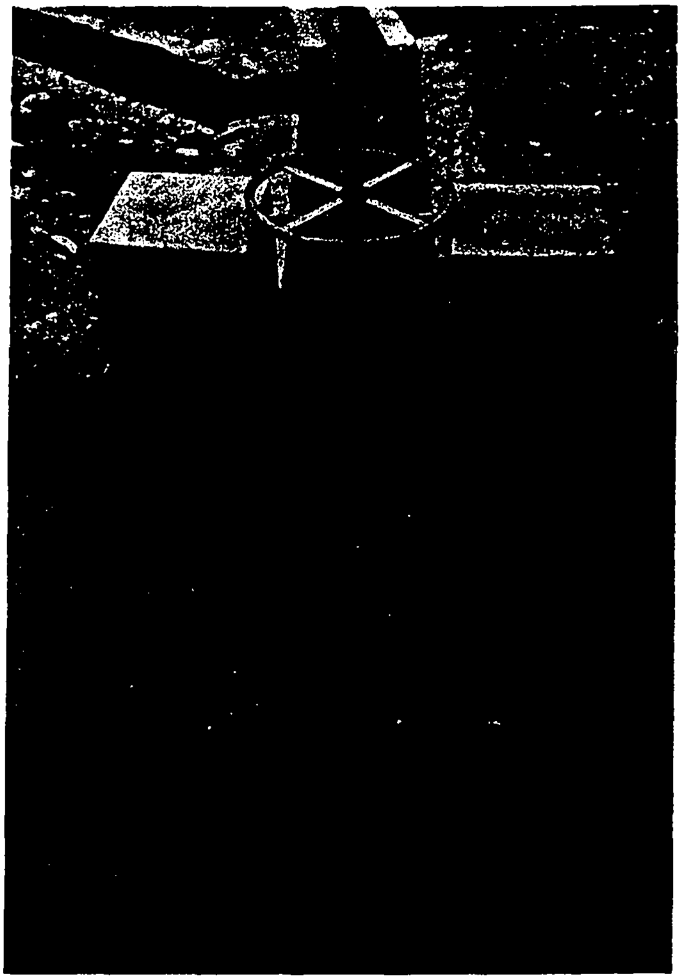


Figure 14: Raw Water Abstraction - Azpitia

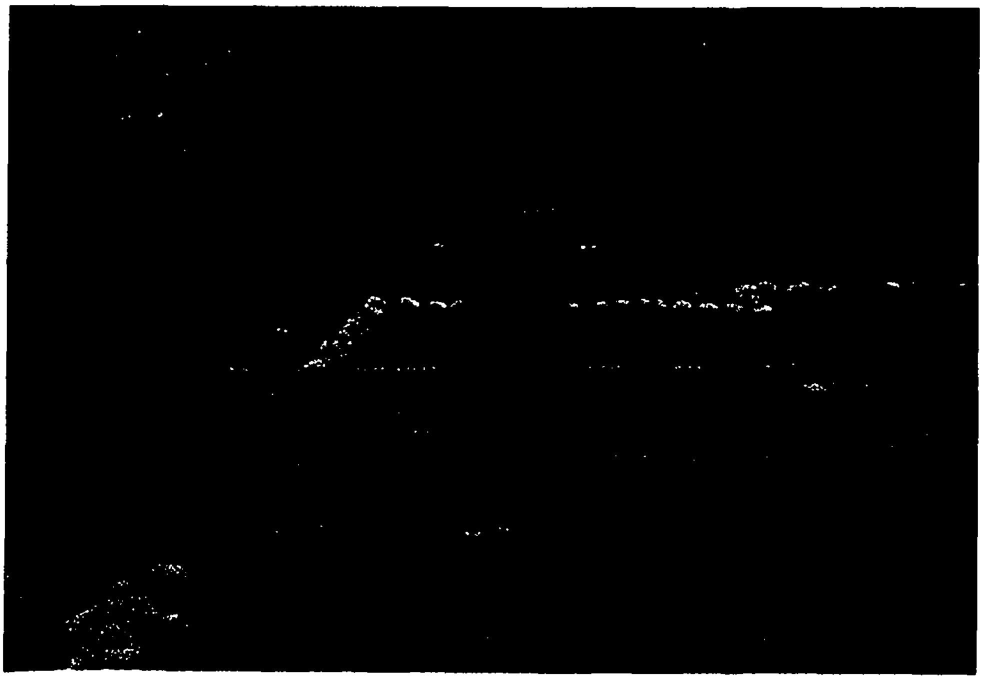


Figure 15: Public Standposts - Azpitia

Figure 16 Slow sand filters - Azpitia

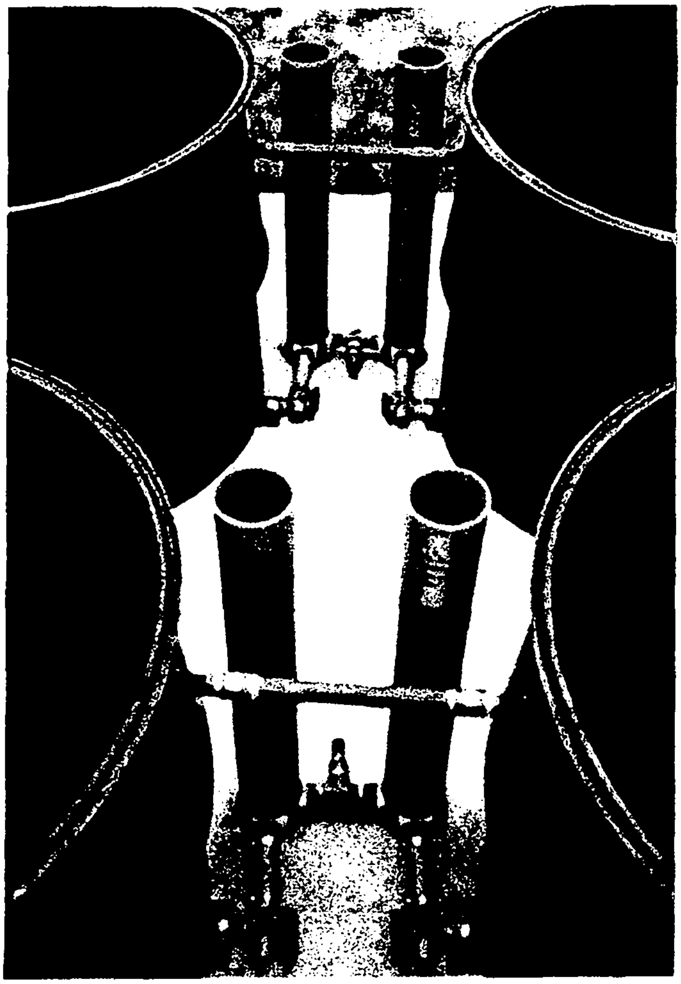


Figure 17. Filters and flow controllers - Azpitia

prefilter also has an underdrainage canal designed to achieve the velocities required for the cleaning of the unit. The plant has a capacity of 35 $m^3$/day operating at a filtration rate of 0.30 m/h, sufficient to supply 750 people with an average daily comsumption of 50 L/person.

The construction of the Azpitia Water Supply Scheme began in the last week of August (see Figures 11,12 and 13). According to the schedule of work it will be completed and commissioned during the first half of December and a continuous evaluation programme will be undertaken throughout the rainy season and until September 1985. The experience gained will help to assess the constraints in operating and maintaining the prototype. The University of Surrey Water Reseach Group is conscious of the potential of Gravel Prefiltration in low-cost treatment systems for rural communities and plans to incorporate it as a standard feature in the present Multiple Stage Filtration Project in Peru. The trials will not be limited to vertical or downflow prefiltration but there are already plans to work both with horizontal and vertical upflow gravel prefilters.

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# APPENDIX I

## SEMINAR ON GRAVEL PREFILTRATION AND SLOW SAND FILTRATION FOR WATER TREATMENT IN DEVELOPING COUNTRIES

---

University of Surrey - Friday 12th October, 1984

Programme

| | |
|---|---|
| Introduction | Barry Lloyd |
| Experience in Peru and the UK | Mauricio Pardon and Chris Symonds |
| Experience in Tanzania & Switzerland | Martin Wegelin |
| Open Discussion | |

The following represents the main elements of the informal presentations plus a more detailed account of the discussions which followed each presentation.

### INTRODUCTION

LLOYD welcomed all visitors and colleagues, in particular Martin Wegelin who had travelled from the IRCWD in Switzerland, and those who have sponsored research at Surrey. He described the thrust of the ODA funded project concerned with the design, development, installation and evaluation of small scale multiple stage water treatment systems for rural communities in developing countries. Problems with rural treatment plants in Peru were identified in 1981, 36% were concerned with sedimentation, 33% with filtration and 89% with disinfection. More specifically, the problems were

1: Lack of maintenance capacity;

2: Lack of operator training;

3: Wasteful water use patterns;

4: Low community perception of the importance of good water supply; thus

5: Unwillingness to pay for service;

6: Use of inappropriate technologies; and

7: Design deficiencies in treatment plants.

Whilst the current project attempted to address all of the above, the seminar was principally concerned with the last two. Although slow sand filtration was demonstrably the most effective single barrier to waterborne disease in the rural sector, its efficient operation is absolutely dependent on effective protection from shock turbidity loadings, or prolonged turbidities greater than 10 NTU. The provision of appropriate prefilters is therefore fundamental to the success of slow sand filtration plants in most circumstances.

## PERUVIAN EXPERIENCE

PARDON described the problem of mineral turbidities in the rainy reason in Latin America. Inappropriate land use patterns, aridity and grazing by herbivores all contributed to the washing of large quantities of inorganic debris into rivers and streams during heavy rainfall. Current collaborative research between the Surrey group, the Centro Panamericano de Ingenieria Sanitaria y Ciencias del Ambiente (CEPIS-PAHO/WHO) and the Ministerio de Salud (Peru) was underway. It was based to a large extent on work promoted by CEPIS which had defined the performance of vertical gravel filters in terms of length of filter and velocity of flow. This work predicted that several in-series filters would be inherently more efficient than one continuous filter. Subsequent work had confirmed the validity of this model and furthermore had indicated peak efficiency to occur at turbidity values 100-300 NTU regardless of velocity.

A filter based on these findings, and other pilot scale work undertaken at La Atarjea treatment works (Lima) is currently under construction in a village of 600 inhabitants 90 Km south of Lima. The plant at Azpitia is designed to perform with turbidities of up to 300 NTU (following simple sedimentation) at a velocity of up to 0.3 m/h. The shallow, in-series vertical prefilter will be followed by protected slow sand filtration.

LLOYD Apart from the first system at Azpitia we intend to install several more systems in Peru, hopefully before the end of the next rainy season. We should have a good idea of their efficiency by the middle of next year.

PARDON Slow sand filtration is not simply inconvenient to operate when influent turbidities are too high; it is also inefficient since it requires stability and continuity for proper operation. We want to protect the sand filter in order that we can simplify maintenance and maximise efficiency.

WEDC Why not have three different gravel types, one on top of the other, rather than in-series filters?

PARDON That has been tried. But we wanted some aeration, and we also wanted to make maintenance easier.

WEGELIN Since the highest loading and therefore maximum deposition would be at the top of such a multistage filter, backwashing would not be very effective.

THE UK EXPERIENCE

SYMONDS drew attention to the IRC guidelines for rural water treatment of surface waters. Pretreatment is indicated wherever turbidities exceed 10 NTU. Sub-sand abstraction had been tried in combination with protected slow sand filtration but it was found that although the reductions in faecal bacteria and turbidity were usually good, backwashing of the prefilters was necessary every 7-10 days. Efficiency was erratic as the sub-sand filter became blocked, and there was a delay in the recovery of efficiency after backwashing. Thus there is a need for adequate storage in order to maintain supply during down-time due to cleaning.

Trials have been conducted with horizontal gravel prefilter modules 8'x1'x1' in series and in parallel. There was little correlation between suspended solids and turbidity in raw waters. There was a better relationship between turbidity and a filterability index.

10 mm gravel was more efficient than 20 mm gravel which was better than 40 mm gravel at all velocities for both turbidity and faecal bacterial reductions. 80% reductions in turbidity were achieved by 10 mm gravel at 0.5 m/h, and bacterial reductions reached 90% after full maturation.

Aeration is clearly vital. Dissolved oxygen levels were depleted from 20 mg/L to 3-4 mg/L after 24 ft horizontal filtration in series. In conclusion, Symonds commented that although turbidities were much lower than could be observed in Peru during the rainy season, it has been demonstrated that for waters of high algal content, gravel prefiltration was very effective in protecting slow sand filters.

SLADE How do the gravel filters differ in function from conventional slow sand filters?

LLOYD The phenomenon of maturation indicates substantial biological activity eg predation by microbiota, and scrapings from superficial zones around the media show the same organisms as one would expect to find in a slow sand filter.

SLADE It seems that the UK filters may be more efficient in removing organic material than mineral suspended matter.

SYMONDS In fact they removed both efficiently. When there were high mineral loadings, they were reduced well, but this was not usual for the raw water source used in my study.

PROFESSOR IVES The maturation period was obvious from your data with efficiency changing with respect to time; so when you quote overall efficiency for different gravel types or velocities, at what time is the efficiency being quoted?

SYMONDS After 7 days of maturation.

PROFESSOR IVES But if you ignore the first 7 days, you miss part of the time during which you slow sand filter suffers from turbidity higher than desired. What was the efficiency at time 0; surely there must have been some sort of efficiency immediately after the filter was switched on.

LLOYD Agreed, but we expect filter runs to last for several months rather than weeks. Thus the first few days after commissioning are probably the least relevant.

PROFESSOR IVES But when you come to surface waters with very high mineral content, I do not think that the biological mechanisms are the dominant ones.

LLOYD Yes, for 3 months of the year in our Andean waters, suspended solids are 90-99% inorganic.

PROFESSOR IVES I have experience of more than 200 days of suspended solids over 500 mg/l and this was virtually all inorganic suspended matter! You did have in your (UK) experimental set-up means of monitoring head loss profiles - what did these show?

SYMONDS There was a small increase in head loss after a period of time at normal flow rates, but when high flow rates were applied head losses became significant. This was when flow was probably in the turbulent mode - this was also reflected by some erratic head loss readings.

PROFESSOR IVES In this case was head loss increase reflecting load?

SYMONDS Yes, and it was particularly noticeable for 10 mm gravel.

## TANZANIA AND SWITZERLAND

WEGELIN gave a presentation in three parts:

1: The identification of problems;

2: An overview of research in Tanzania and Switzerland since 1979;

3: A view of future developments

The identification of problems was presented in an international language in the form of a "peep show'

Work in Dar es Salaam was commenced in 1979 in response to major problems of malfunction with slow sand filtration. The study comprised a) a raw water survey; b) laboratory trials; and c)field trials.

Different sizes and types of filtration media were considered. Vertical filters, though initially efficient, soon blocked and therefore required backwashing. Vertical filters are limited by structural constraints and thus horizontal flow was selected for study.

Firstly a 13 m horizontal arrangement consisting of gravel in the ranges 16-32 mm, 8-16 mm and 4-8 mm was tested at various velocities. At 0.5 - 1 m/L the effluent matched the quality required for slow sand filtration ie less than 10 NTU. Later, field work was undertaken at a non-functioning SSF plant preceeded by clarification. Due to carry over of material, slow sand filter runs were only a few days. A horizontal roughing filter (HRF) was installed upstream of one of the two sand filters while the other was run directly on clarified water. Performance was compared using head loss increase as the critical parameter.

At the end of 1981, several parameters were investigated in Switzerland in order to help construct a mathematical model for HRF. They included flow rate, grain size, material type and filter loading. As in the Dar es Salaam pilot studies, kaolin was employed since it is a good model for the sizes of suspended matter commonly found in natural river waters ie 1-20 u. Kaolin was mixed with ground water, and samples were taken for size analysis by Coulter counter. Transparent tubes showed that the main mechanism in HRF was sedimentation : settlement on grains followed by a downward drift to the filter bottom leading to a self regeneration of upper horizons.

Tests with quartz gravel, charcoal, pumice and glass spheres were undertaken in order to employ as wide a range of surface characteristics as possible. Total filter efficiency was virtually the same in each case, thus it was suggested that any filter medium could reasonably be employed according to local availability eg even broken bricks could be used.

Where draining was used to flush the filter bottom after 280 hours, the hydraulic gradient was sufficient to allow filter resistance to be recovered.

Trials were conducted for different materials at rates up to 4m/h and filtration coefficient ($\lambda$) plotted against load. Ives' model (1960) was related to the results of the pilot scale studies.

3 x 4 m lengths of filter in closed channels with head loss monitors were employed for different gravels at 0.5 m/L, 1 m/L and 2 m/L for up to 200 mg/L influent suspended solids loading (kaolin). Draining was again used to encourage regeneration. Results were compared with calculations from the model. Hydaulic gradient or filter resistance should not be used as the decisive criteria for filter design - it should be effluent quality.

Future work should be concerned with the practical implementation of filter designs using local resources. A simple relationship was suggested.

20L gravel + 20L sand = 30 L safe water.

Danish and Norwegian aid agencies were planning to implement HRF in five regions of Tanzania. Workers should co-operate with such agencies to construct similar demonstration schemes including training and monitoring which will continue for 3 years giving performance data and socio-cultural feedback.

IRCWD would like to promote such initiatives in other parts of the world, in different socio-cultural environments, hence the 'call for cooperation' recently published.

We do not want to make the same errors as were made with SSF 20 years ago - schemes should be small and dispersed.

A more scientific article will soon appear in AQUA, and guidelines will be available at the end of the year.

LLOYD The parallel developments between the Surrey group and IRCWD are very encouraging but there are differences eg upflow/downflow and horizontal/vertical. Are these significant?

TOMS When we consider the filtration of natural waters, we should bear in mind the fact that effluent quality may bear little relationship to influent water quality due to internal transformations within the filter. For example in slow sand filtration, effluent organics may exceed 50 ug/L but very little of this will be derived from the raw water. The simple quoting of % age removals is fraught with difficulties.

LLOYD In the great majority of areas in the world the main problems of turbidity are caused by inorganic rather than organic suspended material. Organic material would naturally support the build-up of biofilms within filters. With our system, we are unlikely to come upon eutropic waters like the river Thames impounded waters, and we do not permit light to enter our sand filters. Thus there is no photosynthetic activity and heterotrophic bacteriological activity will be minimised.

DUNCAN What sort of temperature differences do you encounter?

LLOYD In Peru, we are working at altitudes of of up to 3000 m. Temperatures can be as low as 4°C and as high as 20 or 25°C.

WEGELIN In Tanzania the raw water temperature varied between 15 and 25°C. In our laboratory in Switzerland the temperature was 10-15°C. It is possible that water temperature may have a slight impact on the sedimentary properties of small particles. We have not looked so much at the organic loading to date, being mostly concerned with the physical efficiency of filters. With prefiltration, we should also address algal problems ie particulate matter of all kinds including microorganisms.

DUNCAN What were your raw water sources?

WEGELIN Our raw water was a river with very low organic content. The permanganate value was generally 4-6 mg/L.

PARDON In Peru we have looked at the microbiological improvement across prefilters in a similar way to the UK trials.

SYMONDS Raw water in the UK trials was usually in the range 10-30NTU. Even when there were very high levels of algae however, we still achieved 60-80% reductions in turbidity and faecal bacteria.

PARDON If we extrapolate to developing countries, we can see that during the rainy season there can be very high levels of inorganic suspended material, but outside the rainy season there may be prolonged periods when turbidity is low and would appear suitable for direct slow sand filtration. But if an upstream community was contaminating the water course, during such periods the main problem would be bacteriological rather than physical - particularly with low river flows. So a prefilter shoud act as a protection to slow sand filtration for both microbiological and mineral contamination. This fits in well with the previously mentioned multiple barrier principle of water treatment.

LLOYD We have interesting information which adds to relevance of turbidity - particlarly at the lower range when algal productivity may be of more importance.

WHEELER When there are low levels of turbidity, this parameter seems to have less relevance to slow sand filter run length than filterability. This has been underlined in recent experience with our protected slow sand filter plant operating with fairly constant influent turbidities of 2-3 NTU but with filterability varying from 30 - 75 units.

This is why we have been looking at the interaction of filterability, suspended solids, turbidity and filter run legnth.

LLOYD As a rider to that, in highly inorganically loaded waters, say in the rainy season, we are happy to use turbidity as the main criterion for planning with regard to water treatment intervention. But in low flow, summer conditions, or with highly eutrophic waters, then turbidity as a single parameter breaks down, and we have to go over to filterability in order to predict filter performance.

WEGELIN I am glad to hear of the efforts of the Surrey group because field engineers need simple, relevant field methods rather than sophisticated metering. Turbidity is just one parameter, but it is one which includes sediments, suspended solids, colour, algae and so on, and of course we are concerned with all particulate matter which might affect SSF. We have also developed a field filterability index. We pour 500 ml of sample through a standard filter paper and plot the total volume filtered with respect to time. Distilled water gives a straight line, turbidity gives a curved line. We have shown the relevance of this in design terms in Tanzania.

We introduced a candle flame Jackson turbidimeter into one laboratory, but were disappointed to find that the instrument had failed when we returned. Unfortunately, the candles had disappeared! We then introduced a standard lettering technique instead. These are the type of methods needed by field engineers.

DUNCAN You can also dry your filter papers, return them to the laboratory, estimate carbon and chlorophyll. It all helps you to characterise the suspended solids type.

WEGELIN I have another question which is giving me a headache! Why should filter efficiency decrease (in the Peruvian data) for turbidities greater than 300 NTU? Theory would predict increasing efficiency of turbidity removal with higher levels of influent suspended matter. Perhaps it is due to overloading.

PROFESSOR IVES First of all, I am very embarassed that you have quoted my work from 1960 which shows how long I have been playing with filters! Of course, as you say, one point is accumulated load, and that you are on the downward part of the efficiency curve. The other point however, is that just as you (WEGELIN) have shown the downward drift of material when you drain down due to the different stresses on deposited material and changes in surface tension, such effects may also be occuring during the process of filtration. We have recently been able to use optical fibres to inspect the internal functioning of filters. When there is heavy loading, there is a large amount of unstable deposit similar to snow on mountain tops in Switzerland. If one throws stones at snow, it may dislodge, or even avalanche. It follows that the more stones one throws, the more snow is dislodged. The incoming particles in a filter actually represent 'thrown stones' transported by the water and they hit unstable, mounted deposits as you progress through the filter operation. I was impressed by your picture taken through the filter wall which confirmed our observation of mounted deposits.

LLOYD Professor Ives' comments are supported by the graphs which showed an increasing effect with velocity. We have seen something similar with slow sand filters which are competent in maintaining efficiency up to 0.5 m/L after which breakthrough occurred.

PROFESSOR IVES It may not be quite the same thing in SSF where the picture is complicated by the different strengths and structures of biological material on sand grains. Biological growth can be very sticky and tenacious. However, with clays (and we also used kaolin) the unstable deposits are quite characteristic.

I would also like to comment on the IRC (Hague) checklist which indicates pretreatment above 10 NTU. Mr. Wegelin suggested at one point 20 NTU. We might suggest it could be even higher. I would like to know where the figure came from, and what was its significance.

LLOYD I would say 20 NTU was already too much for a conventional slow sand filter. In our experience, such loadings caused filter blockage every 7-10 days. As soon as we incorporated pretreatment and reduced turbidity to around 5 NTU, we achieved filter runs in excess of 100 days.

PROFESSOR IVES I know that the particle size distribution is not linear and so it is possible that with pretreatment, the larger particles are removed leaving the finer material to carry over onto subsequent filters.

GREGORY Filter run length is not the only criterion. If you want to achieve a final treated water of less than 1 NTU, then with a typical efficiency (as quoted) of 90%, the maximum influent turbidity would have to be 10 NTU.

WEGELIN I was grateful for Professor Ives analogy with snow in Switzerland, he put it in such a nice way- he is obviously a real professor. I need another clear explanation. With different gravel sizes one would expect the slope of efficiency to be steepest with the smallest gravel - this is not the case with some of the data from Peru.

PROFESSOR IVES First of all, that is not true for the lower curves, but in any case I would argue that it is probably incorrect to join in straight lines data based on single points. If it is a moded filter, it is unlikely that a single point gives sufficient detail to apply that interpretation. (That is a <u>real</u> professor speaking!).

PARDON The data was based on mean results over a seven day period. However, the main point is that these curves allowed us to predict effluent turbidity so that we could design our prefilters accordingly to maximum influent turbidities.

LLOYD I would like to get Professor Ives' opinion on another matter.

PROFESSOR IVES I obviously did not get that free lunch for nothing.

LLOYD Which type of multi-medium filter would be most efficient : one with dead spaces betrween each medium, or one without? We have some evidence to suggest that incorporating water spaces leads to greater efficienty.

PROFESSOR IVES They may be acting as sedimenters.

LLOYD Could it be that the change in velocity is greater in a filter with dead spaces, leading to turbulence at the interface, followed by aggregation and enhanced sedimentation?

PROFESSOR IVES I doubt that. But it is quite possible that flocculates or aggregates formed within the first stage filter medium, or indeed material which detaches from the medium due to dislodging may well sediment in the dead space before the next stage.

CAIRNCROSS I presume that Dr. Lloyd is drawing his evidence from the Peruvian data which howed the first four centimetres of filter medium to be much more efficient than the downstream medium. This showed that increased efficiency was actually recorded within the medium, not in advance of it as Professor Ives was explaining.

WEDC Were you using the same medium in your spacing or was it always reducing in size at each stage.

PARDON First of all just one medium type had been employed (1979-80); but later (1984) it was proposed to use different media.

BULMAN Is there not a danger that in isolated communities, the filters may be run at rates which are too high for efficient operation? This is a big problem in developing countries.

LLOYD Yes it is one we have already experienced with our slow sand filters where the constant flow device was immediately opened up once we had commissioned the plant.

WEGELIN In Tanzania, the horizontal roughing filter effluent was produced in such quantities in comparison to the output from the slow sand filters that is was diverted straight to the clear water chamber when water was in short supply.

LLOYD There are a number of variables which can be controlled with respect to filter design and we would be grateful for comments on their relative importance.

TOMS It seems that whilst very good and relevant models may be devised for the roughing filters which are designed to protect slow sand filters, it is very difficult to define the efficiency of a slow sand filter - particularly with respect to filter run length. Run time depends on i) initial head loss at normalised flow; ii) rate at which head loss increases with time and with water treated; and iii) final head loss.

LLOYD A lot of our data was derived from a collaborative study with Imperial Collge on the OXFAM water tratment package.

GRAHAM In our case the constraints were a little different than those for River Thames derived water. To a certain extent we were able to optimise the variables quoted but there are other difficulties : for example the type of sand used.

IVES Things can be simplified to a certain extent. Starting head loss may be calculated from knowledge of sand type, and finishing head loss is defined by hydraulic design. However the third term - rate of head loss increase - is dependent on water quality factors and we need more information on filterability. The Thames Water Authority and previously the Metropolitan Water Board used gauze or lint pads to assess filterability. But we must take into account changing conditions throughout filter runs, for example those caused by biological productivity. If that problem can be solved, then everything falls into place.

GRAHAM Have you looked at the maintenance aspects of prefiltration sufficiently yet? It seems that you have little experience of routine operation to date.

LLOYD This is true. The Lima study only commenced in April, and the UK work in February. We therefore have no long term practical operational experience with regard to operation and maintenance. I would be loath to extrapolate from pilot scale studies.

PARDON Cleaning velocities have been investigated in Peru - both upflow and downflow (separately and in combination) and it was concluded that velocities needed to be between 1 and 1.5 m per minute in order to drag material from the bed efficiently. Our plant in Azpitia was designed accordingly and we should soon find out the filter run times and hopefully these will be predictable according to the time of year.

GRAHAM Does this mean that someone will continuously monitor effluent quality of the unit and maintain the filter when breakthrough occurs?

PARDON We are still in the developmental phase and so we will be monitoring for the next 12 months. We hope then to be in a position to give operator guidelines.

LLOYD When we were discussing the alternative benefits of horizontal versus vertical gravel filtration, we eventually decided on shallow in-series prefiltration for Azpitia because the backwashing literally only takes a few minutes. Otherwise one has to dig out a horizontal filter - a much more labour intensive process.

WEGELIN Concerning the HRF, filtration run depends on hydraulic load and mass load. We commissioned our horizontal filters in Tanzania in March 1981 and they were cleaned for the first time in July 1984. We had no means of draining down the filters.

GRAHAM Did you have high raw water turbidities?

In equilibrium, where Reynolds Number is less than 1 and drag force is due to viscous effects only (ie $C_D = 24/R_e$):

$$(V_s - V_v) V = \frac{C_D \ Ap \ V_s^2}{2}$$

DW5/1:

## SEDIMENTATION

There are two principal types of sedimentation : i) the removal of non-flocculating, discrete particles in a dilute suspension, under these circumstances, settling is unhindered and a function of fluid properties and those of the suspended particles (for example the settling of heavy, inert particles); and ii) the settling of dilute suspensions of flocculating particles. In the second case, heavier particles with relatively high settling velocities coalesce with smaller, lighter particles forming aggregates with still higher rates of sedimentation, this form of settling is therefore depth dependent as well.

The driving force (F) is the net effect of particle weight and the buoyant force. Thus:

$$F = (\gamma_s - \gamma_v)\, V$$

where: $\gamma_s$ is the specific weight of the solid;

$\gamma_v$ is the specific weight of the fluid; and

$V$ is the particle volume

Drag force ($F_C$) is given by:

$$F_D = \frac{C_D A\, \rho V_s^2}{2}$$

where: $C_D$ is Newton's drag coefficient;

A is the projected area in the direction of flow; and

$V_s$ is the settling velocity of the solid.

$$n = \frac{V_b - V_c}{V_b} \times 100$$

where n is porosity

$V_b$ is the experimentally determined bulk volume of rock plus water; and

$V_c$ is the volume of rock.

Permeability is defined as a measure of the fluid transmitting capacity of a porous medium. From Darcy's Law it may be calculated thus:

$$k = \frac{\mu q\ L}{Dh\ A}$$

TRANSPORTATION, TURBULENCE AND DEPOSITION

In fluids, the principal factors which affect the transport of suspended solids are : turbulence, the ratio of settling velocity to lateral velocity of water, and the shape, size and density of the particle.

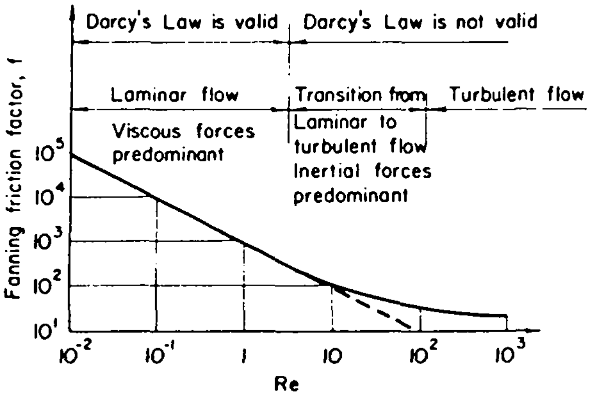
Turbulence is a non-linear motion of mass in a moving body of water. The principal factors which affect the transport of solids by turbulence are: volume of water, velocity, temperature, load and shape and angularity (roughness of the material over which the water flows).

The deposition of suspended solids is related to energy, location and time. The main effect of time with respect to deposition in water is the rate of change of velocity ($ds/dt$). Together with the change in direction and rate of change of direction, the rate of change of velocity defines the dependence of turbulence on deposition. Small rates of change of velocity promote only slow rates of solids deposition. As turbulence increase this form of linear deposition reduces and a more random process occurs.

1: At low Reynolds Number, flow is laminar, viscous forces predominate and the linearity predicted by Darcy applies;

2: As Reynolds Number increases there is a transition zone;

3: At high Reynolds Number there is turbulent flow, inertial forces begin to predominate and Darcy's Law no longer applies (see below)



DEFINITION OF POROSITY AND PERMEABILITY

Porosity is that property of a rock or gravel containing interstices, without regard to size, shape, interconnection or arrangement of openings which expresses the percentage of total or bulk volume occupied by the interstices.

Whereas, Effective Porosity is that property possessed by a rock of continuous intercommunicating interstices eg gravel, and Isolated Porosity is that property possessed by a rock of non-communicating interstices.

Porosity is calculated by the following relationship:

material by weight. Collin has suggested that:

$$d = \left[\frac{k}{n}\right]^{.50}$$

where k is the permeability; and

n is the porosity,

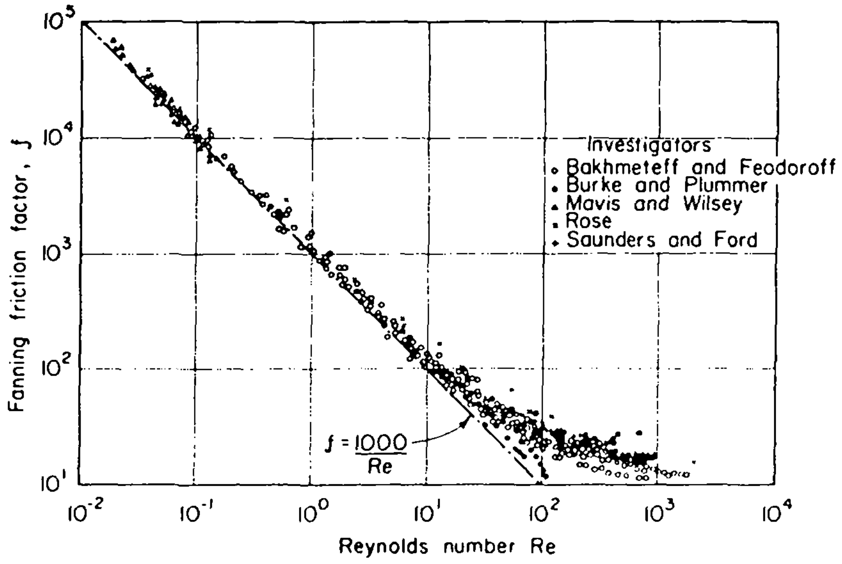
but Ward used $k^{.50}$ as the representative length dimension (d). However, in all cases, Darcy's Law is valid as long as the Reynolds Number based on average grain diameter does not exceed some value in the range 1-10. We have considered laminar flow to cease at $R_e = 5$.

This may be deduced from the relationship between friction factor and Reynolds Number, thus:

$$f = .50\ d\left[\frac{DH}{L}\right]\left[\frac{Y}{\rho V^2}\right]$$

where: f is the Fanning friction factor

This may be represented thus:



From this graphical information it is possible to draw the following conclusion:

# APPENDIX IV

## DARCY'S LAW AND REYNOLDS NUMBER

From experiments conducted by Darcy on vertical homogeneous sand filters, flow was described in the following terms. The rate of flow (Q) is proportional to the cross-sectional area (A) and head loss through the medium (Dh), and inversely proportional to the length L.

Thus:

$$Q = \frac{k \quad A \quad Dh}{L}$$

Where k is the coefficient of permeability

Darcy's Law specifies a linear relationship between discharge flow rate (Q) and the hydraulic gradient (J) which is defined as $\frac{Dh}{L}$, however, this relationship does not hold in all circumstances.

Reynolds Number, the ratio of inertial to viscous forces, is used as a criterion for distinguishing between laminar and turbulent flow. It is defined in the following manner:

$$Re = \frac{pVd}{\mu} \quad \text{or} \quad \frac{Vd}{\nu}$$

Where: V is the mean velocity of flow; p is the fluid density

d is the distance representing elementary channels; and

$\nu$ is the kinematic viscosity.

However, for gravel:

$$Re = \frac{Vd}{\nu}$$

Where: d is the diameter of gravel

Although d should theoretically represent the length dimension for elementary channels in the porous medium, this is not used. Occasionally $d_{10}$ is used where $d_{10}$ is the grain size which exceeds the diameter of 10% of the

# Filterability Index

Following a further test on the reliability of the Whatman GE/A Filters it was found that there was an unacceptably high variation in times for a known volume of water to percolate through a filter.

Time (secs) 84.1 , 96.4, 85.7, 41, 64.4, 54.3

Average Value = 70.27 secs

Standard deviation = 19.3

This is in comparison with an earlier test

Time (secs) 56.4, 56.6, 56.8, 56.5, 57, 59.

Average value = 57.0 secs

Standard deviation = 0.893

Such a large variation in filter performance is unsatisfactory and as a result a new method has been devised.

Using a vacuum pump, with a head of 27mm Mg, a 150 ml sample is sucked through a sartorious membrane, the time taken being noted.

The filterability Index is still expressed as :-

$$\frac{\text{Time taken for distilled water}}{\text{Time taken for test water}} \times 100$$

The variation in time for 150 ml of distilled water passing through a sartorious membrane has been tested

Time (secs) 19.0, 18.0, 17.5, 18.1, 19.6, 17.1, 21.6, 19.7, 19.0

Average value = 18.86 secs

Standard deviation = 1.31

Aothough there is some variation the new method to assess filterability is accurate to ± 10%

# APPENDIX III

## FILTERABILITY METHOD

### METHOD

Using a Buchner flask, with a 7.0cm diameter funnel the time taken for a known volumn of 'test' water to percolate through a Whatman GF/A filter is recorded.

Similarly for the same volume of distilled water; the time taken to percolate througn a whatman GF/A filter is recorded
The filterability Index is expressed as:-

$$\frac{\text{Time taken for distilled water}}{\text{Time taken for 'test' water}} \times 100$$

To accurately evaluate the filterability index a set procedure is required to time the passage of the water through the filter. This is established by timing how quickly a water sample passes between two lines on the Buchner Funnel. The distance between the two lines represents a volume of 100 ml.

This has been found to be the most accurate way of timing the passage of water through the filter. Using a vacuum pump ( 25" $H_g$) to suck the water through the filter was tried but the samples of distilled and 'test' water passed very quickly through the filter leading to a wide spread in results due to different interpretations of when the water sample had finally passed through:-

The percolation method has also been chosen as it is more appropriate to the action of a slow sand filter. Suspended solids, and turbidity data can be linked to the filterability index, the suspended solids being analysed using the same Whatman GF/A filters.

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WEGELIN They were not very high, but in Thailand, where Thanh is working, one horizontal filter has functioned for six years. But now we have the mathematical model which should allow us to optimise design. Perhaps by incorporating the drainage and self-regeneration principle we can make filters much smaller.

AT this point the recording terminated

LLOYD thanked everyone for their participation and looked forward to continued dialogue and co-operation in this field.

The above account involved substantial paraphrasing. If anyone's comments have been misrepresented we would be grateful to be given the opportunity of correcting the error.

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