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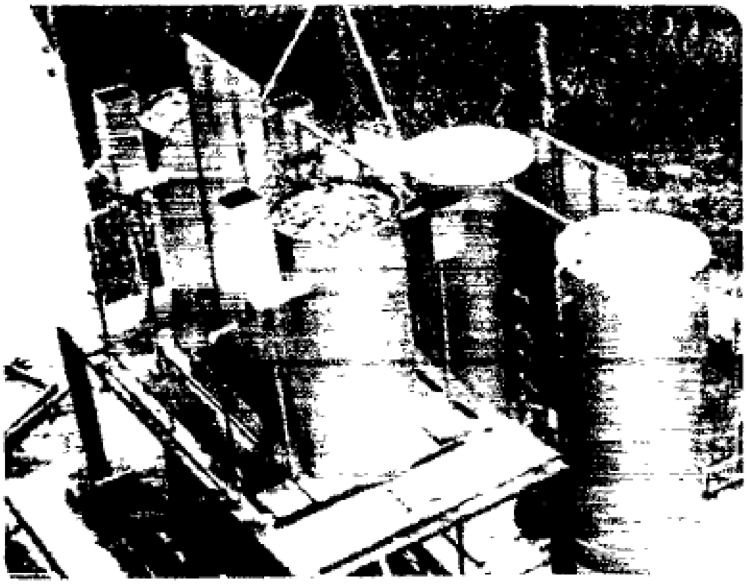
The potential for the use of roughing – slow sand filtration systems in Zambia

Mwiinga Godfrey



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TUDelft

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"THE POTENTIAL FOR THE USE OF ROUGHING - SLOW SAND FILTRATION SYSTEMS IN ZAMBIA"

by

MWIINGA GODFREY

A dissertation submitted to the University of Zambia in partial fulfilment of the requirements for the Degree of Master in Engineering (Environmental)

THE UNIVERSITY OF ZAMBIA
LUSAKA
1998

DECLARATION

I Godfrey Mwiinga do hereby solemnly declare that this dissertation represents my own work, and that it has not previously been submitted for a degree at the University of Zambia or any other university.

Signature :..

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APPROVAL

This dissertation of Godfrey Mwiinga is approved as fulfilling the partial requirements for the award of the Degree of Master in Engineering (Environmental) by The University of Zambia.

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ABSTRACT

There is growing concern in most developing countries regarding the use of technologies that are inappropriate to local conditions. In the area of treating surface water to drinking water quality, consideration of alternative treatment methods is receiving great attention particularly with regard to small and medium community water supplies. In Zambia, surface water treatment to potable water is mainly by conventional methods. A recent evaluation of these methods revealed that operation and maintenance problems associated with the chemical pre-treatment stage were rampant, particularly in small and medium community water supplies. To date, there have been hardly any studies on alternative methods. The current trend in the water sector is largely inclined towards addressing the rehabilitation of water supply systems so that private sector participation is facilitated. One of the sector principles, however, is to consider alternative treatment methods to alleviate current problems.

The combination of roughing and slow sand filtration systems has emerged to be an appropriate alternative to conventional methods in most small and medium community water supplies. Roughing filtration as a pre-treatment method neither requires expert supervision nor chemicals. However, current studies elsewhere reveal that adequate design guidelines for roughing filters are not yet fully established. Slow sand filtration, as the main and final filtration stage, is excellent in producing potable water. However, new applications of slow sand filtration require pilot testing to ascertain their suitability. Operation and maintenance needs of roughing and slow sand filtration systems are reported to be simpler and economical compared to conventional systems. Nevertheless, for new applications, and where local experience is lacking, this can only be ascertained through pilot studies.

The principal objective of the study was to evaluate the potential of a combination of roughing filtration and slow sand filtration systems for small and medium community water supplies in Zambia (using local materials) as alternatives to conventional systems. A pilot plant encompassing up-flow roughing filtration in layers and slow sand filtration processes was designed, constructed and investigated. Local filter media were used for the filtration processes. The pilot plant treated *Kafue* River water and high turbidity simulated raw water. The use of simulated raw water was inevitable since the investigation period did not cover the rain season when high turbidity raw water is common. The characteristics of the actual *Kafue*

River water during the period of investigation were: daily average turbidity < 5 NTU, total suspended solids < 5 mg/l, faecal coliforms < 200 FC/100 ml. Those of the simulated raw water were: daily average turbidity < 300 NTU, total suspended solids < 2000 mg/L and faecal coliforms < 4000 FC/100 ml. The performance of the pilot plant was evaluated by analyzing the quality of the filtrates. Roughing filters were operated at filtration rates ranging from 0.4 to 1.25 m/h, while slow sand filters were run at an average filtration rate of 0.24 m/h.

Up-flow roughing filters in layers managed to pre-treat raw water to quality suitable for slow sand filtration, by significantly reducing the levels of turbidity, total suspended solids and faecal coliforms. There was no significant difference in performance, with respect to turbidity and suspended solids removal, of the roughing filters by varying filtration rates from 0.4 to 1.25 m/h. However, the removal of faecal coliforms was slightly lower at 1.25 m/h. The final slow sand filtrates showed acceptable turbidity levels (<1 NTU). However, faecal coliform levels occasionally exceeded the less than 1 FC/100 ml recommendation by the World Health Organization. Hence, slow sand filtrates may still require disinfection to guarantee potable water supply. Because of the sufficient pre-treatment provided by roughing filtration, slow sand filters were characterized by longer filter-runs than those reported for slow sand filters applied in Zambia, and elsewhere where chemical pre-treatment methods are used. The operation and maintenance of the pilot plant was easy, simpler and economical, managed by a local, compared to reported operation and maintenance requirements of conventional systems.

It was therefore concluded that the use of roughing and slow sand filtration systems has great potential for small and medium communities in Zambia. Local materials can readily be utilized to construct these systems. The systems are able to treat raw water of high turbidity to potable water without the use of pre-treatment chemicals. Operation and maintenance procedures are relatively easy and can even be met at community level management. The results of the study provide the first basis for designing roughing and slow sand filtration systems in Zambia based on local practical investigations.

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ABBREVIATIONS AND VARIABLES

1. Aver. : Average
2. AWWA : American Water Works Association
3. CINARA : Central Inter Regional de Abastecimietoy Remocion de Agua
4. cm : centimetre
5. $d_{10}(d_e)$: diameter at which 10% of grains are equal or smaller than a given diameter (mm)
6. d_{60} : diameter at which 60% of grains are equal or smaller than a given diameter(mm)
7. DRFS : Down -flow Roughing Filters in Series
8. FC : Faecal Coliform
9. HRF : Horizontal-flow Roughing Filters
10. LWSC : Lusaka Water & Sewerage Company
11. m : metre
12. m/h : metres per hour
13. m^2 : metre square
14. m^3/d : cubic metres of water per day
15. m^3 : cubic metres of water
16. $m^3/ m^2/d$: Cubic meters of water per filter surface area per day
17. m^3/h : cubic metres of water per hour
18. Max. : Maximum
19. mg : milligram
20. mg/L : milligrams per litre
21. ml : millilitres
22. mm : millimetre
23. MPN : Most Probable Number
24. NTU : Nephelometric Turbidity Unit
25. RF : Roughing Filtration
26. RSF : Rapid Sand Filtration
27. SSF : Slow Sand Filtration
28. TCU : True Color Units
29. TSS : Total Suspended Solids
30. UC : Uniformity Coefficient
31. URFL : Up-flow Roughing Filtration in Layers
32. URFS : Up-flow Roughing Filters in Series
33. v_f : filtration rate (m/h)
34. WEF : Water Environmental Federation
35. WHO : World Health Organisation

Chapter one

INTRODUCTION

1.1 Background

The treatment of raw water to potable quality is a world wide problem. Conventional water treatment processes (coagulation, rapid mixing, flocculation, sedimentation, slow or rapid sand filtration, disinfection) are widely used in developed and developing countries [*Schulz* and *Okun,* 1984]. The chemical pre-treatment stage (coagulation, rapid mixing, flocculation, sedimentation) improves raw water to quality suitable for effective performance of the main treatment (slow or rapid sand filtration). Chemical pre-treatment combined with rapid sand filtration has disadvantages, particularly pronounced in poor developing countries [*Wegelin et al.,* 1991]. These disadvantages include high capital and operating costs, and the need for expert supervision for the complex operation and maintenance. These setbacks have rendered conventional processes inappropriate in most developing countries, especially for small water supply systems [*Visscher et al.*, 1987; *Wegelin et al.,* 1991]. In most developing countries, equipment, spare parts, and chemicals have to be imported and small water supply systems are usually unable to attract skilled manpower and adequate funding. Slow sand filtration alone is an effective, cheap, and easy to operate and maintain option, and it has been widely recommended in most developing countries.

One of the early mistakes in the sole use of slow sand filtration was to subject it to highly turbid raw water [*Graham et al.,* 1994]. In an attempt to pre-treat such raw waters to quality acceptable for slow sand filtration, chemical pre-treatment has been widely applied. However, where chemical pre-treatment is not efficient due to lack of reliable chemical supplies, equipment and expert supervision, slow sand filters are fed with inadequately pre-treated raw water which leads to rapid clogging of the filters and accompanying problems of frequent cleaning. Frequent cleanings reduce the production reliability and increase running costs. Short filter-runs are also not effective in removing pathogens [*Visscher et al.,* 1987].

Of the various pre-treatment options which can alleviate slow sand filter clogging problems, roughing filtration has emerged to be an appropriate method. It has received considerable attention because it does not use chemicals [*Wegelin,* 1996; *Galvis et al.,* 1996].

Multi-stage filtration by roughing and slow sand filtration systems is regarded as an alternative to conventional water treatment methods in most developing countries [*Wegelin,* 1996; *Wegelin et al.,* 1991; *Galvis et al.,* 1996; *Clarke et al.,* 1996; *Shenkut,* 1996]. The systems are economically competitive and are less demanding in operation and maintenance. They are being applied in developed and developing countries. Studies in Colombia have shown that running costs are reduced by a factor of more than five where the systems are applied instead of conventional methods [*Galvis et al.,* 1993]. *Lambert* and *Graham* (1995) report that the systems have a long service life which reduces annual depreciation rates of the capital costs. Roughing and slow sand filters are of equal technical level, and their operation is characterised by a high process stability which permits treating raw water of fluctuating quality [*Galvis et al.,* 1993; *Wegelin,* 1996]. They make full use of natural purification, without any use of chemicals. In combination with terminal disinfection, the systems provide multi-barriers to water borne diseases [*Clarke,* 1996]. Well operated slow sand filters are even capable of producing potable filtrates without disinfection. However, the main disadvantage of roughing and slow sand filtration systems is the low production capacity (water produced (m^3) per filter area (m^2) per day) compared to conventional systems using rapid sand filtration. This aspect limits their application to small and medium water supply systems although there are known applications in large cities, especially where land is abundant.

Logsdon (1994) and *Sharpe et al.* (1994) suggest that the best way to determine if slow sand filtration will treat a specific raw water is to conduct pilot plant studies. *Wegelin* (1996) states that the three salient concerns that can be answered by roughing and slow sand filtration pilot plant studies are: (1) can roughing filters reduce raw water turbidity to levels acceptable for reasonable slow sand filter operation, (2) establishing filter-runs of slow sand filters or the rate of head-loss increase, and (3) establishing design values of a proposed full-scale plant. The first concern centres on pre-treatment efficiency of roughing filters with regard to turbidity and suspended solids reduction. The second concern is crucial in determining the filter capability to treat a specific pre-treated raw water. The last concern aims to optimise the treatment plant design. Other pilot research concerns include effectiveness of available filter media and filter cleaning [*Collins et al.*, 1994]. The problem with new filter media for slow sand filtration is the "bleeding out" of turbidity from sands that contain excessive amounts of clay. *Logsdon* (1994) reports that one slow sand filter plant in the USA produced filtrates with

turbidity above 1 NTU for over a year, occasionally exceeding raw water turbidity. Hence, pilot studies of new filter media are significant, even though they may meet the grain size specifications. Pilot studying of the hydraulic cleaning of roughing filter media is vital as well since back-washing as practised in rapid sand filters is impossible because of the heavy coarse filter media used. *Collins et al.* (1994) report that adequate guidelines for the design of roughing filters are not yet fully available and research on these filters is still necessary. Operation and maintenance characteristics of roughing and slow sand filtration systems can be studied on pilot plants if local practical experience is not available.

In Zambia, surface water treatment employs conventional methods, and direct filtration by slow sand filters without any pre-treatment [*Holzhaus* and *Versteeg,* 1993]. Slow sand filters are usually applied in rural areas and townships. The number of rapid sand filters is about twice as high as that of slow sand filters and they are mainly applied in large cities. The potential of roughing and slow sand filtration systems has not been studied in Zambia [*Versteeg* and *Holzhaus,* 1993]. The study of these systems would provide alternatives to the current conventional systems which are characterised by operation and maintenance problems. This is particularly significant for small and medium water supply systems where the problems of conventional systems are rampant. For sustainable use of these systems in Zambia, local experience is also significant.

1.2 Rationale

The water sector in Zambia is undergoing reforms which include the conversion of existing water supply systems into commercially viable utilities. The current approach is mainly considering rehabilitating these systems to improve their operation and reduce maintenance requirements and possibly attract private sector participation. The promotion of appropriate technologies is also one of the sector principles [GRZ, 1994].

In 1992, fourteen townships' water supply systems in Zambia were studied, seven of which use slow sand filters [*Holzhaus* and *Versteeg,* 1993]. *Mwiinga* (1994) studied the water treatment facilities at *Monze* township (Zambia) which use slow sand filtration. The main conclusions from these studies indicated that many problems faced related to lack of funding and inappropriate designs that have resulted in inadequate operation and maintenance of the

facilities. Most water treatment systems in Zambia have been rehabilitated before. However, original problems usually do not take long to resurface. Currently, conventional water treatment methods used in most townships Zambia in are characterised by the following problems:

a) The main treatment stage (rapid or slow sand filtration), is usually fed with inadequately pre-treated raw water, resulting in rapid clogging of the filter media. In some cases the filters are subjected to treating raw water directly.

b) Poor funding, inadequate tariffs and tariff structures, and inappropriate use of generated income have led to lack of chemicals, equipment, spare parts and inability to attract skilled personnel.

c) Inadequate or inappropriate designs: shallow filter-beds which shorten retention times, hence reducing purification efficiencies further, filter medium coarser than recommended is often used permitting deep penetration of turbid matter resulting in low quality filtrates. In some cases there is incorrect control of filtration rates.

d) Lack of skilled or expert manpower for operation and maintenance requirements. Operators lack training and sensitisation in operation and maintenance.

e) Lack of adequate stocks of filter media(usually imported) to replace depleting filter-beds due to frequent cleanings.

The above problems are the rationale for carrying out this study. It is evident that the need to consider alternative technologies for the treatment of surface water in Zambian townships is enormous. Hence the need to study on the potential of roughing and slow sand filtration systems in Zambia. A pilot plant comprising up-flow roughing filters in layers and slow sand filters was constructed and used to realise the objectives of the study, presented in the following section.

1.3 Objectives

The overall objective of the study was to investigate the potential of using a combination of up-flow roughing filtration in layers(URFL) and slow sand filtration (SSF) as an alternative to conventional water treatment systems in Zambia. The functional objectives were:

a) to investigate and compare the ability of URFL to pre-treat surface raw water to quality acceptable to slow sand filtration with reported data from elsewhere.

b) to investigate the treatability of *Kafue* River water by URFL-SSF systems.

c) to study the filter-run times of URFL and SSF, and compare with results reported elsewhere,

d) to establish the suitability of local filter media for URFL -SSF systems,

e) to investigate the influence of filtration rates on the performance of up-flow roughing filters in layers,

f) to investigate the operation and maintenance aspects of URFL-SSF systems, with emphasis on the cleaning procedures.

1.4 Scope

The performance of URFL to pre-treat surface raw water to quality acceptable for SSF was investigated by analysing the levels of turbidity, total suspended solids and faecal coliforms in grab samples of the raw and pre-treated water. Levels of these parameters in URFL filtrates were then compared to values that are recommended for effective performance of SSF.

The ease with which *Kafue* River water can be treated to potable water (treatability) was studied with respect to filter-run times and quality of the final filtrate. During the study period, the quality of the actual *Kafue* River water was: turbidity <5 NTU, TSS < 5 mg/L, faecal coliform < 200 FC/100 ml). The ability of URFL-SSF systems to treat highly contaminated and polluted *Kafue* River water, common during the rain season was achieved by simulation of the raw water (daily average turbidity up to 300 NTU, total suspended solids up to 2000 mg/L and faecal coliform levels up to 4000 FC/100 ml) since the investigations were carried out over a period which did not include the rain season.

A filter-run of URFL was defined as the operation period of time over which the head-loss/filter resistance or filtrate quality remained acceptable. For SSF, the filter-run was considered to be the period of time over which the head-loss remained acceptable. SSF filtrate quality usually does not deteriorate with time. The minimum appropriate filter-runs recommended in literature are one week and one month for URFL and SSF respectively.

The establishment of the suitability of the local filter media for URFL-SSF systems was limited to one source of the filter media. The investigations of the availability of various filter media sources is beyond the scope of this study. The suitability of the filter media used was assessed by their capacity to produce acceptable filtrates. The availability aspects were not analysed quantitatively, but visual observations were made.

The influence of filtration rates on URFL performance was studied with average filtration rates of 0.4, 0.5, 0.75, 1.0 and 1.25 m/h. Each filtration rate was tested for at least two weeks.

The operation and maintenance aspects were assessed by comparing with conventional systems. The need of expert supervision for operation and maintenance, and the ease of filter cleaning aspects were the key considerations.

Chapter two

LITERATURE REVIEW

2.1 General

The treatment of surface water by RF-SSF systems has emerged to be competitive to conventional methods in small and medium water supplies. The systems have particularly become more attractive in developing countries because of their simplicity in design, operation and maintenance. They are characterised by low operating costs since the pre-treatment by RF does not need chemicals. The main treatment by SSF is very effective in producing potable filtrates. The operation of the systems is less likely to go wrong under less experienced operators because of their simplicity in design. Construction of these systems usually utilises local materials and labour, thus providing economic benefits.

This chapter mainly presents a literature review on RF-SSF systems. However, since RF and SSF are different processes characterised by unique operation and maintenance aspects, they are presented in separate sections. Firstly, SSF is reviewed in detail, being the main treatment process, so that the need for incorporating RF as the pre-treatment step is clearly perceived. After identifying the need for pre-treating raw water, several pre-treatment methods are briefly reviewed to justify the selection of roughing filtration. A detailed review of roughing filtration is thereafter presented. The economic aspects of RF-SSF systems are also presented. The chapter also presents a review of water treatment practices in Zambia, with emphasis on SSF and the associated problems, and ends with a review of pilot plant studies since this study was based on a pilot water treatment plant.

2.2 Slow sand filtration

2.2.1 Components of a slow sand filter

A slow sand filter is a box containing a filter-bed (with supernatant raw water) provided with a scum outlet/overflow, an under-drain system, supporting gravel for the filter-bed, an inlet and outlet structure, and filtration rate control devices (see Figure 2.2-1 (a) and (b)).

(a)Filter box

It is usually constructed of reinforced concrete, but fero-cement, stone or brickwork masonry can also be used [*Visscher et al.,* 1993]. It should be water tight to prevent water losses and possible contamination from shallow ground water or surface runoff.

(b)Inlet structure

It allows raw water inflow into the filter box without making the filter-bed surface uneven [*Visscher et al,* 1994; *Huisman* 1989]. Uneven filter-bed surface may result in puddles of water when the filter is drained for cleaning, and make cleaning by scraping difficult. An inlet structure can be a box, which at the same time can be used to drain the supernatant water during maintenance (see Figure 2.2-1). However, an inlet pipe provided with a baffle plate below the discharge end (above the filter-bed surface) can suffice.

(c)Supernatant water layer

The is the raw water layer on top of the filter-bed which provides the hydraulic head to drive the raw water through the filter-bed.

(d)Scum outlet and overflow provision

The scum outlet removes scum formed from algae and floating materials on the surface of the supernatant water. It also serves as an overflow for the supernatant water.

(e)Filter-bed

The filter-bed constitutes the filter media, which usually is fine sand ($0.15<d_{10}<0.35$, UC<5).

(f) Under-drain system and support gravel

Under-drain systems, located at the bottom of the filter-bed-evenly collect filtered water. Layers of graded gravel are placed on top of the under-drains to support the sand and prevent it from reaching and blocking the openings of the under-drains. The latter is achieved by ensuring that the pore size of the gravel layer in contact with the sand is less than the d_{10} of the sand.

Outlet structure

The outlet structure normally consists of two sections separated by a wall equipped with a weir (see Figure 2.2-1).

The weir crest level is set above the sand surface level to prevent below atmospheric pressures (negative pressures) in the filter-bed which can lead to the release of dissolved air. The resulting air bubbles promote short circuiting; raw water passing through the sand is insufficiently filtered [*Huisman,* 1989]. Outlet structures ensure that filtration rates are independent of the fluctuating water levels in the clear water tanks. Purification mechanisms in SSF consume oxygen resulting in low oxygen levels in filtrates [*Huisman,* 1989]. Low oxygen levels permit anaerobic conditions to set in, which produce taste and odour producing substances. Acceptable oxygen levels are usually restored through appreciable aeration provided by gravity flow over the outlet weir.

(g)Filtration rate control

Slow sand filtration rates are controlled either at the inlet line or outlet line of the filter (see Figures 2.2.1 (a) and (b)). Inlet and outlet controlled filters are characterised by variable and constant supernatant water levels respectively.

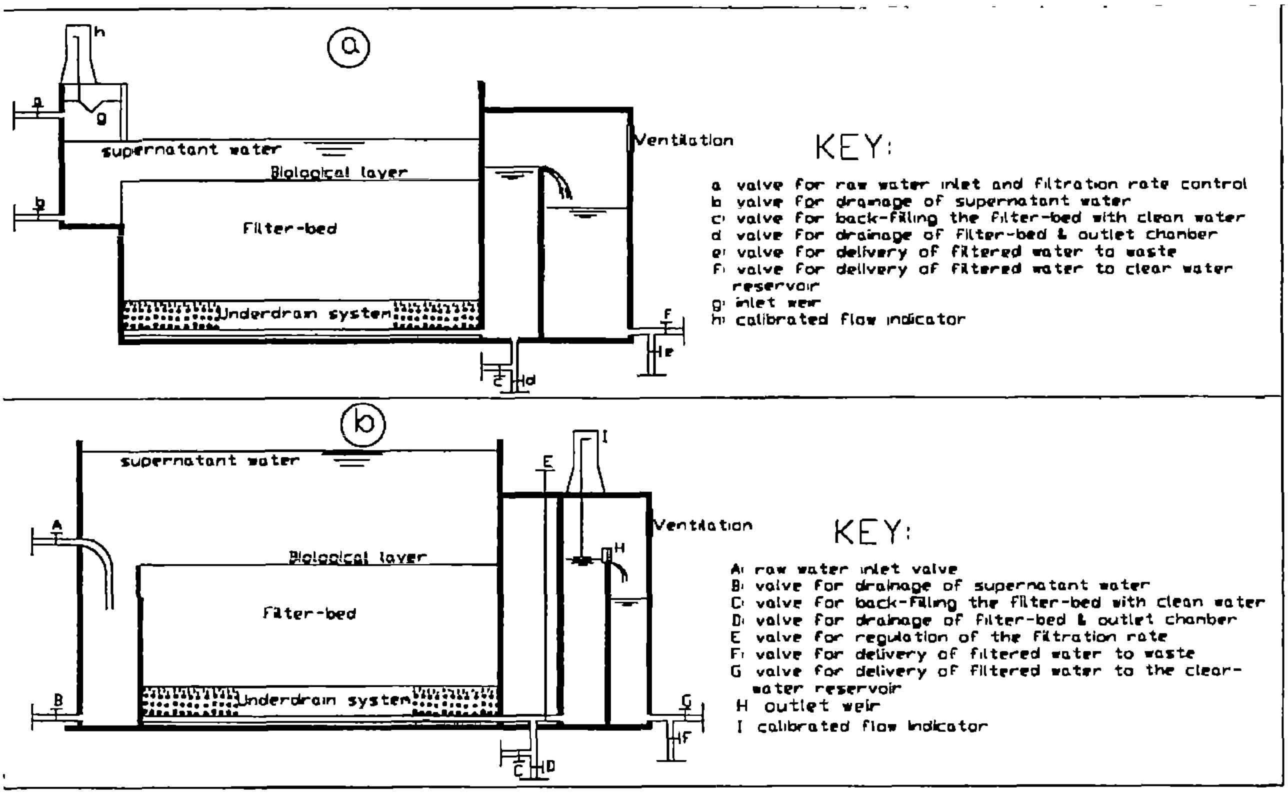


Figure 2.2-1: Components of inlet (a) and outlet (b) controlled slow sand filters
[Source: *Visscher,* 1988]

(i) Inlet-controlled or variable supernatant water filters (refer to Figure 2.2-1 (a))

The filtration rate (quotient of the inflow rate (m^3/h) and surface area of the filter-bed (m^2)) is set by adjusting the inflow rate, using valve 'a' on the inlet line, to the equivalent filtration rate. The initial low supernatant water level rises with time due to filter-bed clogging, to compensate for the head-loss and thus ensure a constant filtration rate. When the supernatant water reaches a set overflow, the filter is due for cleaning.

(ii)Outlet-controlled or constant supernatant water layer filters (refer Figure 2.2-1 (b))

The filtration rate is set by adjusting valve 'E'. To compensate for the increasing head-loss with time and maintain a constant supernatant water level, hence constant filtration rate, valve 'E' is frequently opened. When this valve is fully opened and further increase in head-loss results in lower than desired filtration rate, the filter is due for cleaning.

The disadvantage of **(ii)** is the need for almost daily adjustments of filtration rate control valves. This increases the amount of work for operators and chances of human error in setting filtration rates. In **(i)**, once desired inflow rates are set, no further manipulation of the control valve is required. The rising supernatant water level compensates for head-loss and also gives a clear indication of head-loss development. However, the initial low supernatant water level may make the removal of scum and floating objects difficult. This problem can be eased by installing an adjustable overflow pipe within the supernatant depth. Fixed supernatant water levels in **(ii)** make the removal of scum and floating objects much easier. The reduced amount of work in **(i)** and the fact that filtration rate control is not subjected to human error makes them preferable.

2.2.2 Mechanisms of slow sand filtration

The treatment of raw water by SSF is brought about by various processes, which include screening, sedimentation, adsorption, bio-chemical and bacteriological or micro-biological. Basically, particles to be removed have to be transported to the grain surface where they should remain attached before being transformed by biological and bio-chemical processes [*Wegelin*, 1996]. Three SSF mechanisms are distinguished: transport, attachment and transformation. In nature no such partition of these mechanisms is present. Their interaction is still not fully understood [*Huisman,* 1989;, *Wegelin,* 1996;, *Galvis et al.,* 1993].

(a)Transportation mechanisms

(i) Screening

It removes particles too large to pass through the pores of the sand. It takes place almost entirely at the surface of the sand because of the small pores. The smallest pore is roughly one sixth of the grain size [*Huisman,* 1989]. With 0.15 mm diameter sand grains, particles larger than 0.02 mm in diameter are completely removed. Further partial removal of smaller particles (down to 5 or 10 µm) is enhanced by reduced pore openings due to the continuous particle deposition [*Huisman,* 1989]. Colloidal matter (0.001-1 µm), bacteria (0.3-10 µm), and viruses (0.01-1 µm) are hardly removed in this way [*Barret et al.,* 1991].

(ii) Sedimentation

Sedimentation removes easily settled particles by gravity. Such particles are retained within the top layer of the sand and on the sides of the sand grains. It plays a perceptible role in removing particles larger than 10 µm [*Yao et al.,* 1971]. In principle, the large part of the combined surface area of all the sand grains is available for sedimentation in slow sand filters, making sedimentation more effective than in an ordinary sedimentation tank in which deposits only form at the bottom.

Sedimentation depends on the surface loading rate (quotient of inflow rate{m^3/h} and settling area{m^2}) and the particle settling velocity(m/h). The settling velocity is influenced by mass density, particle size and shape, viscosity and hydraulic conditions of the water. Particles with settling velocities greater than the surface loading rate are removed. Hence, the large settling area provided by sand grains lowers the surface loading rate to promote particle removal. Natural flocculation of colloidal particles aids sedimentation.

(iii) Interception

The pore openings of the sand are gradually reduced by accumulation of particles [*Wegelin,* 1996;- *Galvis et al.,* 1993]. Particles already retained on the sand grains intercept those trying to pass. Interception is significant in SSF because of the small pore space.

(iv) Hydrodynamic forces

Hydrodynamic forces (inertial and centrifugal) ensure continuous water flow through the sand pores [*Galvis et al.,* 1993]. The flow-lines of water around sand grains are not straight but curved. Due to inertial and centrifugal forces, particles within the flow-lines are forced to leave and come into contact with the sand grains where they remain attached.

(b)Attachment mechanisms

The removal of suspended and colloidal particles by attachment is considered to be the most important purification process during SSF [*Huisman,* 1989]. Unless attachment occurs, the removal of particles can not be effective.

Electrostatic and mass attraction are the main forces that hold particles once they have made contact with sand grains. A combination of these forces is referred to as adsorption [*Galvis et al.,* 1993; *Wegelin,* 1996]. These forces exert their influence over small fractions of the pore space, hence efficient adsorption is only possible after transport mechanisms have brought particles in the vicinity of the sand grains. Adsorption is effected passively when a particle is retained by a slimy sticky gelatinous coating formed around the sand grain by previously deposited bacteria and organic matter, and actively by electrostatic and mass attraction forces.

(c)Transformation mechanisms

(i) Bio-chemical processes

Bio-degradable organic matter accumulated on the sides of sand grains is oxidised and broken down to smaller aggregates and finally into water, carbon dioxide and inorganic salts (nitrates, sulphates and phosphates) [*Huisman,* 1989;, *Wegelin,* 1996]. Soluble manganese and iron compounds are oxidised to easily precipitated insoluble oxides. Bio-chemical actions play an important role in removing colour and dissolved solids as well. They yield good results when enough time is available and temperature is not low [*Huisman,* 1989]. Compared to rapid sand filters, slow sand filters provide higher retention times since filtration rates are lower.

(ii)Bacteriological or micro-biological processes

These processes are most important in removing pathogenic micro-organisms. As filtration progresses, a thin dirty layer of retained impurities is developed on top of the sand. This layer is called the "*Schmutzdecke*" (*German* word meaning dirty skin) [*Huisman,* 1989;, *Visscher et al.,* 1987;, *Barret et al.,* 1991]. It is reported to be biologically active and responsible for the removal of pathogens. Predatory organisms in this layer eliminate pathogenic organisms. Micro-biological life thrives when particles of organic origin are retained. Bacteria and other organisms will form a sticky and slimy layer around the grains or may build a chain of organic material on the pores in which the organisms thrive. Micro-organisms produce antagonistic actions, such as killing or at least weakening intestinal bacteria with chemical (antibiotics) or biological poisons (Viruses) [*Huisman,* 1989].

2.2.3 Design of slow sand filters

The design process of slow sand filters for a particular location can be split into two stages. The first stage deals with the system capacity, main components and sizing of the water supply, and estimating construction and operating costs. First stage results are used as a basis for fund-raising, planning and organisational aspects. The second stage involves the preparation of structural designs, and specifications for the equipment and materials.

This section only presents the design criteria of a slow sand filter unit with respect to its components presented in section 2.2-1, to aid the design of the pilot plant for this study. The systems capacity, main components of the water supply (design period, population and daily water demand, water demand per capita, raw water intake/pumps, balancing reservoirs, clear water storage/pumping, the distribution system), and structural designs and specifications were not reviewed as they are beyond the scope of the study.

The design of a slow sand filter unit depends on local conditions and usually maximises the use of local materials to lower construction costs. Therefore, the design criteria given by different authors should be seen as guidelines rather than absolute. *Visscher et al.* (1994) suggest that it is more important to understand the rationale behind given criteria. Table 2.2-1 presents some design guidelines from literature, and a review of these guidelines is presented thereafter.

Table 2.2-1: Design criteria for slow sand filters

Design Criteria	**Recommended level**				
	***Wegelin* (1996)**	**Ten States Standards USA (1987)**	***Visscher et al.* (1987, 1994)**	***Schulz & Okun* (1984)**	***Huisman* (1989)**
1.Design period (years)	no data	no data	10-15	no data	10-15
2.Operation period (h/d)	no data	no data	24	24	24
3.Minimum # of filter units	2	no data	2	2	2-4
4.Filter-bed area(m^2/ filter)	10-50-(100)	no data	5-200	10-100	15-(100-200)
5.Filtration rate (m/h)	0.1-0.2 (0.2-0.3)	0.08-0.24	0.1-0.2	0.1-0.2 (0.1*)	0.1 - 0.3
6.Depth of filter-bed (m)					
⇒ Initial	0.8-1.0	0.80	0.8 - 0.9	1-1.4 (1*)	0.9 - 1.2
⇒ Minimum	0.6	no data	0.5 - 0.6	0.5-0.8	0.6 - 0.7
7.Sand size specifications					
⇒ Effective size, d_e(mm)	0.15-0.35	0.3-0.45	0.15-0.30	0.15-0.35	0.15 - 0.35
⇒ Uniformity coefficient:	2-5	≤ 2.5	<5	1.5-3	<3
	no data	no data	<3*	<2*	<2*
8.Supernatant water depth (m)	1-1.5	≥ 0.90	1	1-1.5(1*)	1 - 1.5
9.Height of under-drain system + support gravel layer (m)	0.2 - 0.5	0.40 – 0.60	0.3-0.5	0.3-0.5 (0.4*)	0.2-0.3
10.Free board(m)	no data	no data	0.1	0.2	no data

* means the preferred value, # means number

(a)Operation period

The operation of SSF should be continuous to ensure effective bacteriological performance. Intermittent operation disturbs the transformation mechanisms. These mechanisms take place in different steps within the filter-bed and require continuous supply of nutrients present within the raw water. Intermittent operation impairs the supply of nutrients and upsets this balance [*Huisman,* 1989]. Although, transformation mechanisms are able to adjust to suit operation changes, this asks for time. It has been

shown conclusively that an unacceptable deterioration of the bacteriological quality of filtrates occur four to five hours after filters recommence operation [*Visscher et al.,* 1994].

(b)Number of filter units and filter-bed area

To ensure uninterrupted water supply, at least two slow sand filters should be installed. Having more than 2 filters can increase operational flexibility. Whether more than two filters are used or not depends on the maintenance and costs aspects [*Barret et al.*, 1991]. No additional units need to be provided for standby. When one filter is out of operation, filtration rate(s) of the others is(are) increased to maintain desired output.

The filter surface area may be determined by the time required for cleaning, the layout and shape of the filter units. Cleaning should be completed as quickly as possible, preferably within 24 hours, so that the micro-biological life is not starved to death..

(c)Filtration rate (m/h)

SSF rates (0.1-0.3m/h) are much lower than those of RSF (> 20 times) since they are applied to improve the bacteriological quality [*Wegelin,* 1996]. Low filtration rates provide longer retention times, which give more time for effective performance of transformation mechanisms. Attempts to design for higher rates so as to install a smaller plant and thus reduce on construction costs, may result in frequent clogging of the sand and filtrates of lower bacteriological quality. Temporary increase of the filtration rates up 0.4 m/h does not have any adverse effect on the effluent quality [*Visscher et al.,* 1994;, 1987]. The maximum rate can even be higher than 0.3 m/h depending on the raw water quality. In *Amsterdam* (*Netherlands*) SSF operate at a yearly average of 0.48 m/h and has a design filtration rate of 0.65m/h because of very good pre-treated raw water [*Kors et al.,* 1996].

(d)Filter media and depth

Sand is exclusively used in SSF. It should be inert, durable and free from clay and organic matter. Important parameters of the sand for slow sand filters are the effective grain size (d_e) and grain size distribution defined by the uniformity coefficient (UC). These parameters are determined from sieve analysis of the sand (see Figure 2.2-2). The effective diameter is the sieve opening through which 10% (by weight) of the grains will pass, while the uniformity coefficient is the ratio between the effective diameter and the sieve opening (d_{60}) through which 60% (by weight) of the grains will pass [*Hazen,* 1913].

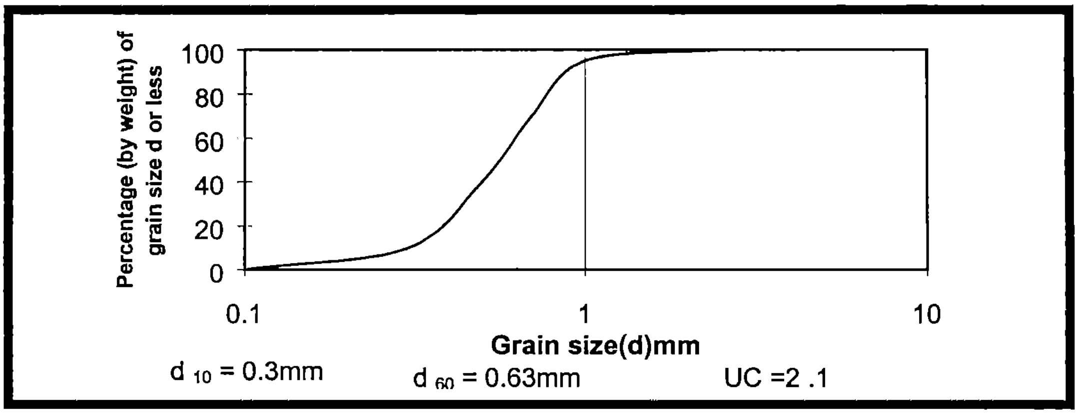


Figure 2.2-2: An example of sieve analysis results for SSF sand

Huisman and *Wood* (1974) stated that: "Ideally, the effective diameter of the sand, d_{10}, should just be small enough to ensure good quality filtrate and to prevent penetration of clogging matter to such a depth that it can not be removed by scraping".

The effective diameter usually lies in the range of 0.15-0.35 mm. It has been asserted that the bacteriological quality of SSF filtrates deteriorate with increasing effective diameter [*Barret et al.,* 1991;, *Visscher et al.,* 1994]. Pore openings increase with increasing grain size. Large pores may not permit full establishment of the *Schmutzdecke* since particles will penetrate deep into the filter-bed. However, large sand sizes (d_{10} >=0.4) have shown to be capable of producing bacteriologically safe water as long as the raw water is not heavily polluted and the filter-bed is biologically mature [*Barret et al.,* 1991]. However, d_{10} varying from 0.15-0.35 mm can be used with confidence. The key to successful use of sand in SSF is to have a mature filter-bed. The upper limits on the UC aims at having a filter-bed with sufficient porosity, and lower limits prevent using very fine sand which would clog rapidly. The use of local sand instead of one which meets the strict specification can save on costs as revealed by some applications in *Canada* and USA [*Barret et al.,* 1991].

The maximum sand depth is determined by the number of scrapings desired before re-sanding is needed and constraints on the filter box depth [*Barret et al.,* 1991]. Suspended matter removal hardly depends on the sand depth. The minimum sand depth limitations relate to the biological and biochemical performance. *Huisman* (1989) reported that the transformation mechanisms need a certain depth of sand, normally determined from pilot studies. Studies done by *Bellamy et al.* (1985a) revealed that deeper filter-beds show better coliform removals (1m and 0.5 m filter-beds showed 97% and 95% coliform removals

respectively). Deeper filter-bed allow a longer operation period before a filter is re-sanded. However, the trade-offs would include stronger walls to handle additional hydraulic pressures and higher initial head-loss. Further, these trade-offs are small compared to the benefits of longer operation periods (see theoretical calculation examples in Appendix A). Despite various recommendations on the minimum and initial sand depths, minimum values vary from 0.30-0.80 m. An initial depth of 1m has become traditional.

(e)Supernatant water depth and freeboard

The supernatant water provides sufficient hydraulic head to overcome the resistance of the filter-bed, and prevent air-binding. In practice, a depth between 1-1.5 m is usually sufficient, although 1.0 m has become conventional. The free-board accommodates and facilitates scum removals. A minimum depth of 10 cm is sufficient. In case of roofed filters, the combined depth of the supernatant water and freeboard should be deep enough to permit a tall man to clean the filter freely.

(f) Under-drain and support gravel systems

The depth of the under-drain system and support gravel varies depending on the availability of desired materials, and economical aspects. Usually, under-drain systems consist of main and lateral drains made of perforated pipes. Filter-bottoms made of stacked bricks, concrete slabs, or porous concrete may also be used. Graded gravel layers are placed on top of under-drain system to support the sand and aid in the uniform collection of filtered water. The top layer (in contact with the sand) should not allow sand penetration into under-drain system and block the openings [*Huisman,* 1989; *Barret et al.,* 1991].

2.2.4 Operation and maintenance aspects

The main task of operating and maintaining a SSF plant is to ensure uninterrupted supply of potable water. A plant operator or caretaker should be knowledgeable and trained for the various tasks involved. To assist the operator, a detailed schedule of his tasks should be drawn clearly (see example, Table 2.2-2).

Table 2.2-2: An example of a schedule of activities for SSF caretakers
[Source: *Visscher et al.*, 1987]

Frequency	Activity
1. Daily	⇒ check the raw water intake ⇒ Visit the slow sand filter ◊ check the rate of filtration and adjust if necessary ◊ check water level in filter ◊ Check the level in the clear water well ◊ sample and check water quality ◊ remove scum and floating objects ⇒ check all pumps ⇒ up-date log book of the plant
2 Weekly	⇒ check & grease all pumps and moving parts ⇒ check stocks of fuel and order if necessary ⇒ check the distribution network ⇒ communicate with users ⇒ clean the site of the plant
3. Monthly or less frequently	⇒ scrape the filter-bed(s) ⇒ wash the scrapings and store the retained sand
4. Yearly or less frequently	⇒ clean the clear water well ⇒ check the filter and clear water well for water tightness
5. Every 2 years or less frequently	re-sand the filter unit(s)

Table 2.2-2 does not show tasks, which are carried out occasionally. These are hereby presented and discussed.

(a)Starting up a new filter (refer to Figure 2.2-1)

The sand of a new slow sand filter, operating for the first time, usually has air entrapped within its pores. This air is driven out by back-filling from the bottom, otherwise starting a filter by directly filling from the top may not drive out all the air. Entrapped air can cause air locks, and possibly short-circuiting. The back-filling valve ‘C’ is opened to allow water to flow upwards from the bottom. When the supernatant water level is about 0.1-0.2 m, valve 'C' is closed. To achieve complete air removal, back-filling rate should be low (0.1-0.20m/h). Clean water is preferred for back-filling because raw water may contaminate the sand and prolong maturation periods. However, for just commissioned filters, clean water may not be available, then temporary connection between the pre-treatment unit outlet or raw water source and valve 'C' can be made.

During back-filling, the surface of the sand may become irregular. With an irregular sand surface, puddles of water form when a filter is drained for cleaning. Therefore, after back-filling to slightly above the sand surface, the filter should be drained again until the water level is about 10 cm below the sand surface to allow levelling.

In inlet controlled filters, when the back-filling has increased the supernatant water level up to 0.1-0.2m, it is stopped and the inlet valve is slowly opened to a filtration rate of 0.02 m/h which is increased every hour until the design rate is reached [*Visscher et al.,* 1987].

Outlet controlled filters are charged by slowly filling the filter through the inlet valve up to its working supernatant water level. Then the filter is put to service by opening the regulatory valve E (see Figure 2.2-1(b)). The initial rate should be low (0.02m/h) and increased gradually by 0.02m/h every hour until the design rate is reached [*Visscher et al.,* 1987]. High initial rates for a new or just cleaned filter can cause breakthrough of coliforms since the filter is not yet mature. The filtrate is chlorinated until quality analysis show that the filter-bed has matured (<1 FC/100 ml).

(b) Filter-bed Cleaning

Slow sand filters are conventionally cleaned by scraping off the top dirty layer (see Figure 2.2-3). Cleaning is due when the maximum head-loss is reached.

Figure 2.2-3: The scraping operation during cleaning of slow sand filters

[Source: *Barret et al.,* 1991]

The cleaning procedure is as follows:

- ⇒ clean the equipment including boots and feet
- ⇒ enter the filter box safely using a short ladder
- ⇒ protect the sand surface by covering with timber boards
- ⇒ mark out narrow strips of sand surface and scrape desired depth (0.5-2 cm) depending on extent of silt penetration. Other areas are scraped by moving the boards to areas already scraped
- ⇒ remove scraped sand to washing platform
- ⇒ level the sand surface
- ⇒ check depth of sand
- ⇒ recharge the filter as described in (a)
- ⇒ allow for ripening or maturing, which should take a few days depending on the depth of scraping and weather conditions.
- ⇒ slowly reduce the filtration rates of other filters whose rates were increased because of having taken one filter out of operation.

(c)Washing scraped sand

Scraped sand must be washed thoroughly, as soon as the scraping is completed to prevent development of unpleasant smells. The washed sand should be dried and stored safely for re-sanding purposes. Storing wet sand results in unpleasant smell. Using water from a hose is a simple method for which a platform should be constructed (see Figure 2.2-4).

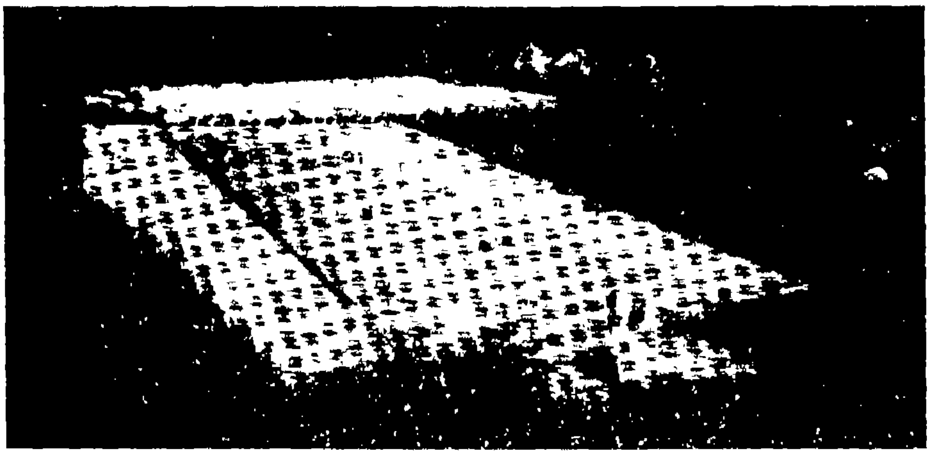


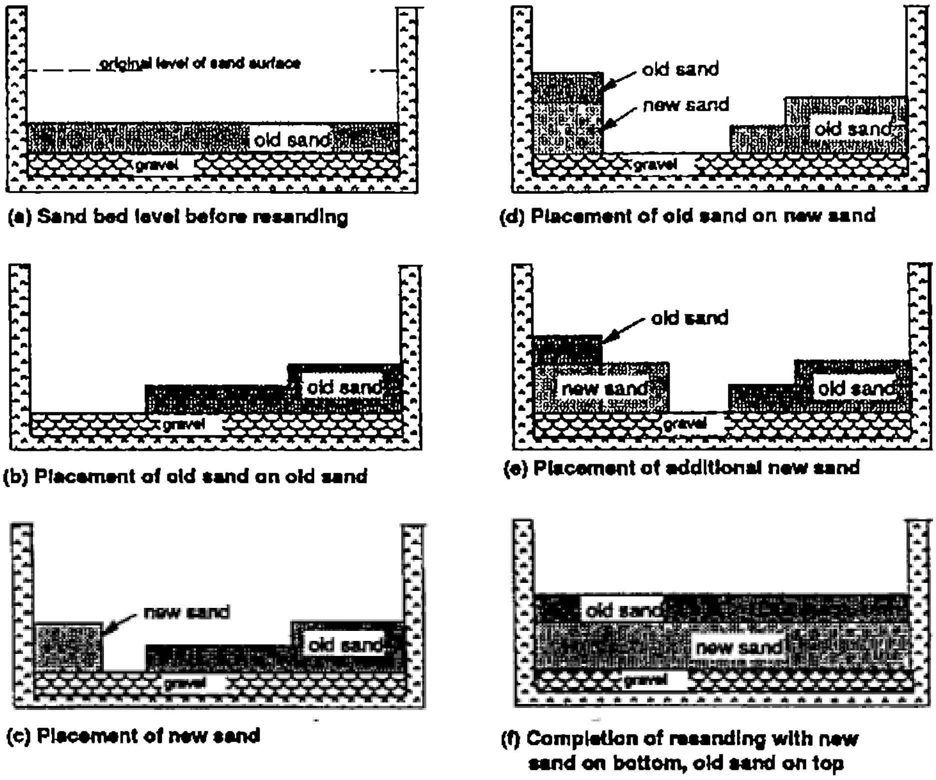
Figure 2.2-4: A platform for washing SSF Sand

[Source: *Visscher et al.,* 1987]

A simple check on how clean the sand is can be done by rubbing a handful of sand between fingers. If there is a sign of dirty on the hands, the sand is not clean enough. The silt content can be checked if possible. Values < 1% indicate enough washing [*Visscher et al.,* 1987].

(d)Re-sanding

Re-sanding is necessary after successive scrapings have reduced the sand depth to the minimum desired. Before re-sanding, the filter must be drained to the support gravel depth. Small and large filters are re-sanded in different ways. For small filters, the old sand is completely removed from the filter and stacked nearby. Then, new sand is placed on top of a thin layer remaining on top of the support gravel. The old sand is then placed on top of the new sand to desired depth to facilitate short ripening periods. In large filters, old sand is moved to one side of the filter, the new sand is placed in position and the old sand replaced on top of the new sand (see Figure 2.2-5). After re-sanding, the filter is re-charged as in **(a)**.



(a) Sand bed level before resanding
(d) Placement of old sand on new sand
(b) Placement of old sand on old sand
(e) Placement of additional new sand
(c) Placement of new sand
(f) Completion of resanding with new sand on bottom, old sand on top

Figure 2.2-5: Steps in re-sanding filter-beds of large slow sand filters
[Source: *Barret et al.,* 1991]

(e) Record keeping

Day-to-today records give useful information about the performance of a SSF plant, the work of the operators, and about planning improvements. These records include:

⇒ water quality parameters such as residual chlorine in clear water reservoirs, turbidity of raw water and filtrates, temperature, coliforms organisms
⇒ interruptions of the filter operation
⇒ changes in filtration rates and flow rates
⇒ filter cleaning
⇒ filtered water production records for each filter
⇒ head-loss development

2.2.5 Limitations of slow sand filtration use

The condition of the raw water, and contamination and pollution levels limit the application of SSF as the sole treatment process. There are aspects not related to the state of the raw water which can as well affect the choice of SSF.

(a) Contamination and Pollution levels

(i) Micro-biological contamination

If the raw water is heavily contaminated with pathogenic micro-organisms, SSF may not produce bacteriologically safe filtrates [*Galvis et al.,* 1993]. *Di Bernardo* (1991) suggests 200 FC/100 ml as the upper limit in raw water for SSF. Experiences in Colombia have shown that SSF can handle raw water with FC exceeding 200 FC/100 ml [*Wegelin,* 1996, *Galvis et al.,* 1993]. These different experiences can be attributed to specific environmental conditions in which the studies were conducted.

(ii)Organic matter loads

SSF is reported to show low removals of organic materials. Despite the aesthetic aspect, the removal of colour has become important because of its ability to react with chlorine and form harmful products [*Galvis et al.,* 1993]. Colour is an indicator of humic acids (organic matter), hence pollution. The removal of true colour by SSF is as low as 25% and can be much lower when highly coloured raw water is treated [*Barret et al.,* 1991; *Cleasby et al.,* 1984; *Ellis,* 1985].

(iii) Turbidity (suspended solids)

Generally, turbidity refers to the cloudiness of water. It is an indirect indicator of the amount of particles in water. It is reported to be a major limitation in most applications of SSF [*Galvis et al.,* 1993;, *Schulz* and *Okun,* 1984;, *Barret et al.,* 1991;, *Huisman,* 1989;, *Wegelin,* 1996]. Raw water with high turbidity levels easily clog the filter media and reduce the filter-runs, necessitating regular cleaning, consequently high operation costs. Upper limits of the raw water turbidity have been established in different applications, and the majority of the references give an upper limit of 10 to 50 NTU. For best performance, less than 10 NTU is considered very appropriate. However, with drinking water quality norms becoming strict in recent years, upper limits of 5 NTU have been recommended [*Galvis et al.*, 1993]. Turbidity mainly caused by very fine particles of colloidal nature may not only reduce filter-runs but also be difficult to remove.

Suspended solids can clog filter sand within hours. *Wegelin* (1996) limits maximum total suspended solids to 5 mg/L in raw water for effective SSF.

(iv)Presence of algae, iron, and manganese

Algae present in raw water will grow in the supernatant water if nutrients and light are available. Algae blooms prematurely block filter sand. They also cause the production of taste and odour substances, and deposits of calcium carbonate which contribute to filter clogging [*Galvis et al.,* 1993].

The presence of insoluble oxides of iron and manganese may significantly contribute to the blocking of the filter-bed.

(b)Raw water Conditions

(i) Temperature

Transformation mechanisms in SSF depend on raw water temperature. Coliform removal can vary from 99% at 20°C to 50% at 2°C [*Huisman,* 1989]. *Toms* and *Bayley* (1988) report filtrate FC levels exceeding 50 FC/100 ml for 4°C raw water. Clearly, biological processes are directly related to temperature. Most tropical countries are characterised by high temperature and hence slow sand filtration become appropriate. The strategy followed in cold climates is to cover the filters and construct them in the ground. Low filtration rates

(<0.10m/h) may cope with low temperatures because the retention times are then augmented thereby providing more time for the biological actions.

(ii) Nutrient levels

Micro-organisms responsible for the bio-chemical activities in SSF require ample supply of carbon, nitrogen and sulphates for their metabolism and growth. Therefore, raw water low in these nutrients will inhibit the development of a mature *Schmutzdecke*. Addition of nutrients can enhance the biological activities in SSF as reported by *Bellamy et al.*, (1985a).

(iii) Dissolved oxygen (DO) levels

The absence of sufficient dissolved oxygen in raw water can cause anaerobic conditions which produce taste and odour substances [*Huisman,* 1989]. Anaerobic conditions can cause the re-suspension of insoluble iron and manganese oxides to soluble forms which may reappear in filtrates, transportation mains or distribution systems when they get oxidised to insoluble forms. Insoluble forms impair the aesthetic quality of the water.

(c)Other aspects affecting the use of slow sand filtration

Apart from the water quality and conditions limitations, other important restrictions to using slow sand filters cited by *Huisman* (1989) include:

- ⇒ high construction costs per unit capacity for large installations in urban areas; about 3 times as large as for rapid sand filtration.
- ⇒ large area of land required; more than 5 times as much as for rapid sand filtration.
- ⇒ large force of unskilled labour for the manual cleaning, compared to a fully automated rapid sand filter; about 10 and 2 men, respectively.

According to *Huisman* (1989), the above disadvantages are pronounced in larger installations. In developing countries, land and cheap labour are abundant, making SSF appropriate. Cost comparisons made in *India* between SSF and RSF have shown that capital costs for SSF are much lower than those of RSF up to a capacity of 3000 m^3/day, and when operation and maintenance costs are heeded the break-even was at 8000 m^3/day [*Visscher et al.,* 1987]. The demand to increase filtrate quantity while reducing the land area use is cited as the cause of reduced SSF use in the USA [*Fox et al.,* 1994]. However, in the early 1980s, the use of SSF in

the USA resurfaced for small communities that use surface water because of the effectiveness of SSF to remove pathogens, and the simplicity associated with operation and maintenance.

Barret et al. (1991) suggest that slow sand filters are more appropriate for small communities with populations up to 10000 persons. Although, there are known applications for over 10000 persons, it is generally acceptable to limit SSF to small communities because of their simplicity in design, and hence low operation and maintenance requirements, which can easily be met at village level management. Many other advocates of slow sand filters recommend them for small communities [WHO; *Wegelin,* 1996; *Huisman,* 1989; *Galvis et al.,* 1993; *Graham et al.,* 1996; *Collins* and *Graham,* 1994].

2.2.6 Practical performances

The use of SSF dates back to over one and half centuries. SSF is credited with being the first drinking water treatment process used to improve the quality of water in both modern Europe and the USA [*Graham and Collins,* 1996]. Some historical events in the 18Th Century underscored the use of SSF. Thousands of people died from epidemics of water borne diseases (e.g. cholera) due to the use of unfiltered surface water. In locations were SSF was applied, few victims were counted [*Galvis et al.,* 1993]. It had then become clear that SSF improve the bacteriological and biological quality of the water and hence contributed to the reduction in the transmission of water borne diseases. To date, SSF has continued to be an important component of surface water treatment systems in developed and developing countries.

In view of the simplicity in design, low technical, economical and organisational requirements, SSF has become competitive with other treatment methods. Although, many SSF advocates recommend it for small systems, it is applied in some large cities of Europe (for instance Amsterdam, London and Zurich).

The efficiency of SSF depends on the condition and quality of raw water as illustrated in section 2.2.5. A properly designed, constructed, operated and maintained slow sand filter is able to produce filtrates with turbidity < 1 NTU. The effectiveness in removing coliforms is usually subject to a mature filter-bed with a fully developed *Schmutzdecke.* Average coliform levels less than 1 FC/100 ml is easily achieved with such a filter-bed. *Galvis et al.* (1993)

report that coliform counts greater than 100 FC/ 100 ml in raw waters can be reduced to less than 1 FC /100 ml over an operational period exceeding one month. However, a just started slow sand filter will show low removals of FC since the *Schmutzdecke* is then not fully developed. Different periods through which the *Schmutzdecke* is fully developed (maturation or ripening period) have been reported since it depends on the raw water quality. For a new filter, the maturation period may take one to three weeks in tropical areas and longer in more temperate regions [*Visscher et al.,* 1987]. Low temperatures in temperate regions slow down biological and bacteriological maturation of a filter-bed. A mature slow sand filter taken out for cleaning would take a few days to one week to re-establish its maturity since the cleaning process usually does not completely remove the S*chmutzdecke* layer.

Filter-runs of slow sand filters vary depending on the raw water quality. A filter-run of at least one month is preferred for optimal operation [*Wegelin,* 1996]. Filter-runs greater than one month are reported for raw water with low turbidity (<5-10 NTU) [*Barret et al.,* 1991; *Galvis et al.,* 1993; *Wegelin,* 1996]. The characteristics of the particles causing turbidity affect the clogging of filter-beds. This has been validated by cases in the USA where shorter filter-runs (<1 month) were recorded for filters which were fed with low turbidity raw water (<1.5 NTU) compared to longer filter-runs (6 months) for filters which were fed with higher turbidity raw water (6-10 NTU).

Typical SSF treatment efficiencies reported in literature are presented in Table 2.2-3. For effective performance of slow sand filters, it is imperative that adequate pre-treatment methods are applied to cope with raw water quality limitations. The world wide needs for raw water pre-treatment prior to slow sand filtration is enormous (see Figure 2.2-6).

Table 2.2-3: Typical treatment efficiencies of slow sand filtration

[Source: *Galvis et al.,* 1993; *Wegelin,* 1996; *Ellis* ,1985; *Collins and Graham,* 1994]

Parameter	Typical reduction
1. Coliform organisms [number/100 ml]	averaging less than 1
2 Protozoan cysts	99 to 99.99 %removal even after filter scraping
3. Cercariae or schistosomiasis	Virtually complete removal
4. Turbidity [NTU]	generally reduced to less than 1
5. Total suspended solids	complete removal
6. Colour	30 to 90 % with 30 % being mentioned as the most usual efficiency
7. Organic matter	COD 30 to 70 ; TOC 15 to 30 Organic matter such as humic acids, detergents, phenols, and some pesticides and herbicides are being removed from 5 to over 90%.
8. Iron and manganese	Considerable removal
9. Heavy metals	30 to 90 % or even higher

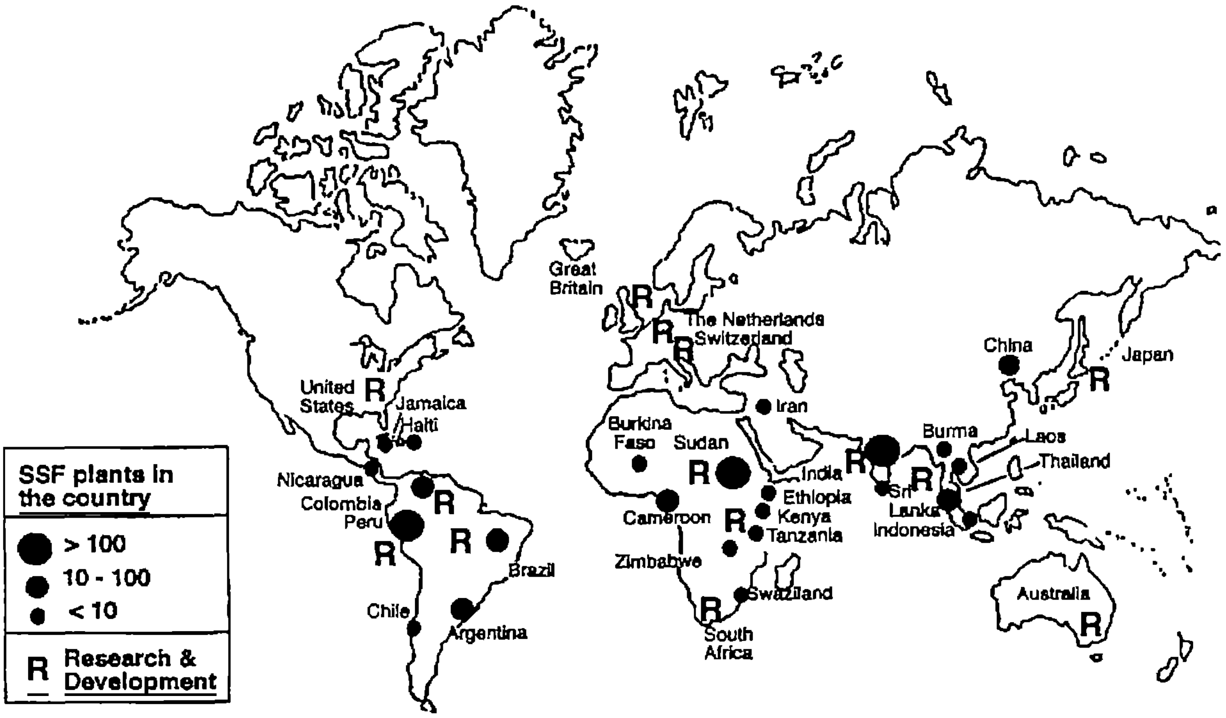


Figure 2.2-6: Reported locations where SSF pre-treatment is required

[Source: *Collins et al.,* 1994]

Although Figure 2.2-6 does not show *Zambia*, the need for appropriate pre-treatment for SSF has been recognised already [*Holzhaus and Versteeg*, 1993; *Mwiinga*, 1994]. The pre-treatment paired with SSF has to have similar levels of simplicity in operation and maintenance as slow sand filtration. The pre-treatment technologies applied prior to slow sand filters are presented and discussed in the next section.

2.3 Pre-treatment technologies prior to SSF

Possible pre-treatment methods which can be used prior to SSF are classified into two categories: chemical and non-chemical. This section briefly reviews these methods. However, the chosen method for this study, roughing filtration (non-chemical), was further reviewed in detail, and is presented in section 2.4.

2.3.1 Chemical pre-treatment

Chemical pre-treatment is conventionally applied for both RSF and SSF. Chemicals (aluminium and iron salts) are added to raw water to aid the removal of turbid matter which can not settle by gravity. Various processes are distinguished in chemical pre-treatment. Details of the structures in which they occur are beyond the scope of this study.

(a)**Coagulation**: This is the process of adding the chemicals which destabilise the particles responsible for turbidity. The destabilisation occurs within a few seconds.

(b)**Rapid mixing**: This process uniformly disperses the coagulant chemical throughout the entire mass of water for the effective destabilisation action.

(c)**Flocculation**: To induce the removal of the initially small destabilised particles, rapid mixing is followed by a period of gentle mixing called flocculation. Flocculation allows small flocs to collide and form fewer but large and easily settleable particles.

(d)**Sedimentation:** This is usually the final process in chemical pre-treatment. It removes flocculated particles, heavier than water, by gravitational settling.

The above processes normally occur in separate units, but can also take place in single units called up-flow sludge blanket clarifiers or suspended solids contact tanks.

Although chemical pre-treatment is applied prior to SSF, it is generally not suitable for small communities because of the stringent and costly operation and maintenance requirements [*Galvis et al.,* 1993; *Wegelin et al.,* 1991; *Wegelin,* 1996]. The processes of coagulation, rapid mixing and flocculation require expert supervision. Most rapid mixing and flocculation facilities are highly mechanical and require constant energy supply. Hydraulic mixers are available, but are not flexible since once constructed, mixing intensities can not be adjusted.

The dosages of chemical coagulants are determined from laboratory tests (Jar Tests) and depend on raw water quality. These tests need to be performed nearly daily since in practice it is rare to have constant raw water quality, especially in wet seasons. A sufficient stock of coagulant chemicals is also very vital for consistent performance of chemical pre-treatment methods. Removal efficiencies of the sedimentation basins are greatly reduced without chemical coagulants. Chemical pre-treatment is very sensitive to operational changes. Improper operation leads to the formation of light flocs which are easily carried over to slow sand filters. *Schulz* and *Okun* (1984) report of a case in *Mharashtra-India* where chemical pre-treatment was used prior to SSF to treat raw water with turbidity ranging from 50-500 NTU. Observations showed that light flocs were carried over to slow sand filters and caused rapid clogging. The entire filter-bed was removed for cleaning. This clearly shows that inappropriate pre-treatment can lead to a premature and rapid clogging of a slow sand filter. Consequently, operation costs increase due to the resulting need for frequent cleaning.

The stringent operation requirements, need for expert supervision, daily laboratory tests and continuous supply of chemicals, have rendered chemical pre-treatment inappropriate or inapplicable for most small and large systems, especially in developing countries [*Wegelin et al.,* 1991]. Most of the water supply utilities in developing countries lack funding, and are therefore unable to afford chemicals, spare parts, and skilled manpower. Moreover, the operation and maintenance of chemical pre-treatment systems is not as simple as that of SSF, making the combination inappropriate. *Galvis et al.* (1993) suggest that pre-treatment methods prior to SSF should be as simple as slow sand filters themselves for compatibility purposes during operation and maintenance.

Non-conventional pre-treatment methods that do not use chemicals are less complex, easy to operate and maintain. They are receiving great attention as alternatives to chemical methods.

2.3.2 Pre-treatment by non-chemical methods

(a) River-bank filtration (Infiltration wells)

River-bank filtration consists of infiltration wells along river banks characterised by permeable soil formations (alluvial sand & gravel sediments). The wells can produce water which may only need disinfecting [*Engels* and *Poggenburg,* 1989]. Limitations of river-bank filtration include: (1) re-suspension of iron and manganese when the raw water in the ground has dissolved oxygen levels less than 1 mg/L [*Engels* and *Poggenburg,* 1989], (2) maintenance is difficult since the wells are underground, and (3) can only be used in permeable soil formations, which can de a limiting factor in terms of production capacity.

(b) River-bed filtration (Infiltration galleries)

Figure 2.3-1 shows a layout and section of infiltration galleries in river-bed filtration.

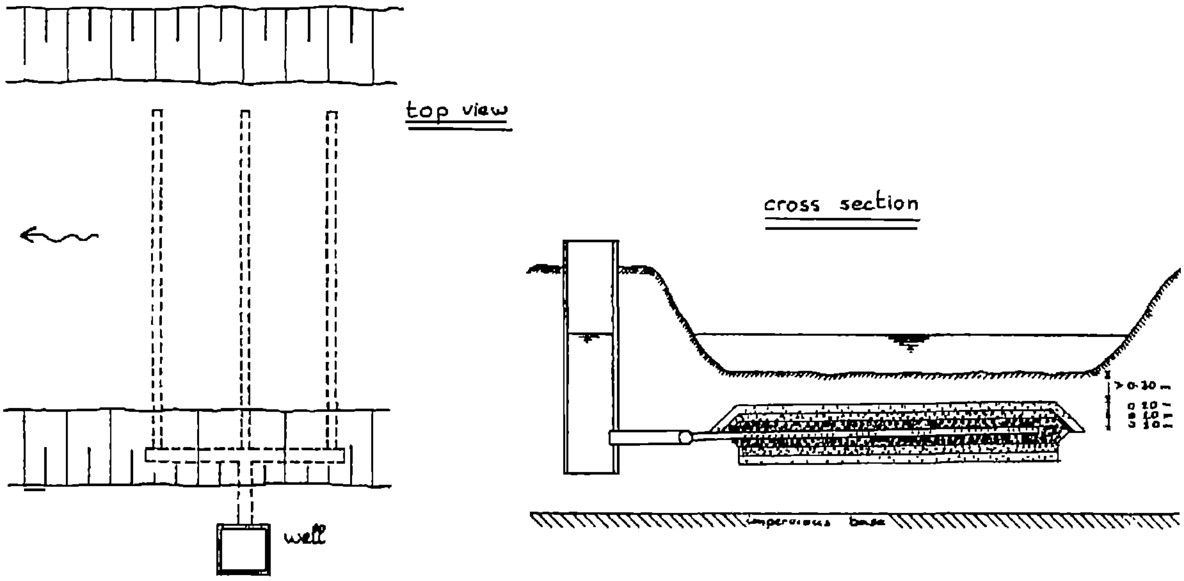


Figure 2.3-1: Layout of infiltration galleries in river bed filtration
[Source: *Smet et al.,* 1989]

River-bed filtration is used to draw river water and pre-treat it to quality acceptable for SSF. Raw water is filtered through a natural or artificial river bed and collected in perforated pipes placed in the river bed. Construction is difficult in water bearing aquifers, and periodic blockage of the infiltration zone (located under water) makes either practical cleaning or repositioning of the pipes and filter material difficult (see Figure 2.3-1). These

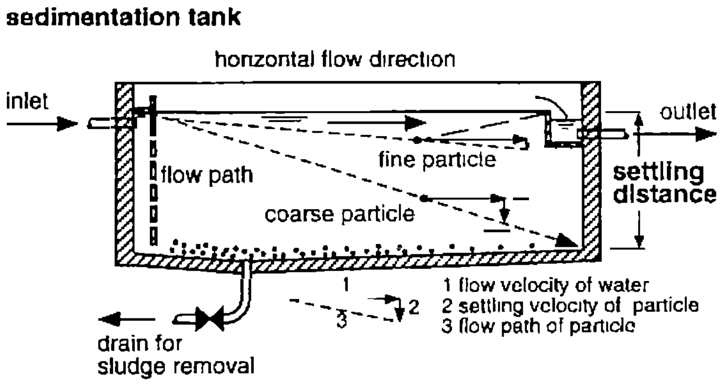
disadvantages limit their use. An evaluation made in Colombia indicates that the systems have low(about 20%) efficiencies [*Galvis et al.*, 1993].

(c) Plain sedimentation

Plain sedimentation removes suspended particles from raw water by gravitation settling, without chemical coagulants. The efficiency of plain sedimentation depends on the particle sizes and the distribution of their settling velocities (v_s). In practice, water is treated continuously through the sedimentation basin. The surface-loading rate (v_o) is the major parameter that affects the performance of plain sedimentation. Sedimentation is effective if raw water has high content of easily settling suspended solids (with $v_s > v_o$). Raw water with a lot of colloidal particles is difficult to pre-treat by plain sedimentation because they are too light to settle. The process does not save any practical purpose for the removal of particles smaller than 0.01 mm [*Schulz* and *Okun*, 1984].

(d) Roughing filtration (RF)

The quality of raw water can be improved when passed through gravel. The efficiency of a gravel layer is enhanced by greatly reduced settling distances for suspended solids compared to the situation in a plain sedimentation tank (see Figure 2.3-2).



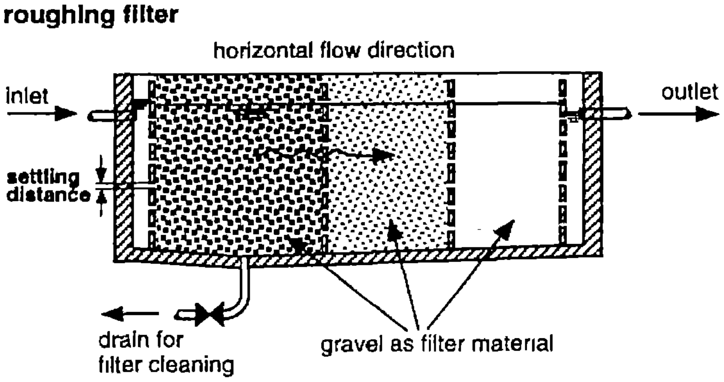


Figure 2.3-2: Particle removal in a sedimentation basin and a roughing Filter
[Source: *Wegelin,* 1996]

The contact frequency of particles with the settling surface becomes high compared to a sedimentation basin where only the bottom is available for settling. This is attributed to the presence of the small pore space system and large internal filter surface area in the gravel. This increased contact promotes the removal of particles by other mechanisms other than sedimentation. Such gravel layers are called **Roughing Filters** since they are composed of relatively coarse (rough) materials [*Wegelin,* 1996].

The significant advantage of RF is that no chemical is necessary to achieve almost similar results of chemical pre-treatment methods. The operation and maintenance of RF is also simpler. Roughing filters are more effective than plain sedimentation, and much easier to operate and maintain than river-bed and river-bank filtration.

2.4 Roughing filtration

2.4.1 Components and types of roughing types

(a)Components

The basic components of a roughing filter include a filter box, filter media, inlet and outlet structures and filter drainage facilities [*Wegelin,* 1996].

(i) Filter box

The filter-box contains the filter media and filter drainage facilities. It can be a single unit or separate units depending on the type of roughing filter in question.

(ii) Filter media

Any inert, clean and insoluble gravel having a large specific surface area to enhance sedimentation, and high porosity to increase the storage capacities can be used for roughing filtration [*Wegelin,* 1996]. Filtration tests have so far revealed that neither the roughness nor the shape or structure of the filter media have a great influence on efficiency [*Wegelin et al.,* 1987]. Therefore, natural gravel, broken stones or rocks, broken burnt clay bricks, plastics materials as chips, burnt charcoal and coconut fibre can be used [*Wegelin,* 1996]. For plastic media, attention has to be paid to up-lifting forces since it is lighter. Coconut fibre should be used with care because it can flavour the water. Gravel has become the conventional filter media in roughing filtration.

(iii) Inlet and outlet structures

These structures are necessary to regulate raw water flow, evenly distribute raw water and evenly abstract pre-filtered water.

Inlet structures must be equipped with accurate flow measuring devices (e.g., V-notch weirs), provided with an overflow to accommodate maximum head-loss. A flow measuring device on the outlet is not recommended because backwater effects can create difficulties with flow adjustment [*Wegelin,* 1996].

(iv) Filter-drainage systems

Filter drainage facilities are essential for the hydraulic cleaning of the filters. They should be able to collect wash water uniformly from the filter-bed. This is important to ensure even cleaning of the filter-media.

(b)Types of roughing filters

Roughing filters are classified according to the location within the treatment area, main purpose, flow direction, filter design and filter cleaning methods (see Figure 2.4-1).

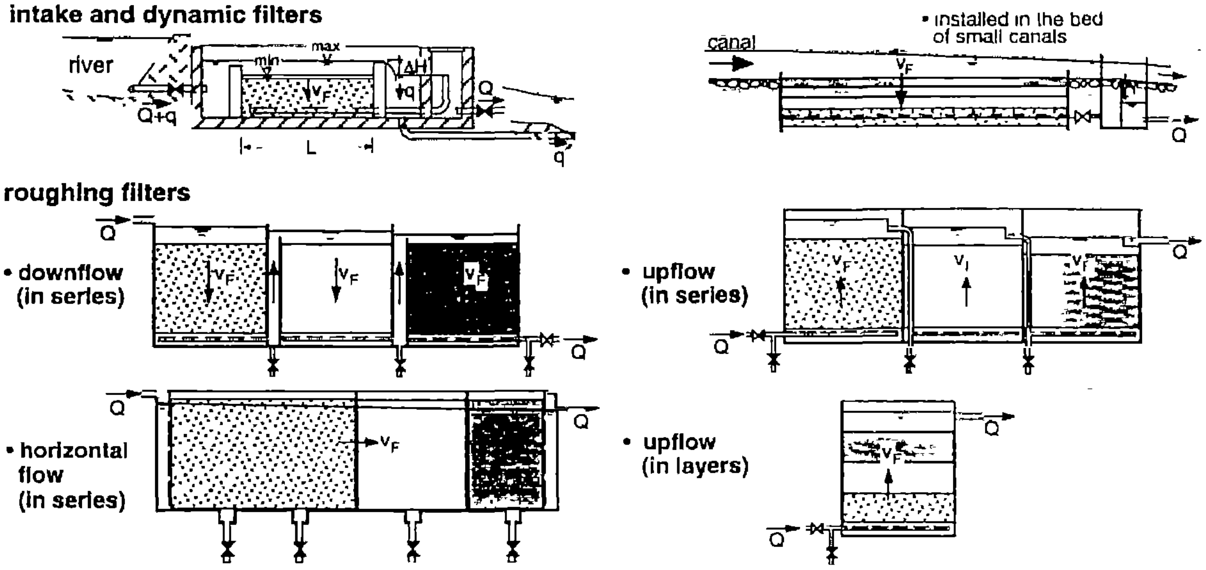


Figure 2.4-1: Types of roughing filters
[Source: *Wegelin,* 1996]

(i) Intake and dynamic filters

These filters are usually located at the raw water intake site. They are applied to abstract raw water, and pre-filter it to protect the main treatment plant against heavy suspended solids common after heavy rains. Their filter media size increases in the direction of downward flow. Therefore, most of the solids are retained on top of the filter-bed, and cleaning is simply achieved by manually scouring the top fine filter media with a rake or shovel. Suspended solids re-suspensions are flushed by the same raw water. Relatively high filtration rates are applied. Usually one filter is adequate for a given treatment plant.

(ii) Roughing filters prior to SSF

These filters are located within the main treatment plant site, before SSF, to improve raw water quality. They are operated as either up-flow, down-flow or horizontal-flow filters. The flow direction identifies four main types: horizontal-flow roughing filters (in series) (HRF), up-flow roughing filters in series (URFS), down flow roughing filters in series (DRFS) and up-flow roughing filters in layers (URFL) (see Figure 2.4-1). The main principle in roughing filtration is to filter raw water through gravel layers decreasing in size in the direction of flow. Hence, for down-flow roughing filters in layers(), most suspended solids would be retained at the bottom where the finest gravel layer is resulting in

deteriorated filtrate quality and frequent hydraulic cleaning by draining. Therefore, it would not be effective to have DRFL. -In HRF, URFS and DRFS, each gravel layer is installed in separate compartments or boxes in series, while in URFL all the gravel layers are placed in one filter box.

HRF, DRFS, URFS and URFL are deep bed filters which allow deep penetration of suspended solids into the filter-beds because of the coarse filter media compared to either RSF or SSF. These solids are only removed hydraulically by periodic draining or flushing of the filter-beds [*Wegelin,* 1996]. Practically, not all retained solids would be flushed out. Hence, with time, the filter media is also changed due to remaining solids. After long periods of operation, hydraulic cleaning is normally unable to restore the filter efficiency. Then, the filter media is manually excavated and washed.

2.4.2 Mechanisms of roughing filtration

Mechanisms of roughing filtration are similar to those of slow sand filtration. However, the extent of the effectiveness of each mechanism is not the same since roughing filters operate under different conditions using coarser filter materials.

(a)Transport mechanisms

(i) Screening

Screening plays a minor role in RF since pore spaces of gravel are larger than those of sand in SSF. With time and near the end of a filter-run, screening could play a perceptive role since the pore spaces are reduced as a result of excessive accumulation of suspended solids.

(ii) Sedimentation

Unlike in SSF in which particles transported to the sand grains by sedimentation are retained within the top thin layer of the filter-bed, sedimentation in RF takes place within the pores of the whole filter-bed. It is reported to be the main transport process in roughing filtration [*Wegelin,* 1996; *Galvis et al.,* 1993]. Laminar flow conditions are necessary for effective sedimentation and promotion of the natural agglomeration of smaller particles to larger and heavier particles. These conditions are ensured by low roughing filtration rates. However,

truly colloidal particles (<100 nm) could be difficult to remove by sedimentation because they are too light to settle, and don't easily agglomerate naturally.

(iii) Interception

Suspended solids retained on the gravel intercept those trying to pass. Because of the large porosity of the gravel used in RF, interception does not play a significant role [*Galvis et al.*, 1993]. However, it is possible that interception could play a perceptive role in the fine gravel layers (1.6-6 mm) especially when the filter is close to reaching its allowable filter load (weight of accumulated solids per filter volume).

(iv) Hydrodynamic forces

Hydrodynamic forces (inertial and centrifugal) could play a more perceptive role in RF since RF is usually applied to remove suspended solids. Large suspended solids have greater inertial and centrifugal forces, hence can easily leave flow lines.

(b)Attachment mechanisms

Attachment mechanisms ensure that suspended and colloidal particles brought in contact with the gravel, by transport mechanisms, remain attached. The absence of the *Schmutzdecke* makes attachment mechanisms the most likely means by which micro-organisms are retained by RF. Electrostatic and mass attraction forces (adsorption) hold particles once they have made contact with the gravel. Compared to adsorption in SSF, adsorption in RF could be less pronounced due to the higher filtration rates (3 to 10 times). High filtration rates may not allow sufficient time for adsorption.

(c)Transformation mechanisms

(i) Bio-chemical activity

Bio-chemical activity involves the oxidation of retained biodegradable organic matter into smaller aggregates, and finally into water, carbon dioxide and inorganic salts (nitrates, sulphates and phosphates). Soluble ferrous and manganous compounds are oxidised to insoluble oxides which are readily precipitated. Bio-chemical actions also play an important role in removing colour and dissolved solids. As mentioned in the case of SSF, bio-chemical actions yield good results when enough time is available. Compared to SSF, RF does not provide enough time because of higher filtration rates, and therefore these actions are relatively less effective.

(ii) Bacteriological or micro-biological activity

The absence of a *Schmutzdecke* layer, due to the coarse filter-media, makes the micro-biological activity less significant in RF. However, removal of coliforms by RF have been reported which indicate the presence of micro-biological activity. It is also most likely that adsorption plays a major role in removing coliforms in RF. Bacteria and other organisms will form a sticky and slimy layer around the gravel grains, in which actions of micro-organisms will thrive. This layer could be responsible for effective adsorption

2.4.3 Design of roughing filters

The main objective of roughing filtration is to remove suspended matter from raw water to a level acceptable for effective SSF [*Wegelin,* 1996]. Pre-treated raw water with turbidity values less than 10 NTU and total suspended solids less than 5 mg/L is generally suitable for SSF. Roughing filter design parameters include operation period, number of filter units and size, flow control and filtration rates, gravel size, number/depth of gravel layers, and under-drain systems.

(a)Operation period

Roughing filters should run continuously because intermittent operation may disturb the bio-chemical and micro-biological activities. Continuous operation is also essential for complete development of attachment mechanisms.

(b)Number of filter units and size of each unit

A minimum of two filters operating in parallel is required to maintain desired plant output, and also for the continuous production if one filter is undergoing maintenance.

Dimensions of a roughing filter are different depending on the type chosen. Structural limitations, operation and raw water quality may decide the filter dimensions and shape.

The length of HRF normally varies from 5-7 m [*Wegelin,* 1996]. Raw water with high suspended solids may probably require longer lengths to provide enough storage capacity. Shallow HRF depths of 1-2 m and widths of 4-5 m are recommended to avoid leakage problems which may result from cracks if larger values were used. In view of possible manual cleaning, shallower depths of not more than 1 m are more suitable [*Wegelin,* 1996]. For URFL, DRFS, and URFS, *Wegelin* (1996) suggests depths varying from 80 to 120 cm. Experiences in *Colombia* suggest depths varying from 85-125 cm for URFL and 50-80 cm

for DRFS [*Galvis et al.,* 1993]. Too deep filters may be characterised by inadequate structural stability and possibilities of cracks, hence leakage, may not be ruled out. Filter surface area perpendicular to direction of flow for URFL, DRFS and URFS should not exceed 25-30 m^2 or 4-6 m^2 for HRF for easy maintenance.

(c)Flow control and filtration rates

(i) Flow control

The control of flow to roughing filters aims to equally and evenly distribute flow to each filter for uniform hydraulic performance of all filters. It is necessary to limit maximum flow through the filter units to avoid overloading the plant, otherwise there can be no allowance to increase flow if need to increase arises when demand increases. The flow control should permit the expected maximum head-loss (normally 10-30 cm).

Weirs, overflow pipes, and valves, are used to control flows. The location of the outlet structure controls the water level in the filter. Although, a normal effluent pipe can maintain a desired water level, it would not allow for discharge measurements. V-notch weirs allow accurate discharge measurements, while still maintaining a desired water level. Flow control devices are used to set inflows equivalent to desired filtration rates.

(ii)Filtration rates

In roughing filters, filtration rates generally vary between 0.3-1.0 m/h [*Wegelin,* 1996; *Galvis et al.,* 1993]. *Wegelin* (1996) has shown that filtration rates can occasionally be increased to 1.5 - 2 m/h if one of the filters is out of operation for maintenance.

Applied filtration rates have an impact on the penetration of the particles into the gravel bed, and retention times. With increasing filtration rates, the performance is expected to decrease since more solids would penetrate and eventually breakthrough. Studies by *Galvis et al.* (1993) on filtration rates of 0.30-0.60 m/h show that the removal efficiency did not vary much. Although filtration rates are reported to affect removal efficiencies, the removal efficiency for a given filtration rate will significantly be affected by the quality of raw water. It is easier to reduce high turbidity (say 1000 NTU to 100 NTU) than low turbidity (10 NTU to 1 NTU). Raw water originating from clay bearing areas is more difficult to treat because clay forms colloidal suspensions which do not easily settle.

(d)Size and layout of the filter media

RF usually employs several layers of gravel with different sizes decreasing in size in the direction of flow [*Galvis et al.,* 1993; *Wegelin;* 1996]. Therefore, raw water first comes in contact with coarse gravel. Arranging the gravel in this way ensures that fine gravel does not directly treat highly turbid raw water, otherwise it would clog rapidly. However, in intake or dynamic filters, the layout is opposite: raw water first comes in contact with fine gravel to block high suspended solids from reaching the main treatment plant. This gravel configuration also ensures easy cleaning by simply raking and flushing the top fine gravel.

Wegelin (1996) recommends a gravel size range of 20 - 4 mm for RF prior to SSF. Experiences in *Colombia* have revealed a range of 25 - 1.6 mm [*Galvis et al.,* 1993]. The limitation on the lower limit is associated with effective hydraulic cleaning of the gravel. It would be difficult to dislodge solid particles if very fine gravel is used.

Theoretically, the number and depth of gravel layers to be installed is not limited. Several deep layers can give best results. But construction costs and overall benefits limit the number and depth of gravel layers. One gravel layer would require a longer overall length (HRF) or depth (URFL, URFS, DRFS) to achieve the same efficiency achieved by several gravel layers of different sizes (see Figure 2.4-2).

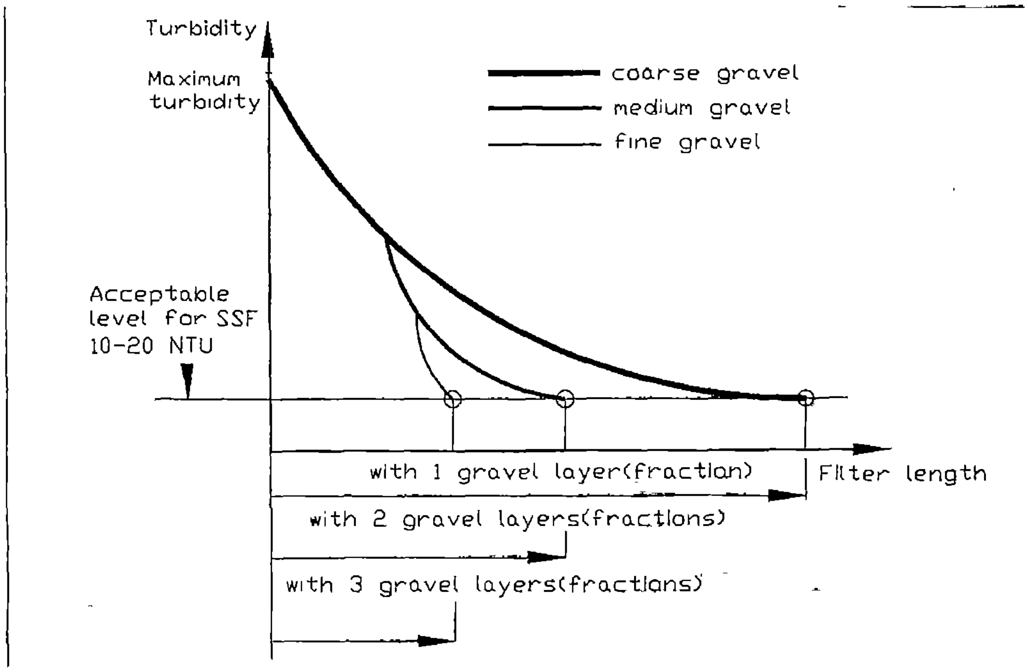


Figure 2.4-2: Turbidity reduction along a roughing filter-bed

[Source: *Wegelin,* 1996]

When more than two gravel layers are used, each gravel layer lightens the suspended load on the next layer. Therefore, the use of several layers with different sizes aims at optimising the filter performance. The optimal number of gravel layers that have shown to give adequate results is three [*Wegelin,* 1996; *Galvis et al.,* 1996; *Rietveld* and *Matsinhe,* 1993]. Each gravel layer should be uniform to achieve large and uniform porosity for adequate storage capacity. *Wegelin* (1996) recommends uniformity coefficients not exceeding 2 within each layer. For simplicity, he defined the uniformity coefficient as the quotient between the largest and smallest gravel size in each gravel layer. According to *Wegelin* (1996), the bulk of the solids is retained in the first coarse layer, the second (medium) layer has a polishing effect while the third (fine) layer removes remaining traces of solid matter. Therefore, the depth/length of individual layers can be designed in the ratio 3:2:1. Despite the larger storage capacity, the bottom and coarse gravel layer retains most of the suspended solids because of the fact that sedimentation is the principal RF mechanism. Hence, most suspended solids have to settle near or at the bottom.

In URFL and DRFS, depths gravel layers can vary from 20-35 cm [*Galvis et al.,* 1993]. *Wegelin* (1996) suggests that depths can range from 20-80 cm depending on the raw water quality. In HRF, the length of the first, second and third layers can vary from 3-5 m, 2 - 4 m, and 0.5 - 2 m, respectively [*Galvis et al.,* 1993; *Wegelin,* 1996]

The filter media is normally supported by a much coarser gravel layer. The support gravel should not be too large to permit penetration of the gravel it supports. This should also hold for the 1st, and 2nd layers in URFL, which support the 2nd and 3rd layers respectively.

(e)Filter drainage systems

As filtration progresses, accumulated solids reduce the gravel bed porosity, and eventually lower the efficiency in terms of filtrate quality, output, and filter resistance. Removal of accumulated solids becomes necessary to restore the storage capacity and efficiency. Back-washing , as done in rapid sand filters, is not feasible in roughing filtration because of the heavy filter media used. It would require very large amounts of energy and water to expand the gravel beds. Hence, filter media cleaning in roughing filtration is achieved either manually (excavating, and washing) or hydraulically (draining the filter unit). The former

method is labour intensive and cumbersome. Draining the filter unit dislodges retained matter from the filter media and flushes it out through the drainage systems. This is an easier option used in roughing filtration.

For drainage systems in roughing filtration, *Wegelin* (1996) recommends false bottoms for up or down-flow roughing filters and perforated pipes or prefabricated culverts for horizontal roughing filters (see Figure 2.4-3).

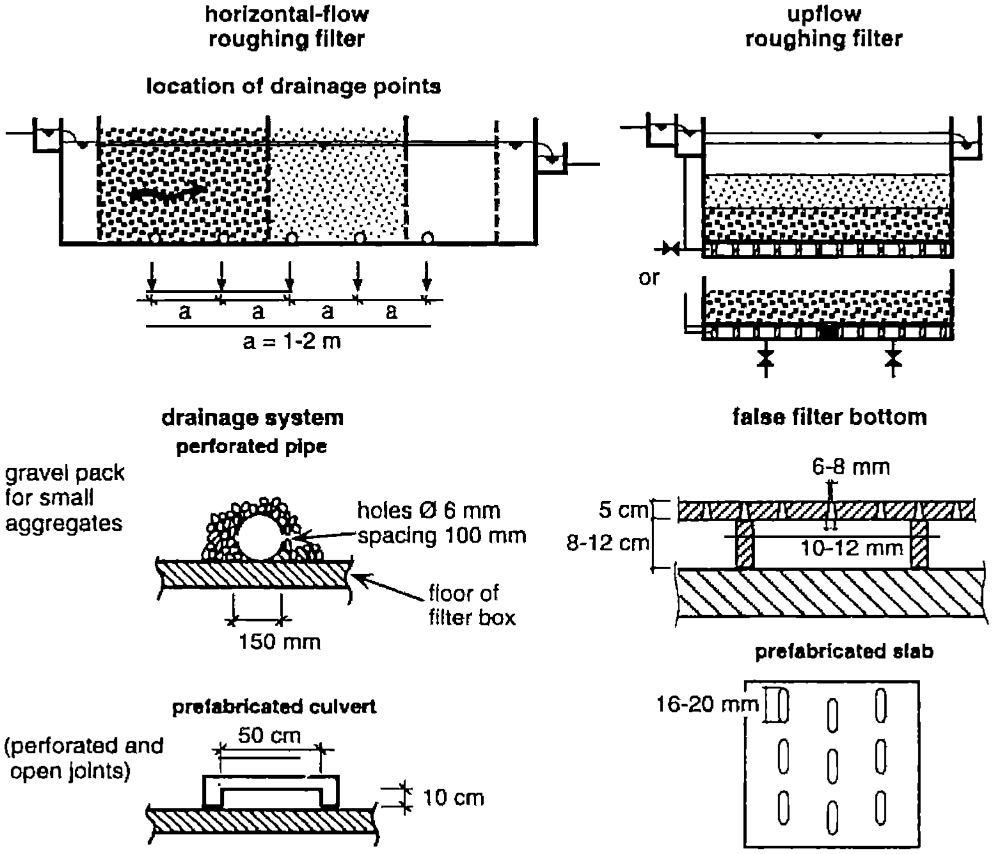


Figure 2.4-3: Layout of drainage systems in roughing filtration
[Source: *Wegelin,* 1996]

In horizontal roughing filters, false bottoms can cause short-circuiting along the opening below the false bottom since the flow is horizontal. *Galvis et al.* (1993) have established preliminary design criteria for drainage systems made of perforated pipes.

Drainage systems should be provided with simple, sturdy and easy to operate drainage valves. These valves must be able to complete open suddenly. This initiates high drainage velocities for effective cleaning. Additionally, the valves should be able to be completely

shut suddenly to initiate water hammer effects within the filter bed. These effects dislodge retained suspended solids. Butterfly valves are appropriate but could be expensive. A model of milk-can valves has been very successful in *Colombia* for draining.

2.4.4 Operation and maintenance aspects

The operation and maintenance of roughing filters is critical for their performance. Methods developed so far are simple and easy, demanding neither special equipment nor expert supervision. Nevertheless, operators to be employed need adequate on-the-job training and an environment that supports, respects and stimulates them. Operation and maintenance activities should be scheduled, illustrating the key ones and frequency. The schedules can be reviewed depending on the performance of the plant. Pilot and full scale plants in *Colombia* have shown that regular maintenance ensures good performance of roughing filters [*Galvis et al.,* 1993].

Daily tasks of the operator include monitoring the head-losses, flow rates and water quality (e.g. turbidity, temperature, colour). These data help to detect operation problems and will assist in decision making. Additionally, keeping the plant site and structures clean establishes a pleasant and professional environment which raises the confidence in consumers.

Intake and dynamic filters are normally cleaned by manually scouring the top filter-bed with a rake or shovel, and flushing the re-suspensions using raw water. They are cleaned more often during rain seasons when surface waters carry heavy loads of suspended solids.

For roughing filters prior to slow sand filtration, cleaning of gravel is carried out either manually or hydraulically [*Wegelin,* 1996]. Hydraulic cleaning is achieved by draining the filter unit, hence flushing out accumulated solids. When draining does not restore the filter capacity anymore, the gravel is removed and washed manually. Hydraulic cleaning frequencies can range from days to weeks to months depending on the quality of raw water. The need for cleaning is normally indicated by the head-loss which gives an idea of the extent of dirt retained. If the head-loss exceeds an allowable limit (normally 30 cm), then cleaning is due. High turbidity levels speed up filter-bed clogging and effluent quality deterioration. The need for manual cleaning may be required after 3-5 years of operation.

2.4.5 Limitations of roughing filtration use

Since the main application of RF is to reduce turbidity and suspended solids in raw water prior to SSF, the type of roughing filter to be employed is usually limited by the levels of these parameters in the available raw water source. Generally, URFL is suitable for the treatment of lower turbidity raw water. This is attributed to its reduced total gravel depth/length compared to other types [*Wegelin,* 1996; *Galvis et al.*, 1993]. Shorter gravel bed depth/length means reduced retention times for effective performance of the filtration mechanisms. Some indicative water quality limits recommended by *Galvis et al. (*1993) for filtration rates between 0.3 to 0.60 m/h are presented in Table 2.4-1.

Table 2.4-1: Indicative raw water limits for roughing filters used before SSF

[Source: *Galvis et al.*, 1993]

Filtration rate (m/h)	RF Type	Turbidity (NTU)		True colour (TCU)		Faecal coliforms (*1000/100 ml)		Total iron (mg/L)		Manganese (mg/L	
		Max[1]	Aver	Max	Aver	Max	Aver	Max	Aver.	Max.	Aver
0.3	URFS[2]	650	85	230	60	300	89	5.5	4.5	1.3	0.9
	URFL	500	70	100	48	200	84	5.5	4.5	1.3	0.9
0.45	URFS	440	53	115	48	300	89	5.5	4.5	1.3	0.9
	URFL	240	44	61	38	200	84	5.5	4.5	1.3	0.9
0.60	URFS	330	44	72	35	300	89	5.5	4.5	1.3	0.9
	URFL	150	39	48	32	200	84	5.5	4.5	1.3	0.9

The limitations indicated in Table 2.4-1 could be lower for higher filtration rates than those given because high filtration rates offer shorter retention time for purification. *Wegelin* (1996) reports lower turbidity limits in his experiences, because he recommends the inclusion of intake or dynamic filters as well, unlike the limits in Table 2.4-1 (compare to Table 2.4-2). The significance of intake or dynamic filters is demonstrated in the practical results shown in Tables 2.4-3 and 2.4-4, demonstrating how they are able to improve raw water quality.

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[1] Maximum values indicated correspond with changes in raw water quality during a duration of less than 3 hours

[2] The limitations for URFS also apply to DRFS and HRFS

Table 2.4-2: Raw water turbidity limitations for roughing filters
[Source: *Wegelin, 1996*]

Average turbidity level -NTU (raw water)	Type of roughing filter
maximum < 5	none
5-30 NTU	URFL
30-200 NTU	URFS
>200 NTU	URFS or HRF

It is worthwhile to mention that the suggested raw water quality limitations from literature, so far mainly depend on the specific characteristics of the particles causing turbidity. Therefore, they are quite flexible. The construction of the filters and the materials used are also likely to contribute to the performance of roughing filters, and hence their limitations.

Since sedimentation is reported to be the main solids removing process in RF, laminar flow is essential for effective performance. The need for laminar flow limits the application of RF to low filtration rates, usually 0.30 to 1.0 m/h. This means that specific production of pre-treated water ($m^3/m^2/d$) in RF is low compared to conventional chemical pre-treatment. This aspect limits the application of RF prior to SSF since it is also characterised by low specific production capacities ($m^3/m^2/d$) compared to RSF. Large land areas, hence high construction costs, would be required if RF were applied before RSF. Besides, RSF best treats coagulated raw water with large flocs retained by the coarser filter media compared to that of SSF. Usually, RF does not use chemicals and therefore cannot produce flocs acceptable for RSF.

2.4.6 Practical performances of RF prior to SSF

Practical experiences with roughing filtration (reported from literature so far) reveal that its performance depends on raw water quality characteristics, plant layout, type of roughing filter and applied operation and maintenance. Identical roughing filters, operated in the same manner can perform differently with different raw water sources [*Wegelin,* 1996]. Even a specific filter cannot have a constant efficiency with the same raw water source. As filtration progresses, accumulating impurities usually influence further removal efficiencies. Filter media size, filter-bed length-depth, filtration rates and cleaning operation are some of the key

factors which determine the efficacy of roughing filtration. Therefore an exact indication of RF efficiencies is generally quite impossible.

Combinations of roughing filters and slow sand filters have been studied both on pilot and full-scale plants world-wide (see Figure 2.4-4). To date, HRF have been widely studied since it was the first type of roughing filtration to be used. The first known HRF used in a public water supply was constructed by *John Gibb* at *Paisley, Scotland* in 1804 [*Baker,* 1981].

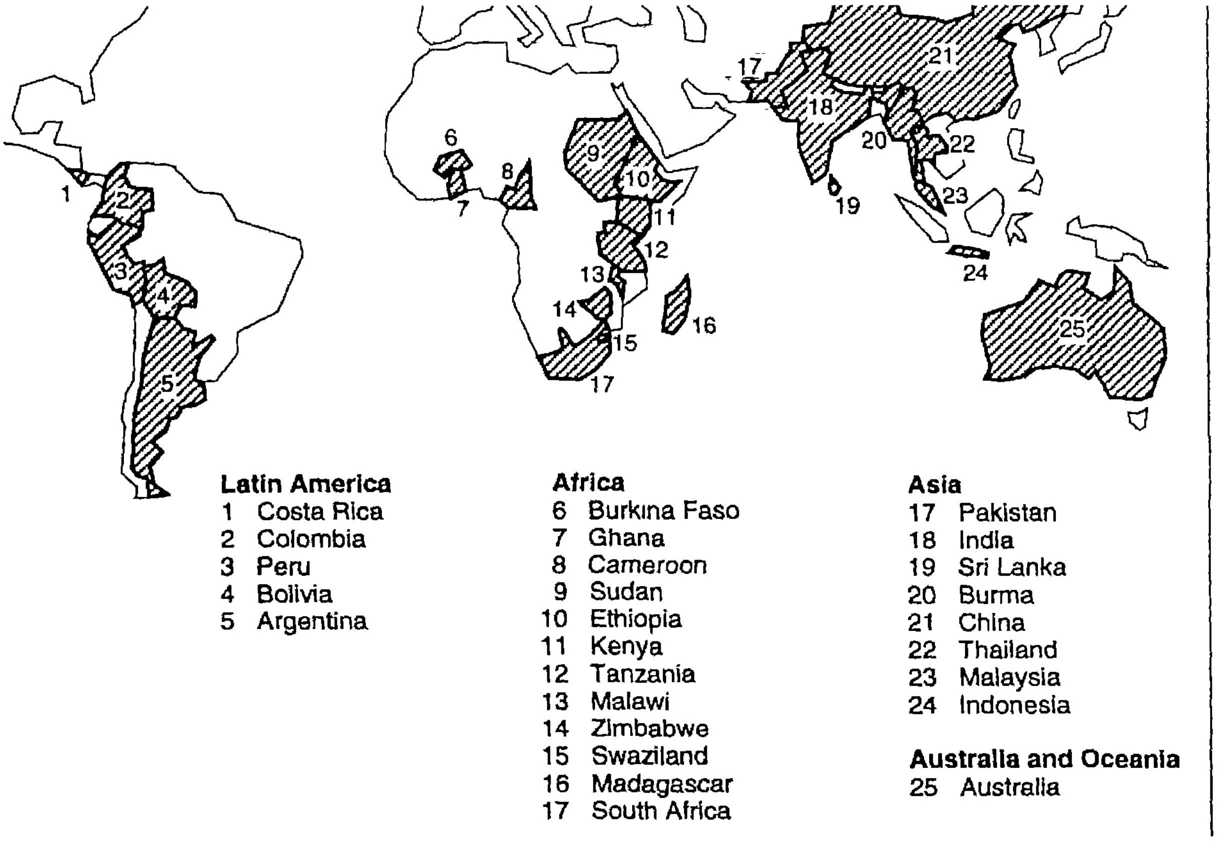


Figure 2.4-4: Geographical distribution of rouging filtration use
[Source: *Wegelin,* 1996]

The efficiencies of different pilot roughing filters with similar gravel fractions, for studies done in *Puert Mallarino, Cali, Colombia* by CINARA, are given in Figure 2.4-5. The filtrate of each roughing filter in Figure 2.4-5 was fed to a slow sand filter. Total suspended solids and faecal coliform removals were analysed (see Tables 2.4-3 and 2.4-4).

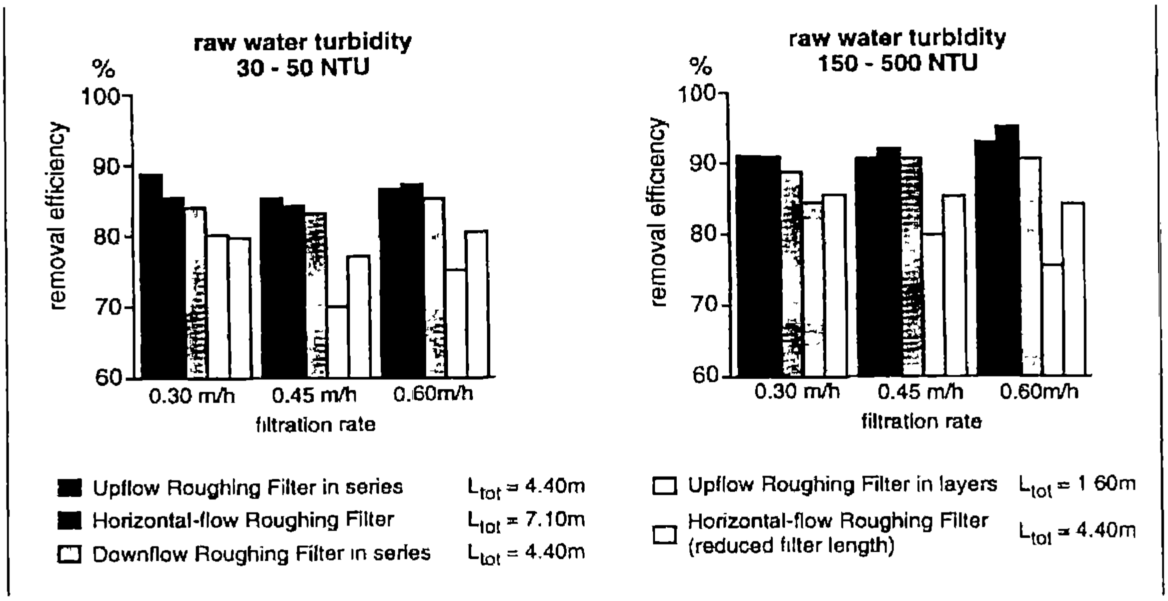


Figure 2.4-5: Turbidity removal by different roughing filters in *Cali, Colombia*
[Source: *Wegelin,* 1996]

Table 2.4-3: Suspended solids removal by RF-SSF pilot plants in *Cali, Colombia*

[only data adapted from *Wegelin,* 1996]

	Raw water	**Intake filter (IF)**		**Roughing Filter**		**Slow sand filter**		**Overall % removal**
Treatment system	**SS mg/l**	**Effluent SS mg/L**	**% removal**	**Effluent SS mg/L**	**% removal**	**Effluent SS mg/L**	**% removal**	
IF-URFS-SSF-1	198.3	86.8	56.2	2.2	97.5	0.3	86	99.85
IF-HRF-SSF-2	198.3	86.8	56.2	1.7	98.0	0.2	88	99.90
IF-DRFS-SSF-3	198.3	86.8	56.2	2.1	97.6	0.2	90	99.90
IF-URFL-SSF-4	198.3	86.8	56.2	5	94	0.2	96	99.90
IF-MHRF-SSF-5	198.3	86.8	56.2	4.2	95	0.3	63	99..85

NOTE:

⇒ All suspended solids figures are mean values, and the number of samples was not given

⇒ IF – Intake roughing filter was installed to intercept highly polluted and contaminated raw water

⇒ MHRF – modified horizontal-flow roughing filter with reduced filter length compared to normal HRF

Table 2.4-4: Faecal coliform removal by RF-SSF pilot plants in *Cali, Colombia*
[only data adapted from *Wegelin,* 1996]

	Raw water	**Intake filter (IF)**		**Roughing Filter**		**Slow sand filter**		**Overall log removal**
Treatment system	**FC # /100 ml**	**Effluent** FC #/100 ml	**log removal**	**Effluent** FC #/100 ml	**log removal**	**Effluent** FC #/100 ml	**log removal**	
IF-URFS-SSF-1	39527	23644	0 22	100	2.38	0.2	2.70	5.30
IF-HRF-SSF-2	39527	23644	0.22	187	2.10	0.9	2.32	4.64
IF-DRFS-SSF-3	39527	23644	0.22	136	2.24	0.6	2.36	4.82
IF-URFL-SSF-4	39527	23644	0.22	341	1.84	0.6	2.74	4.80
IF-MHRF-SSF-5	39527	23644	0.22	834	1.45	2.6	2.51	4.18

NOTE:
⇒ All FC figures are mean values, and the number of samples was not given
⇒ IF - Intake roughing filter was installed to intercept highly polluted and contaminated raw water
⇒ MHRF – modified horizontal-flow roughing filter with reduced filter length compared to normal HRF

The percentage turbidity removal differences by RF in Figure 2.4-5 brings out some points for discussion. URFS, HRF and DRFS indicate marked differences in removal efficiencies compared to either MHRF or URFL. Two observations can be drawn here;

(1) the reduced filter length in URFL, compared to all other filters, can be attributed to its lower removal efficiency since the retention time (which directly influences filtration mechanisms), is reduced. The effect of reducing filter length is also evident when you compare HRF (7.10m) and MHRF (4.40); the former show a higher removal efficiency.

(2) the layout of the filter media and direction of flow may affect the efficiency of RF to some extent. URFS, DRFS and MHRF have the same filter-bed lengths but different efficiencies. The effect of the direction of flow is seen when URFS is compared to DRFS. In RF, most of the solids are retained at the filter bottom. The URFS filtrate outlet is at the top while in DRFS, it is at the bottom (see Figure 2.4-1). It is therefore possible that scouring of the retained solids at the DRFS bottom could affect the filtrate quality since the effluent point is at the bottom.

Despite distinct removal efficiency differences in Figure 2.4-5, the actual filtrate turbidity levels for the 30-50 NTU raw water range from 4 to 15 NTU, for all filters. This is suitable for

SSF. Hence, URFL in this case can suffice and would be appropriate due to their reduced length, hence low construction costs. For the 150 to 500 NTU raw water, URFS, HRF and DRFS offer the best performance. How long high turbidity lasts, is an important question because URFL is also reported to withstand short periods of high turbidity.

In Table 2.4-3, URFL filtrates showed relatively high levels of suspended solids in the effluent, again possibly an indication of low process stability due to the reduced filter-bed length. Otherwise, all roughing filters here showed that they can reduce suspended solids levels of the raw water in question, to levels acceptable for SSF. Faecal coliform removals by RF (see Table 2.4-4) indicate the presence of adsorptive and micro-biological mechanisms, since neither sedimentation nor screening mechanisms are able to remove FC in RF. The combination of RF-SSF here show great removal of faecal coliforms.

Rietveld and *Matsinhe* (1993) studied a pilot URFL (v_f = 0.5m/h, gravel size: 5 to 38 mm) before SSF. Their study revealed that URFL with three gravel layers perform better than with one or two gravel fractions. For the raw water turbidity greater than 10 NTU (11-100 NTU), about 70%, 40% and 45% of the samples analysed had turbidity levels less than 10 NTU for the three, two and one gravel layer(s) filters respectively. These results confirmed the adequacy of a three gravel layer URFL.

The performance of a full scale treatment plant (at *La Javeriana, Colombia*) comprising an intake filter (v_f = 1.3 m/h), two HRF (v_f = 0.6 m/h), and two SSF (v_f = 0.08 m/h), is summarised in Figure 2.4-6.

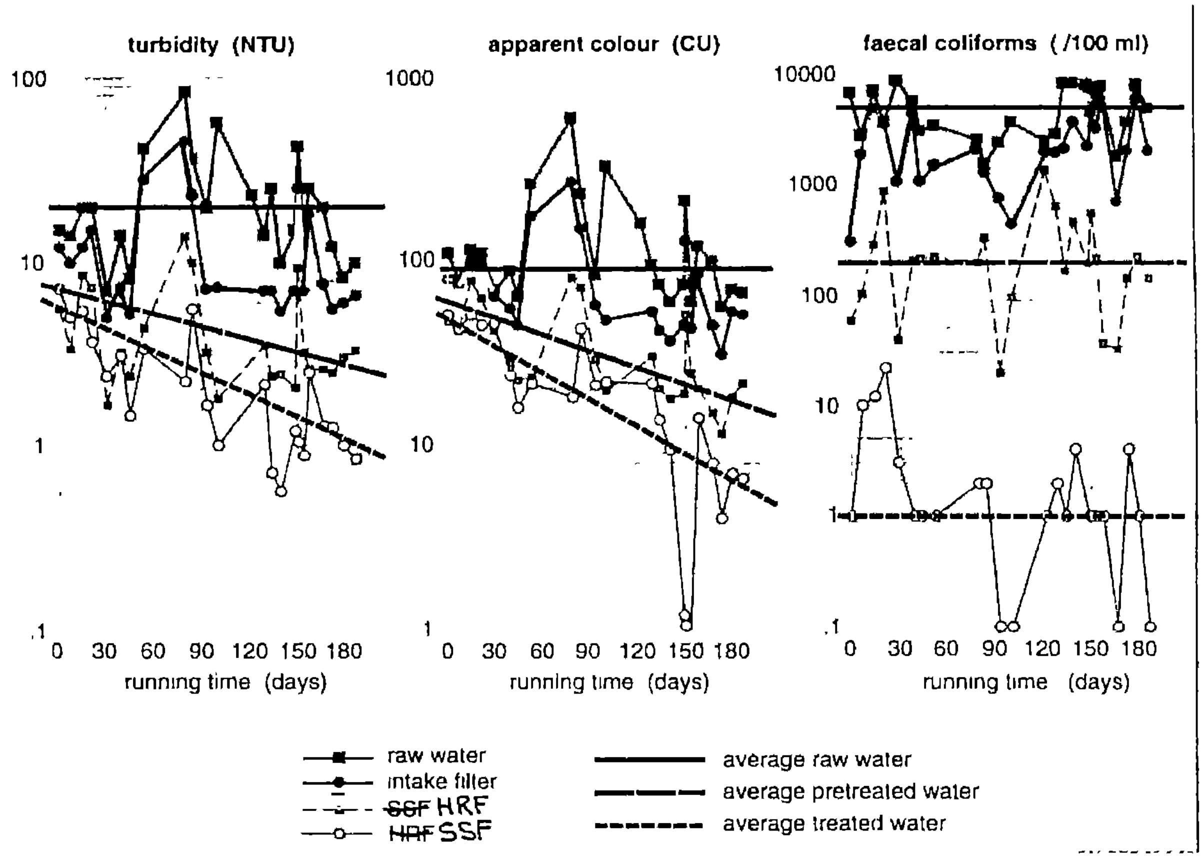


Figure 2.4-6: Performance at the treatment plant *La Javeriana, Colombia*
[Source: *CINARA, 1990]*

FC levels ranging from 1000 to 10000 FC/100 ml were reduced to about 200 FC/100 ml . This performance did not decline during the six months monitoring period. Subsequent SSF filtrates had elevated FC contamination of more than 10 FC/100 ml which levelled out to about 1 FC/ 100 ml over a period of three weeks. This period represents the ripening period for the studied SSF. Turbidity, colour and FC removal also increased with time, probably on account of the gradual development of attachment and transformation mechanisms.

Other examples of full-scale applications of roughing filters prior to slow sand filters are summarised in Tables 2.4-5 and 2.4-6. For the plants in Table 2.4-5, the filter material for down-flow and horizontal flow roughing filters is rather coarser than that used for URFL. However, URFL were run at more than double the filtration rates of the others. Nevertheless, in all the three treatment plants, turbidity reduction by all rouging filters ranged from 70 to 90 % and the bacteriological water quality improvements was about of the same order.

Table 2.4-5: Examples of Full scale experience with roughing filters
[Source: *Wegelin*, 1996]

	Azpitia, Peru	**El Retiro, Colombia**	**Blue Nile Health Project, Sudan**
1. Type of roughing filter	Down flow	Up-flow in layers	Horizontal-flow
2. Filtration rate-m/h	0.30	0.74	0.30
3. Design capacity-m^3/d	35	790	5
4. Depth(cm)- gravel size(mm)	60, ϕ 40-25 60, ϕ 25-12 60, ϕ 12-6	20, ϕ 18 15, ϕ12 15, ϕ 6 15, ϕ 3	270, ϕ 25-50 85, ϕ 15-20 85, ϕ 5-10
5. Turbidity			
• raw water	50-200	10-150	40-500
• Pre-treated water	15-40	5-15	5-50
6. Faecal Coliforms			
• Raw water	700	16000	>300*
• Pre-filtered water	160	1680	<25*
Note: *As E-coli			

Table 2.4-6: Performance of full-scale roughing filters preceding slow sand filtration
[Source: *Wegelin et al.*, 1991; *Wegelin*, 1996; *and Collins et al.*, 1994]

Location	Raw water quality	Treatment system	performance
1. Jinxing city, Zhejiang province CHINA, Asia,	♦ Canal water contaminated by small scale industries & heavy navigation ♦ turbidity 20-90 NTU	♦ Sedimentation-HRF(1.7m/h)-SSF(0.25m/h) ♦ 240 m^3/day	♦ turbidity reduction: HRF (4 -20 NTU), SSF (< 5 NTU) ♦ HRF filter-run =< 40 days, SSF filter-run >4 months
2. Mafi Kumase Village; GHANA, Africa;	♦ lake water with high algae concentrations	♦ HRF (1.5m/h)-SSF (0.25m/h)	♦ reduction of algae: HRF (75-90%), SSF (90-99.99%) ♦ SSF filter runs > 4 months
3. Aesch, Switzerland, Europe	♦ Groundwater with high silt content	♦ HRF -SSF ♦ 17300 m^3/day	♦ high suspended solids and turbidity removals
4 Sao Paulo, Brazil, South America,	♦ High algae and turbidity levels	♦ Up-flow roughing filters-SSF	♦ Total algae reduction: URF (82-92%), SSF (25-55%) ♦ Turbidity reduction: URF (50%), SSF (80-90%)

Full-scale practical experiences with RF-SSF systems presented in Table 2.4-6 revealed the great potential for these systems. The case in Ghana showed the ability of HRF-SSF systems for treating algae loaded surface water. The experience in *Switzerland* illustrates that industrial countries can benefit from the development of simple and inexpensive technologies. Remarkable experiences in *China* attracted local authorities [*Wegelin et al.*, 1991].

2.5 Economic aspects of RF-SSF systems

The selection criteria of treatment systems cannot be complete without considering social-economic aspects. This section presents a brief review of cost aspects of roughing filters and slow sand filters. Social aspects are not covered due lack of literature. However, all practical applications of RF-SSF systems that were reviewed did not mention any social problems with these systems. Therefore, it can be said that these systems are socially acceptable.

Costs of a water treatment plant are affected by numerous factors. Citation of absolute costs is impossible. These factors include the type of treatment plant, local materials, labour costs, method of implementation (private contract, government institute or self help) and geographic location. Overall costs comprise construction, operating and maintenance costs. These can further be separated into local and foreign costs, an aspect of great importance for developing countries which have to import part of the equipment and materials [*Wegelin,* 1996].

2.5.1 Construction costs

Construction costs relate to earthwork, structure, filter media, piping and accessories. Topography, soil conditions and filter unit type are decisive parameters for costs related to earthwork and structure. Topography will affect plant layout and transportation of materials. Soil conditions may determine the amount of digging and filling to be done. Whether the filter unit structure is of earth, reinforced concrete or brickwork is another aspect. The availability of local filter media in required sizes and quantities affects the purchase of the filter media. Earthworks, structures and filter media have low economies of scale, but relative costs of piping and accessories will decrease with increasing plant size [*Wegelin,* 1996].

An evaluation of the construction costs of different roughing filter projects (design capacities 70 to 750 m^3/d) located in *Tanzania, Kenya, Indonesia* and *Australia* revealed the following breakdown of construction costs (*Wegelin,* 1996):

⇒ Earthwork and structure ~70%
⇒ Filter media ~ 20%
⇒ piping and accessories ~10%

From this study, specific RF construction cost per m^3 of the installed volume ranged between 100 - 175 US$, except for the plant in *Australia* (US$ 600). The plant in *Australia* was the smallest in size, and was constructed by a private company. The cost difference reflects how private contractors in an industrialised country can reflect on the construction costs. In developing countries, specific construction costs ranging from 150-200 US$/$m^3$/d will cover roughing filter construction costs [*Wegelin,* 1996]. These costs can be reduced by 30 to 50 % in self help projects, where most of the labour force is supplied by the benefiting community.

Factors influencing the specific construction costs of roughing filters per m^3/d water output are filter length/depth and applied filtration rate. Assuming total filter length of 5 m and v_f = 0.5 m/h for 24 hours per day, specific costs can range from 60 to 80 US$/$m^3$/d. It can further be reduced by 30 to 40 US$/$m^3$/d in self help projects [*Wegelin,* 1996]. These costs are lower for URFL which normally have filter depth less than 2m.

Construction costs for slow sand filters are dependent on filter layout and design, filter box (earthen basin and reinforced concrete are two extremes), and the price of the filter media (sand). Studies done in *India* revealed specific costs of about 25 to 45 US$/$m^3$/d for design capacities from 60 to 750 m^3/day [*Paramasivan et al.,* 1981]. A comprehensive cost evaluation was made for 15 slow sand filters constructed in the USA [*Logsdon,* 1991]. Five of the SSF (capacity ranging from 130 to 189220 m^3/d), which were gravity operated without any electrical equipment, revealed the following subdivision of construction costs.

⇒ Earthwork-site work ~ 10%
⇒ Filter media ~ 25%
⇒ Pipes, valves, metres ~ 20%
⇒ Filter box structure ~ 10%

For uncovered slow sand filters in the USA, specific construction costs show the following relationship [*Wegelin,* 1996]:

$$\mathbf{C = 9\,120x\ A^{0.49}\ (R = 0.88)}$$

in which:	C is the construction costs in dollars
	A is the filter surface area (m^2)
	R is the regression value

The above relationship shows economies of scale. For instance, for a 50 m^2 slow sand filter operated at 0.15m/h, hence having a capacity of 180 m^3/d (50 m^2 x 0.15 m /h x 24 h), the cost of construction is US$ 62 000. But for a plant operated at the same filtration rate having double the area and capacity would have construction costs amounting to US$ 87 000. The specific construction costs for the two plants become:

$$\Rightarrow \text{Plant 1 : US\$ } 62000/\ 180\ m^3/d = \text{US\$ } 345/m^3/d$$

$$\Rightarrow \text{Plant 2: US\$ } 87000/360\ m^3/d = \text{US\$ } 242/\ m^3/d$$

These calculations demonstrate the economies of scale of construction costs in relation to the filter surface area. This may suggest that one can not save much by constructing a small capacity plant which within a short period of time may prove inadequate due to growing water demand with increasing population..

Lambert and *Graham* (1995) drew construction costs comparison between SSF and RSF. Their study revealed that construction costs for small capacity slow sand filters appear to be substantially lower than for equivalent rapid sand filter plants. They also pointed out that RF-SSF systems have long service life, thus reducing the annual depreciation rates of construction costs. These findings were probably on account of the simple design and minimum mechanical/electrical equipment requirements for slow sand filters. Another comparative study between RSF and SSF done in *India*, revealed that capital costs of slow sand filter plants are lower up-to a capacity of 3000 m^3/day [*Visscher et al.,* 1987]. In this study, a break-even point was reported at a capacity of 8000 m^3/day after considering operation and maintenance costs.

2.5.2 Operation and maintenance costs

Cleaning aspects of RF-SSF systems constitute the main operating costs [*Wegelin,* 1996]. Salaries of plant operators vary world wide, therefore the cleaning costs of RF-SSF systems can best be related to the duration of the cleaning. A RF-SSF plant would normally consist of

at least two identical production lines which are cleaned successively to guarantee an uninterrupted water supply.

(a)Cleaning of roughing filters

Roughing filters are usually cleaned by one operator, hence operation costs will remain low in relation to total operating costs incorporating manual cleaning. Manual cleaning is known to be labour and cost intensive since it normally requires additional labour.

The frequency of manual cleaning differs for each type. According to *Wegelin* (1996), it may range from 3 to 5 years or more if the under-drain system is properly designed. Intake and dynamic filters are cleaned after every episode of heavy rains because of heavy loads of suspended solids due to runoff. Manual cleaning entails removing the filter media, transporting it by wheel-barrows to the washing site, washing it, and then reinstalling the clean filter media. The experiences of *Wegelin* (1996) suggest that 1.5 m^3 of gravel can be cleaned by one man in one day, a duration he called one-man-day (considering a working day of eight hours). Therefore, a one metre bed of roughing filter gravel, operated at 0.5 m/h and producing 240 m^3/d, will require a total labour input of about 14 man-days for manual cleaning. Practically, one man cannot be employed to do the work because the down time would be too long. Therefore, if three men were engaged, the cleaning time of five man-days would be sufficient.

(b)Cleaning of slow sand filters

The conventional cleaning of a slow sand filter entails scraping off about one to three cm of the top layer of dirty sand. The cleaning frequency usually ranges from 1 to 6 months. *Wegelin* (1996) reports that a man's ability to scrape off a 2.5 cm layer and transport the sand in buckets to the sand washing bay, may be in the order of 100 m^2 of filter area. However, it is impossible for one man to work for the whole day non stop. Hence, it is more practical to allow, say, two men in this case. To ensure, continuous and reliable supply the washing of the sand can be done after the just cleaned filter has been put back to service.

2.6 Drinking water supply in Zambia

Zambia, like many other countries, faces the challenge of supplying its population with adequate and potable water. About 30% and 70% of the rural and urban populations respectively, have access to potable water [GRZ, 1994]. This means that a large part of the population is still susceptible to water born diseases due to lack of access to potable water.

Problems faced by rural and urban water supply systems in Zambia are technical, poor funding and management. The technical aspect has become important because most current water treatment technologies are inappropriate. Until the advent of the third republic, Zambia never had a coherent water policy. In recognition of the vital role water plays in life, the Zambian Government established the National Water Policy to guide developments within the Water Sector [GRZ, 1994]. One of the water sector principles emphasises on the promotion of technologies appropriate to local conditions.

Holzhaus and *Versteeg* (1993) carried out a survey on township water supply in Zambia and they recommended that appropriate water treatment methods should be considered since most of the current ones are not performing satisfactorily. The current surface water treatment practices in Zambia are limited to conventional methods.

2.6.1 Water treatment practices

(a)Raw water sources

Water resources in Zambia are considered adequate to meet both short term and long term needs. About 75% of drinking water treatment systems in Zambia use surface raw water sources (*Chipungu* and *Kunda,* 1994). These sources include rivers, streams, reservoirs, dams and lakes. Groundwater is widely used in rural and individual water supplies. However, some water supply systems combine surface and ground water sources.

The quality characteristics of most raw water sources in Zambia are not known due to lack of effective water quality monitoring systems [*Chipungu and Kunda* 1994]. However, most of these sources are known not to be adversely polluted, except during rain seasons when surface sources are usually characterised by high turbidities and suspended solids due to run-off after heavy rains. Groundwater is often of better quality because of its natural protection underground.

(b)Treatment methods

Groundwater is naturally protected from contamination and quite often is used directly without any treatment. However, in cases were contamination is known, it is only subjected to disinfection by chlorination because the physical quality is usually still acceptable. It should be mentioned that whether groundwater contamination is known or not, disinfection is always recommended because contamination can also occur after the water is abstracted from the ground. Moreover, contamination does not give a warning. It can only be noticeable from adverse effects resulting from taking contaminated water, then it can be too late to disinfect. Hence, the emphasis of continuous safety disinfection.

Surface raw water sources are subjected to natural or human pollution and contamination as they are not naturally protected like groundwater. Hence, the treatment of surface water entails extra difficulties compared to groundwater. In Zambia, surface waters are mainly treated by conventional systems, comprising chemical pre-treatment, filtration (rapid or slow sand) and finally chlorination. Some rural locations use raw surface water which is only subjected to batch disinfection or without any form of treatment. An overview of the water treatment practices in Zambia is summarised in Table 2.6-1.

Table 2.6-1: Overview of drinking water schemes in Zambia

[Source: WSDG]

Raw water source	Treatment scheme	Number of schemes
Surface	◊ Chemical pre-treatment ⇒ Rapid sand filtration ⇒ Chlorination	~43
Surface	◊ Chemical pre-treatment ⇒ Slow sand filtration ⇒ Chlorination	~18
Surface	◊ Slow sand filtration ⇒ Chlorination	~3
Surface	◊ unknown or direct consumption from source	~11
Ground	◊ Chlorination	~17
Ground	◊ unknown or direct consumption from source	~19

Rapid sand filters are mainly applied in large cities (e.g. *Kitwe, Lusaka, Ndola*, etc.), and to a lesser extent in townships, because of their high production capacities ($m^3/m^2/d$). Performances of a combination of chemical pre-treatment and RSF are usually acceptable in some big cities where chemicals and expert supervision are available (e.g. the *Iolanda* Water Works which supply the city of *Lusaka*). The chemical pre-treatment at *Iolanda* Water Works produce effluents with turbidity less than 5 NTU through out the year, and the final rapid sand

filtration filtrates have turbidity less than 1 NTU. However, for township applications of chemical pre-treatment and rapid sand filtration, performances are not usually satisfactory due lack of chemicals and expert supervision [*Holzhaus* and *Versteeg,* 1993]. Chemical pre-treatment in most townships produce effluents of turbidity greater than 10 NTU. RSF filtrates are often unacceptable because of high turbidity levels which exceed WHO guideline values (upper limit 5 NTU). Most SSF applications in Zambia are confined to rural and township water supplies.

2.6.2 Slow sand filtration in Zambia

(a)Applications

In Zambia, there are at least 20 applications of slow sand filters in townships serving populations ranging from 2300 to 60000. In 1992/3, a technical survey of the water supply systems in fourteen townships in Zambia was carried by *Holzhaus and Versteeg* (1993) covering seven SSF and seven RSF installations. *Mwiinga* (1994) evaluated the water supply system, incorporating SSF as the main treatment process, for the township of *Monze.* In all these applications raw water is drawn from surface sources.

(b)Pre-treatment methods

Slow sand filters applied in Zambia are either preceded by the conventional chemical pre-treatment methods or directly receive raw surface water. To date, there are no known installations of roughing filters in Zambia.

(c)Problems

Many problems faced by SSF systems in Zambia are related to lack of financial input and proper management [*Holzhaus and Versteeg* ,1993]. Additionally, most plants lack adequate raw water pre-treatment and are not usually well operated or maintained. This means that even when money could be made available for rehabilitation, without incorporating other aspects such as training of operators, funding, monitoring or even alternative pre-treatment processes, the rehabilitated systems still experience the same problems with time. The major problems noted by *Holzhaus* and *Versteeg* (1993) in most SSF plants incorporating chemical pre-treatment in Zambia are outlined below.

(i) Pre-treatment chemical supplies

The use of chemicals for pre-treatment constitutes the major operating cost. Normally, the lack of chemicals is attributed to lack of funding and good management. Absence of chemicals means a slow sand filter is subjected to raw surface water. This is undesirable since it causes rapid clogging of the sand, especially in the rain seasons, necessitating frequent filter cleanings which, in turn, increase operating and maintenance costs.

(ii) Lack of skilled manpower

Most rural and township water supplies are unable to attract qualified personnel because of their remoteness and inability to pay workers. The problem of unqualified personnel is also common in most urban water supplies. Large water supply systems in big cities manage to collect part of their water revenues from the large customer base and are able to retain some of the qualified staff. Hence, most qualified personnel in water treatment are lured to large cities and private industries. The lack of skilled manpower has led to:

⇒ Inappropriate operation of conventional treatment systems. This has led to carry-overs of light flocs which subsequently clog the slow sand filter media. Some inlet controlled slow sand filters are controlled from the outlet, a situation which may lead to application of inaccurate filtration rates. Monitoring of the treatment systems is poor since responsible staff or operators are not adequately trained. Wrong slow sand filter cleaning procedures are common; a slow sand filter is drained completely and allowed to dry for at least two days. This is not acceptable because drying the filter-bed kills all the bacteriological life, responsible for the removal of pathogens, in the filter bed. When a filter cleaned in this way is put back to service, its filtrates are often of low bacteriological quality. It also can take long for the filter to mature. In certain plants, raw water bypasses treatment just to increase production without considering the quality consequences.

⇒ Inaccurate dosing of pre-treatment chemicals which results in poor pre-treated effluents since personnel in charge in most cases hardly understand the processes. Normally, chemical dosages are supposed to be determined from experiments, but operators just add estimated quantities.

⇒ Inability of available personnel to request management or higher authorities to undertake certain measures: there are cases where filter sand has not been replenished after several cleanings resulting in very thin filter beds (<20 cm) or even the whole filter unit being out of sand, and yet nothing has been done.

(iii) Lack of equipment and spare parts

Laboratory facilities for evaluating and optimising treatment processes are not available in most water treatment plants. Water quality parameters such as turbidity and residual chlorine can easily be measured by simple portable equipment. Jar test equipment for optimising the coagulant chemical dosing is needed, but not available in most cases.

Treatment process like mechanical rapid mixing, mechanical flocculation, and chemical dosing process are operated by moving mechanical/electrical components. Quite often, once such equipment breaks down, spare parts are hardly available or acquired. This when the need for funding and skilled manpower to properly maintain or repair these facilities comes in.

For slow sand filters that directly treat turbid surface raw water, the main problems faced are operation and maintenance due to rapid clogging of the filter-beds. Well trained operators are required to operate these filters.

(d)Performances

The performances, obtained during field visits to the respective plants, of some slow sand filter applications in Zambia are summarised in Table 2.6-2 [*Holzhaus and Versteeg,* 1993; *Mwiinga,* 1994]. The information in Table 2.6-2 was obtained during the dry seasons. It is therefore most likely that raw water turbidities during the rain seasons, and after some rains, are higher than those shown in this table due to run-off which carries a lot of clay and other suspended matter.

Table 2.6-2[3]: Examples of SSF application in township water supplies, Zambia

[Source: Holzhaus and Versteeg, 1993; Mwiinga, 1994]

Township, YOC; population	Raw water source - Treatment scheme	Turbidity				Remarks
		RW	PTW	FW	Tap	
Chadiza; 1976; 3500.	Nsanzu River C-2SB-4SSF	65.7	42.4	1.94		Malfunction ALUM feeder; no spare parts; high turbid raw waters in rain season, SSF filter runs-4 weeks (wet season) and 12 weeks(dry season)
Gwembe; 1957; 2300	dam-chikumi river C/R/F-2SB-3SSF-Chl	33.6	32.4	13.1	20.3	Rehabilitated in 1984; Chemical shortages; SSF filter-runs: 2 weeks (wet season), 4 weeks (dry season), < 60 cm filter bed; improper filter control; high turbid raw waters in wet season
Lundazi; 1971; 10000	River C/F-2SB-4SSF-Chl.	18.1	4.15	0.69		ALUM dosing equipment broken, hence dosing is direct to Sedimentation tank; no residual chlorine at tap, high turbid raw waters in wet season
Mansa; 1976; 44000	Mansa river 4SSF-Chl.	4.8	-	1.2	3.4 cwt	No pre-treatment; clogging problems common with filter-runs as short as 3 days, some raw water by pass treatment
Nyimba; 1970; 2300	Dam-Chikuyu river C-2SB-2SSF-Chl.	9.9	-	-	0.77	high turbid raw waters in rain season; short filter-runs
Samfya; ~1986; 17000	lake Bangweulu 8SSF-Chl	5	-	3	5	high turbid raw waters in wet season; filter-runs: 4 weeks (dry season), 2 weeks (wet season), no pre-treatment and some raw water by passes treatment to increase production
Zimba; 1985, 7000	Zimba dam C/F-1SB-2SSF-Chl	42.2	17.9	8.16		ALUM stocks inconsistent; filter(sand) bed <15-20 cm; filter-runs 4 weeks (dry seasons), 1 week (wet season)
Monze; ------ 2000	Dam-Magoye river C/F-2SB-6SSF	36	40	40	32	Rehabilitated in 1994; ALUM shortages for long time, high turbid raw waters both in Dry and wet seasons; Short filter runs (<1 week)

---

[3] NOTE: RW-raw water, **PW** - pre-treated water, **FW** - filtered water, **YOC** - year of construction, C-coagulation, C/F - coagulation/flocculation, C/R/F - coagulation/rapid mixing/ flocculation, **SB** - sedimentation basin, **Chl.** - chlorination

From Table 2.6-2, it is clear that the raw water fed to slow sand filters does not meet the acceptable SSF quality (<10 NTU) for the plants in *Chadiza, Gwembe*, *Zimba* and *Monze*. From the remarks column in Table 2.6-2, it is obvious that chemical shortages in these locations are common. Considering all locations, it is certain that inadequate funding, operation and maintenance could be another problem even if chemicals were made available.

Sufficiently designed slow sand filters are expected to produce effluents of turbidity less than 1 NTU, regardless of the raw water quality because of the fine sand. The high slow sand filter filtrate turbidities in Table 2.6-2 are attributed to poor designs with respect to the filter media used and the control of filtration rate, and inadequate pre-treatment. Raw water sources shown in Table 2.6-2 are reported to exhibit high turbidities during the rain season which consequently clog slow sand filters due to inadequate pre-treatment of highly turbid raw waters. Slow sand filter runs less than one month, and even as short as three days (for the direct SSF in *Mansa*), are reported.

2.7 Water treatment pilot plant studies

Currently, water supply systems world-wide are being challenged by drinking water quality regulations; increased water demand; ageing water systems; and high costs of construction, operation and maintenance. Considerations of new or at least non-conventional treatment methods to face these challenges is becoming frequent, and pilot plant studies are needed to study these alternatives.

A pilot plant can be defined as a physical embodiment of the conception of a process or processes, constructed on a small-scale for the evaluation of the process to the extent desired, while providing for the ease of control, monitoring or even modification, if necessary, at reasonable costs. Small-scale may include anything from a bench size to a pilot plant handling several cubic meters of water per day. However, the important distinction is that a pilot plant is significantly smaller than a full-scale unit.

In drinking water treatment, filtration pilot plants have a much reduced filter area, but the rates of filtration and vertical dimensions fully duplicate the values expected in the full-scale plant. The filter surface area does not affect performance, hence constructing large filters can

unnecessarily be costly. However, filtration rates and filter-bed depths affect performance, hence keeping these parameters as expected in the full-scale plant would give conclusive indications of how the desired full-scale plant will perform.

Pilot plants must be carefully planned, designed and monitored to achieve results that are applicable for the development and performance prediction of future full-scale plant.

2.7.1 Purposes of water treatment pilot plants

The overall purpose of pilot plant studies is to answer questions about the full-scale plant. The following specific purposes are usually addressed in water treatment pilot plant studies.

(a) the treatability of a given raw water: whether a given raw water can be treated to potable water by a particular method of interest

(b) the effectiveness of alternative treatment methods

(c) establishing design criteria

(d) establishing the suitability of treatment materials, particularly local ones to avoid imports

(e) investigating treatment modifications and unforeseen treatment problems

(f) estimating operation and maintenance costs

(g) establishing confidence in proposed treatment methods

(h) proving the effectiveness of a treatment process to local authorities

2.7.2 General design guidelines of pilot plants in water treatment

The following aspects are important in pilot plant studies [*Thompson,* 1982; *Wegelin,* 1996]:

(a)Flow through the pilot plant

The supply to the pilot plant should preferably be by gravity to minimise on operation costs related to pumping. Since pilot plants are small, they are characterised by low flows. Small discharge pumps for continuous pumping are usually uncommon. In most developing

countries, such pumps may need to be imported. A high raw water lifting pump can be used occasionally to fill an elevated raw water tank, from which the pilot plant is fed by gravity.

(b)Treatment or production lines

To ensure sufficient evaluation and reliability of the results, at least two identical production lines should be constructed.

(c)Flow control

Since flows to pilot plants are relatively small, they are best controlled by devices that accurately measure such flows. These devices include V-notch weirs, small orifices and rotameters. Use of clamps or small valves is not recommended as they rapidly clog and are thus not capable of maintaining constant flows.

(d)Size and structure of filter unit

The filter unit diameter should not be too small to effect side-wall short circuiting. If the filter unit diameter to filter media diameter ratio is at least 25:1, the side-wall short circuiting effects are minimised. In RF, the media is normally not densely compacted along the side-walls. Thus this ratio can be greater than 25:1, i.e. by increasing filter unit diameter

The structure of the pilot plant must be sturdy, made of either concrete rings, plastic pipes, steel containers or concrete brick-work. Wooden boxes should not be used as they are often not water-tight. The various elements of the plant should preferably be separate and compatible to facilitate modifications and transport, if necessary.

(e)Flow rates

Flow rates should not be too small as they are difficult to keep constant, preferably not lower than 30 L/h. They should be equivalent to the filtration rate desired.

(f) Filter media and under-drain systems

The Filter media used must be the same as the one expected to be used in the full-scale plant and should be as clean as possible.

Because of the small size of the filter units, design of the under-systems is not feasible. However, the filter media are usually supported by graded gravel placed on the perforated filter-bottom plates.

(g)Protection

Pilot plants must be roofed to prevent heating by sunshine and possible disturbances due to heavy rains. However, it is preferable not to roof the plant to have it exposed to the actual conditions to be experienced by the future full-scale plant.

The location of the plant must be well protected to ensure that its operations are not disturbed.

(h)Extent and duration of tests

The investigation period should be long enough to cover the range of conditions expected in practice. This is particularly important to raw water quality variations. It is not imperative that the plant be operated for years, sufficient information can be obtained by operation at those times of the year when adverse conditions are expected.

2.7.3 Monitoring of pilot plants in water treatment

Monitoring should be carried out by local staff, close to the pilot plant, with field equipment stored on site. However, laboratory staff, not stationed on site, may be involved to analyse water samples for specific water quality parameters (e.g. FC). Operators entrusted to monitor the pilot plant must be given adequate on-the-job training by the qualified and experienced engineer. The engineer should be able to visit the plant periodically to attend to unforeseen eventualities, and review collected data as well.

Samples for water quality analysis are taken at the inlet and outlet of the filter units. Several taps included along the filter column depth can serve as sampling points and manometer connections for head-loss measurements. Sampling at these taps must be done with great care not to re-suspend the solids accumulated within the filter-bed.

The frequency of monitoring various parameters is dependent on the extent of evaluation desired. An example of a monitoring programme for a RF-SSF plant is given Table 2.7-1.

Table 2.7-1: An example of field test monitoring programme

[Source: *Wegelin, 1996*]

Parameter	Control / sampling frequency		
	Raw water	RF filtrates	SSF filtrates
a) Flow rate	-	daily	daily
b) Filter resistance	-	weekly	every 2 days
c) Turbidity	daily	daily	daily
d) Filterability or (TSS)	weekly	weekly	weekly
e) Settleable solids	at high turbidity only	-	-
f) Faecal coliforms (FC)	monthly	monthly	monthly
g) Chemical substances	if required at defined intervals	-	if required at defined intervals

Flow rates are used to monitor filtration rates ensuring that they are within the values being studied.

Head-losses or filter resistance indicate the extent of clogging within the filter-bed. It is thus important in signifying the need to clean the filter-bed.

Faecal coliforms are monitored instead of total coliform because they are obvious indicators of possible contamination.

Filterability relates to the amount of water filtered through a filter paper No. 595 in three minutes [*Wegelin,* 1996]. An efficient plant will have RF filterability values between 200 and 300 ml per three minutes and SSF filtrates should have values greater than 300 ml per three minutes. Filterability tests replace TSS measurements if equipment is not available for the more accurate determination of TSS. The tests will produce relative values sufficient to monitor the efficiency of RF in solid matter removal [*Wegelin,* 1996].

Chapter three

MATERIALS AND METHODS

3.1 General

This chapter presents a description of the materials and methods used in a pilot water treatment plant study on a combination of up-flow roughing filters in layers and slow sand filters. The geographical location of the plant is given first, after which the rationale for selecting the treatment processes (based on the reviewed literature and local considerations), design details, investigations done and how the pilot plant was manned, are illustrated.

3.2 Location of the pilot plant

The pilot plant was located in *Kafue* town which is within *Lusaka* province, *Zambia*. The town is about 60 km from *Lusaka*, the capital city of Zambia (see Figures 3.2-1 and 3.2-2).

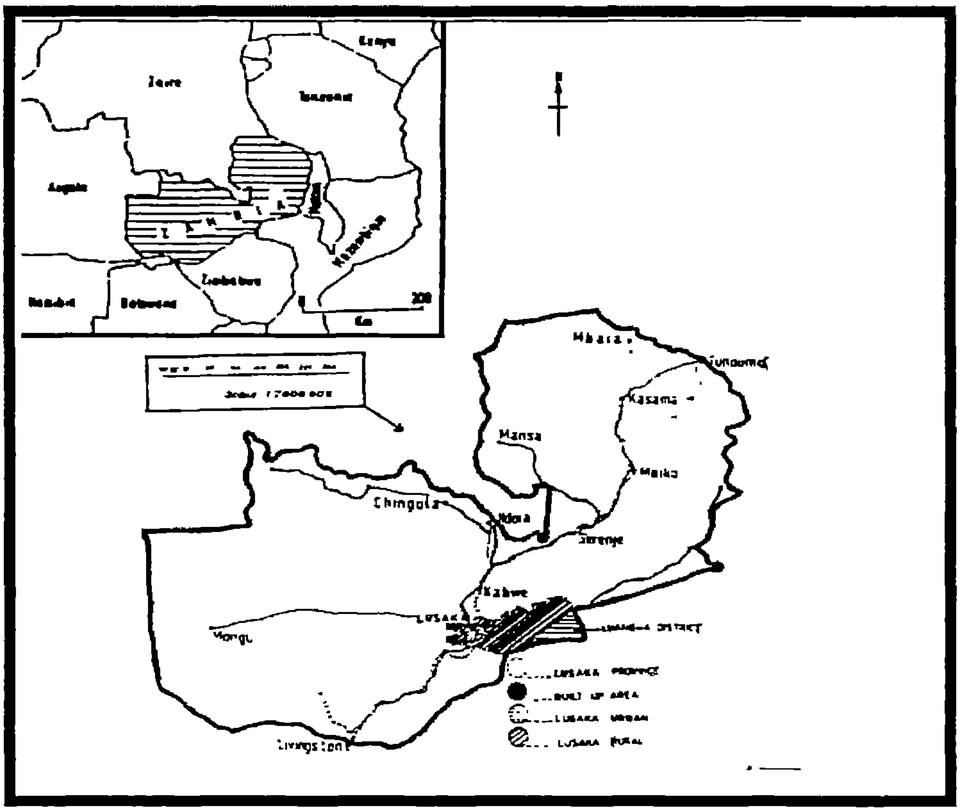


Figure 3.2-1: Location of *Zambia* and *Lusaka* province

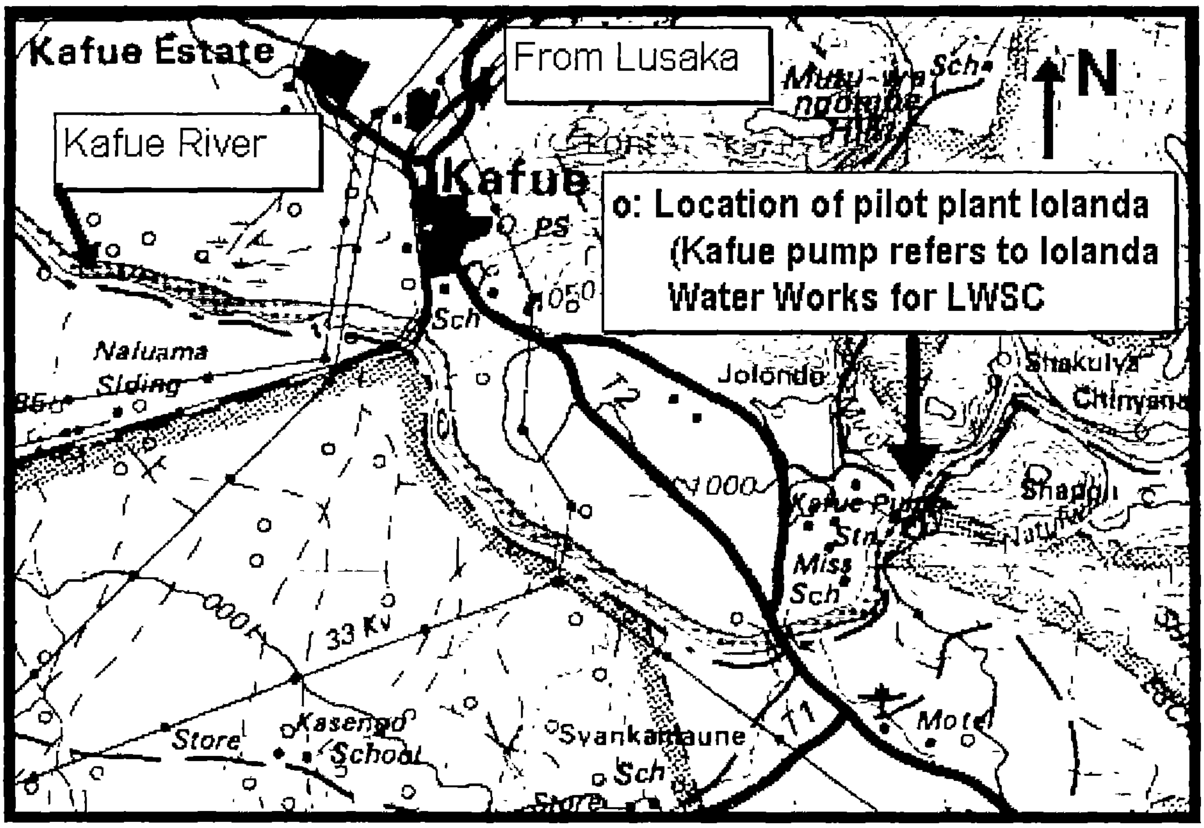


Figure 3.2-2: Location of *Kafue* town and the pilot plant
[Source: University of Zambia, Geography Deaprtment]

Although, the pilot plant site is far from The University of Zambia, located in Lusaka, where all the desk work and some analysis of water samples were done, it was chosen because of its proximity to a reliable surface raw water source; the *Kafue* River. In *Kafue* town, the pilot plant was constructed within the intake area of the *Iolanda* Water Works, which belongs to Lusaka Water and Sewerage Company. Hence, the pilot plant was called "Pilot plant *Iolanda*". The intake area was chosen instead of the main treatment plant area because: (1) the two raw mains within the intake area have existing tapping points, used for sampling raw water. One of these points was easily renovated to supply the pilot plant. In the treatment area, there is no such provisions on the raw water mains, (2) the intake area offers better security since it is not close to residential areas .

3.3 Selection of the pilot treatment processes

3.3.1 Raw water pre-treatment process

The choice of a pre-treatment process is usually between conventional chemical processes and non-conventional processes which do not use chemicals. Although, the former are widely used, their operation and maintenance require expert supervision, costly mechanical and electrical equipment, and consistent chemical supplies. These demands are difficult to meet in most poor developing countries, Zambia inclusive. In Zambia, most installations of chemical pre-treatment systems have caused many operation and maintenance problems which have led to poor performances (see Chapter 2.6.2. (c)).

Recently, roughing filtration has emerged to be an alternative pre-treatment process to conventional processes. The process neither requires chemicals, expert supervision nor highly mechanical and electrical equipment. Current experiences have shown that roughing filters are more effective than plain sedimentation, and much easier to operate and maintain than chemical processes, river-bed filtration or river-bank filtration [*Wegelin,* 1996; *Galvis et al.,* 1993]. Roughing filters are characterized by lower running costs due to easy operation.

It is from the above considerations that roughing filtration was selected as the pre-treatment process. However, from the different types of roughing filters, up-flow roughing filters in layers (URFL) were chosen after considering the following:

(a)Capital costs

Capital costs for URFL are lower than for HRF, URFS and DRFS [*Wegelin,* 1996]. This is evident from the layout and size of URFL (see Figure 2.4-1). In URFL, the installation of all gravel layers in one filter unit, of almost the same height as those of the separate HRF, DRFS or URFS filter units for each gravel layer, means that less filter-media are used. Consequently less construction materials such as piping, concrete, reinforcing steel, and valves are used. The overall capital costs for URFL are thus less than for the other types.

(b)Land use

The smaller size of URFL permits the use of less land area making them more compatible where suitable land area is scarce. However, this parameter is not likely to be decisive in most developing countries where land is abundant.

(c)Operation and maintenance aspects

Cleaning of the filter-bed constitute another criterion for roughing filter selection. Hydraulic cleaning in URFL is much effective and faster. A comparative study done in *Aesch, Switzerland* between HRF and URFL revealed that URFL show higher solids removal during hydraulic cleaning, and were recommended under the study conditions there [*Wegelin et al.,* 1991]. In HRF, DRFS, or URFS, each gravel layer has a separate drainage valve. But in URFL, normally one drainage valve is installed, and opening of this valve washes all the gravel layers at once. This makes the cleaning process less labour intensive and easy to monitor. When it comes to removing the entire gravel media for manual cleaning, less labour is required for URFL since quantities involved are less.

(d)Integration

Existing chemical pre-treatment structures, such as sedimentation and flocculation basins, can easily be reconstructed to URFL. Even a large SSF unit can be reconstructed to encompass URFL. However, for the other types, additional structures are required, since each gravel layer is placed in a separate compartment resulting in longer filter lengths. Possible integration of URFL into existing structures is illustrated in Figure 3.3-1.

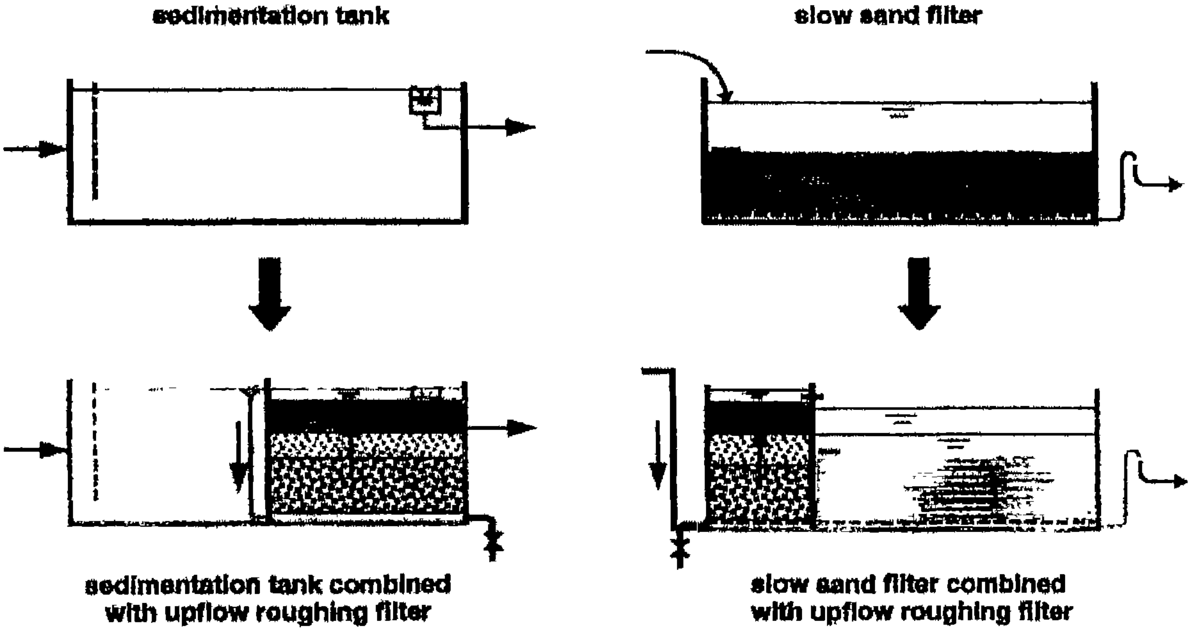


Figure 3.3-1: Possible integration of URFL into sedimentation tanks or slow sand filters
[Source: *Wegelin,* 1996]

(e) Raw water sources and quality

The source and quality of raw water usually determine the type of RF to be used. URFL are reported to handle raw water of relatively low turbidity compared to the other roughing filters (see Tables 2.4-1 & 2.4-2). This is attributed to the shorter filter depth of URFL.

Water supply systems in Zambia usually use dams or reservoirs along rivers to store sufficient raw water for use during dry seasons [*Holzhaus* and *Versteeg,* 1993]. These raw water sources exhibit low turbidity levels except in the rain seasons when higher levels are common due to runoff. The *Kafue* River, which was the source of the raw water supplied to pilot plant *Iolanda*, is one of the largest surface water sources in Zambia [GRZ, 1994]. It is generally characterized by low turbidity levels most of the year (monthly averages < 30 NTU). This makes URFL appropriate for this kind of raw water. During rain seasons, daily turbidity peaks vary from 30 to 250 NTU. However, it is possible that URFL can handle occasional turbidity peaks as reported in literature.

3.3.2 Main treatment process

In drinking water treatment, the choice of the main treatment process normally lies between RSF and SSF. Considering that this study was aimed for small and medium community water supplies, the selection was done after evaluating each process.

(a) Rapid sand filtration

RSF has the benefit of high specific filtered water production (m^3/m^2 /d) compared to an equivalent SSF units [*Huisman,* 1986]. Thus RSF requires less land, and is more appropriate for large urban populations where land is scarce and water demand is high. However, the disadvantages of RSF include: (1) operation and maintenance need expert supervision; (2) highly mechanical and electrical filter media cleaning processes requiring large quantities of treated water and electrical energy; (3) filtrates are usually not bacteriologically safe and always require disinfecting; (4) in most developing countries, construction of RSF plants usually requires importation of some mechanical and electrical installations; (5)construction costs are higher than those of slow sand filters for small capacity plants [*Visscher*, 1987; *Lambert* and *Graham,* 1995].

(b)Slow sand filtration

The advantages of slow sand filters are: (1) does not need expert supervision: less likely to go wrong under inexperienced operation; (2) filter media cleaning is usually manual without requiring any electrical energy or large amounts of filtered water; (3) capable of producing potable filtrates which may not require disinfecting; (4) can readily be constructed from local materials even in developing countries; (5) operation and maintenance costs are lower than those of rapid sand filters [*Huisman,* 1989; 1986]. *Lambert* and *Graham* (1995) report that construction costs of small capacity slow sand filter plants are substantially lower than for equivalent rapid sand filter plants on account of their simple design and minimum mechanical and electrical equipment requirements.

Known disadvantages of slow sand filters are: (1) requirement for large areas of land; (2) high cost of construction per unit area for large installations; (3) labor intensive cleaning procedures. However, these disadvantages are less pronounced in community water supplies of developing countries[*Huisman,* 1989]. In most developing countries, large areas of land, cheap labour and local materials are readily available. Since this study is targeting small and medium community water supplies in Zambia, SSF was selected as the main treatment process.

3.4 Pilot plant design and construction

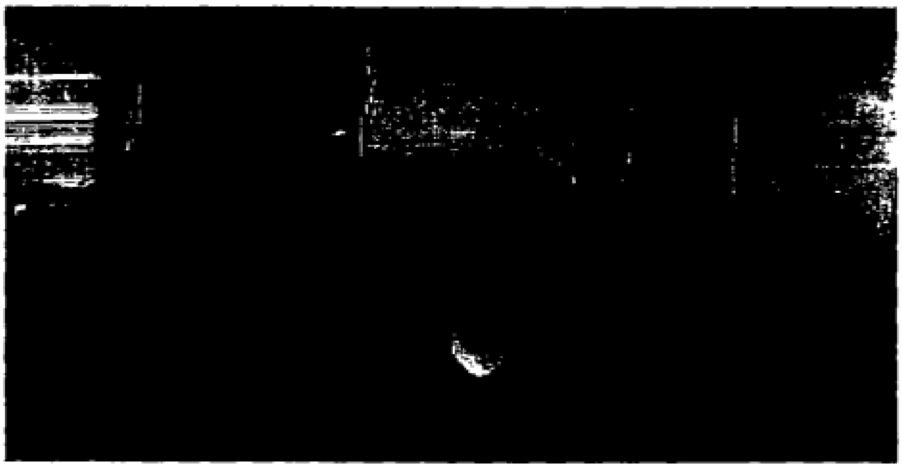
3.4.1 Materials

(a)Filter units, piping, flow control devices and raw water tanks

Options for filter units included steel pipes, brickwork, PVC pipes, fibre glass tanks and concrete pipes. Aspects considered in selecting among these options were: (1) availability; (2) costs; (3) the ease with which to work; (4) and reliability with leakage.

Lusaka Water and Sewerage Company offered off-cuts of steel pipes, available right at the pilot plant site in *Kafue*. Thus steel pipes become an automatic choice. Steel pipes are reliable with respect to leakage and are easily fabricated as desired. However, the pipes were not ready for direct use and had to be cleaned and painted to prevent corrosion (see Figure 3.4-1).

(a) off-cuts steel pipes before cleaning



(b) Cleaned and painted steel pipes

Figure 3.4-1: Steel pipes for pilot plant filter units

The water distribution system for the pilot plant was made of one inch GI (galvanized iron) pipes, elbows, tees and unions, obtained locally. PVC pipes were preferred but are difficult to thread and could have cost more. The pipes were cut and thread on site (see Figure 3.4-2). Cutting and threading of the pipes on site allowed quick modifications and correction of any errors.

Figure 3.4-2: GI Pipes being thread and cut to size on site

Rotameters were used to measure flows. A gate valve was installed before each rotameter for adjusting flow rates.

Raw water tanks were made of two 210 litre drums bought locally. They were thoroughly cleaned and painted with water resistant paint to prevent corrosion.

(b) Pilot plant foundation and filter unit support structures

The filter units were placed on a concrete foundation, cast on site using local sand, crushed stone and cement (see Figure 3.4-3).

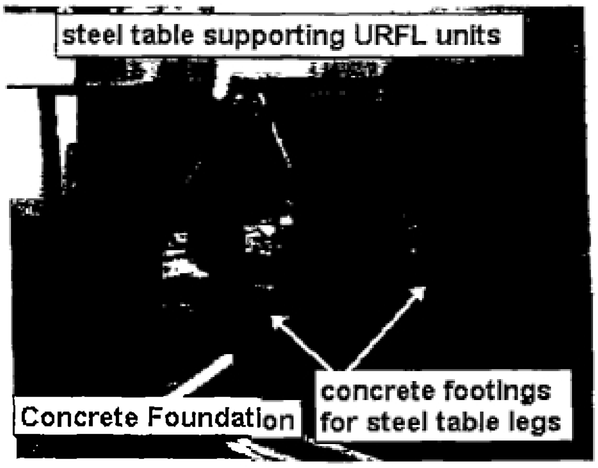


Figure 3.4-3: Pilot plant foundation and filter unit supports

To ensure gravity flow from URFL units to SSF units, URFL units were elevated by a steel table constructed of steel channels (see Figures 3.4-3 & 3.4-11). The steel table was fabricated on site by welding, and its legs were cast in concrete footings for stability purposes. SSF units were place on steel rings, about 18 cm in height, filled with concrete.

(c)Filter media

Natural gravel for URFL and river sand for SSF were obtained from local sources within *Kafue* town. These filter media were not suitable for direct use due to large amounts of clay (visibly noticeable), and were not graded. The washing was done manually in wheel-burrows (see figure 3.4-4). After washing, the media were dried and graded by sieving.

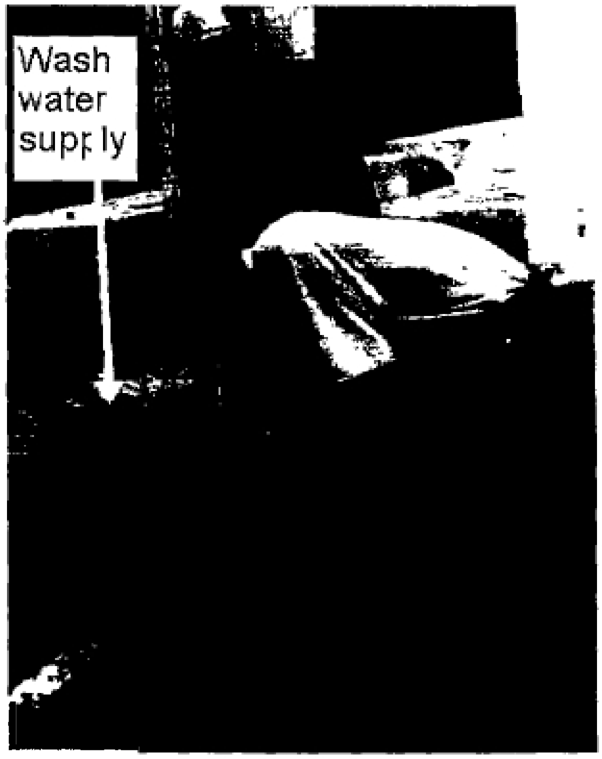


Figure 3.4-4: Filter media washing in wheel-burrows

3.4.2 Design details of up-flow roughing filters in layers

The design of the pilot URFL was carried out with reference to the reviewed design guidelines for full-scale plant, and design considerations for pilot plants (chapter 2). Table 3.4-1 presents a summary of the design parameters for the pilot URFL units.

Table 3.4-1: Design values of URFL pilot plant units

Parameter	**Design value**			
(a) Operation (hours/day)	24			
(b) Number of filter units	2			
(c) Filtration rate (m/h)	0.3 - 1.25			
(d) Filtration media	Size(mm)	$d_{e \text{ or } 10}$, d_{60} (mm)	Uniformity coefficient (UC)	Depth (cm)
• Top layer	2-4.75	1.45, 2.81	1.94 (2.38)*	35
• Middle layer	4.75-9.52	4.54, 6.17	1.36 (2.00)*	35
• Bottom layer	9.52-19.1	9.90, 13.8	1.39 (2.00)*	30
• Support layer	25-38	-	(1.52)*	20
(e) Supernatant depth	20 cm			
(f) Free board depth	20 cm			
(g) Height, Diameter of filter unit	1.6 m, 68 cm			
(h) Ratio of filter unit diameter to effective size of coarsest gravel (bottom layer)	69			

Note: ( )* *Wegelin*'s UC = large gravel size divide by smallest size in a given gravel layer

The above design parameters and aspects not indicated in the table are discussed below.

(a)Operation and number of filter units

URFL units were run 24 hours per day to continuously supply slow sand filters. Continuous operation ensures that the filtration mechanisms are not disturbed.

Two filters units were selected to allow adequate evaluation of the performance and establish confidence of the results. If the two identical units give similar results, then the performance of full-scale plant, designed on the basis of the pilot plant, can be guaranteed.

(b)Filtration rates

Roughing filters operate at filtration rates ranging from 0.3 to 1.0m/h (see section 2.4-3 (c)). Therefore, this range was chosen for this study. In practice, there are cases when one filter is out of operation for maintenance, but production has to be maintained. Therefore, filtration rates of operational filters are normally increased to maintain the desired production, hence an average filtration rate of 1.25 m/h was also studied.

The variation of flow to each URFL unit was determined from the applicable filtration rates and the cross section area of the available filter unit (68 cm diameter, cross section area: A = 0.363 m^2) which gives a range of ~109 to ~365 L/h. However, to allow for greater than

1.0 m/h filtration rates, rotameters measuring flow rates up to 500 L/h (v_f = 1.4m/h) were used.

(c)Inlet structure

The inlet structure for each URFL unit was made of a steel box divided into two compartments separated by a rectangular weir. Raw water flowed into the first compartment, and over the weir to the second compartment. The second compartment allowed the raw water to flow by gravity through the roughing filter. Before the first compartment was a rotameter for reading flow rates (L/h) and a gate valve for flow control. The gate valve was also used to isolate inflows when cleaning URFL.

(d)Under-drain system

Since pilot filtration plants are usually significantly smaller than full-scale plants in surface area, under-drain systems cannot be designed as for full-scale plants. Roughing filter pilot plants usually use perforated filter bottoms and gravel layers as under-drain systems for distributing raw water and collecting wash water during hydraulic cleaning [*Ives* and *Rajapakse,* 1988; *Di Bernardo,* 1988]. The length, width or diameter of pilot filter units are usually less than the recommended spacing of lateral drains for full-scale plants. Therefore, the design of lateral drains would not be practical for pilot plants.

The diameter of the steel pipes used for URFL units was 68 cm, which is less than the lateral spacing of 1-2 m and 1 m for full-scale plants as recommended by *Wegelin* (1996) and *Galvis et al.* (1993), respectively. Hence, a gravel layer (25-38 mm) was used as the under-drain system. This layer also supported the filter media. The inlet of URFL was at the centre of the unit. To aid the uniform distribution of the raw and even abstraction of the wash water, four lateral drains (25.4 cm GI pipes, length 30 cm, perforated with 10 mm diameter openings spaced at 10 cm intervals) were installed. These laterals joined the main drain at the centre of the filter unit. The under-drain system was used both as dividing flow (normal operation) and combining flow (during washing of the filter media).

A fast drainage ball valve, 1.2 m below the filter bottom, was installed to facilitate filter draining (see Figure 3.4-11). Locating the drainage valve at a depth greater than 1.0 m is reported to give additional drainage head which increases the initial drain velocities.

(e)Filter media

Natural gravel used as URFL filter media was not suitable for direct use from source. It had to be washed and graded to ensure good performance (see 3.4-1 c). The selected gravel size for URFL ranged from 2 to 19.1 mm, and was divided into three layers: bottom layer(30 cm): 19.1-9.52 mm, middle layer(35 cm): 9.52-4.75 mm, and top layer(35 cm): 4.75-2 mm. The gravel size range is within the limits suggested by *Wegelin* (1996) and *Galvis et al.* (1993) (see section 2.4.3). Three gravel layers were chosen because so far they have shown to give adequate results and economic benefits (see section 2.4.3 (d)). Sieve analysis (see figure 3.4-5) of the gravel reveal uniformity coefficients (UC = d_{60}/d_{10}) less than two, which are acceptable (see section 2.4.3 (ii)).

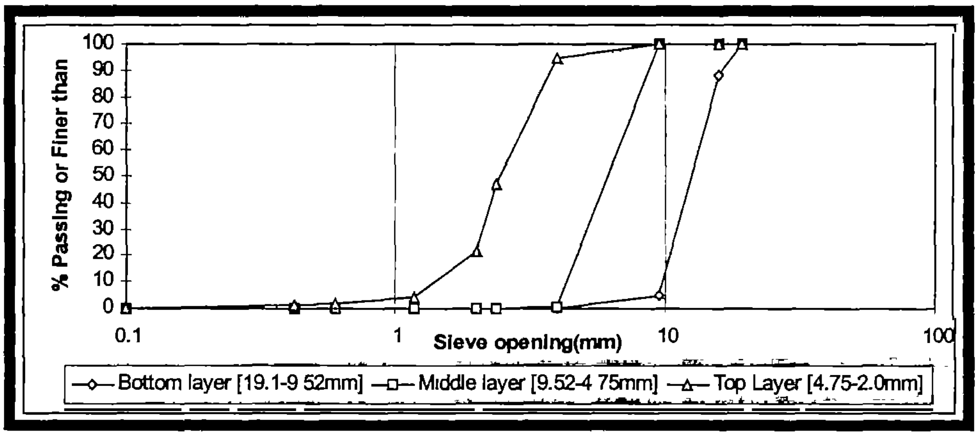


Figure 3.4-5: Sieve analysis for URFL gravel

The gravel layers were separated from each other to prevent mixing in the event of taking out the whole filter media for manual cleaning in future by PVC mesh.

(f) Scale down effects

The reduced cross section areas of pilot filter units compared to full-scale units can cause short circuiting along the side walls where the filter media are not densely packed. Raw water can thus flow along the filter unit side walls without being adequately filtered, and may deteriorate the quality of the filtrate. To check against short circuiting, the ratio of the filter unit diameter to the effective size of the coarsest gravel size was calculated and compared to the minimum suggested value by *Wegelin* (1996)(see section 2.7.2 (d)). A value of 69 was found (> minimum value of 25, and hence is acceptable). Therefore, short-

circuiting effects will not be appreciable. *Barret et al.* (1991) report that pilot filter unit diameters greater than 30.5 cm can be used with little concern about side-wall effects.

(g)Supernatant and free-board depths

A supernatant water depth of 20 cm was chosen as recommended by *Galvis et al.* (1993). A 20 cm free-board depth was allowed to provide extra storage for wash water.

(h)Collecting drains

Pre-filtered water was collected evenly by a one inch perforated (10 mm diameter holes spaced at 10 cm intervals) GI pipe along the filter unit diameter. This drain was installed at the maximum level of the supernatant water, which was the outlet level for URFL.

(i) Outlet structure

The collecting drain delivered the pre-filtered water to an outlet box. This box was provided with an overflow point, below the filter unit outlet point. This design ensures, that the filter unit outlet point is not submerged. A submerged outlet does not provide free outflows due to backwater effects which can cause difficulties with flow adjustments.

3.4.3 Design details of slow sand filters

The design of the pilot slow sand filters was carried out with reference to the reviewed design guidelines for full-scale plant and design considerations for pilot plants (sections 2.2 and 2.7). A summary of the design values is presented in Table 3.4-2.

Table 3.4-2: Design values of SSF pilot plant units

Parameter	Design value
(a) Operation (hours/day)	24
(b) Number of filter units	2
(c) Filtration rate (m/h)	0.1 -0.3
(d) Filtration media : initial depth	0.80 m
:effective size -d_e	0.33 mm
:uniformity coefficient	2.80
(e) Support gravel : Bottom layer	size = 19-38 mm, thickness = 10 cm
: Middle layer	size = 6 - 12 mm, thickness = 5 cm
:Top layer	size = 1.5 - 4 mm, thickness = 5 cm
(f) Supernatant depth	0.90 m
(g) Free board	10 cm
(h) Diameter, height of filter unit	90 cm, 2.0 m
(i) Ratio of filter unit diameter to effective size of sand	2700

(a)Operation and number of filter units

Slow sand filters were run 24 hours per day. Since SSF is a biological process, intermittent operation disturbs the micro-biological life within the filter-bed and can cause breakthroughs of pathogens. Therefore, continuous operation is always necessary.

Two filter units were selected to allow adequate evaluation of the performance and establish confidence of the results. If the two identical units give similar results, then the effective performance of a full-scale plant, based on the pilot plant design, can be expected.

(b)Filtration rates

The chosen range for the variation of filtration rates was 0.1-0.3 m/h (see Table 2.2-1). With the diameter of each SSF unit at 0.90 m (cross section area: $A = 0.636\ m^2$), the flow rates varied from ~65 to ~190 L/h.

(c)Inlet structure and flow control

For each SSF unit a baffle plate below the inlet pipe was installed to prevent erosion and disturbance of the sand surface by the splashing of the inflow water at the beginning of the operation (see figure 3.4-6).

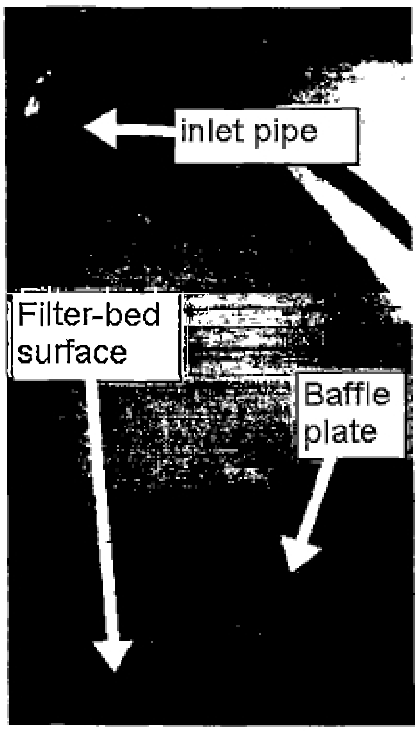


Figure 3.4-6: Inlet for pilot plant *Iolanda* slow sand filters

Filtration rates were controlled from the inlet line. A valve before each rotameter was used to control the filtration rates. This means of control was preferred because it does not demand for daily adjustments of flows to keep the filtration rate constant. Since SSF are operated at constant rates, head-loss development demand daily adjustment of flows in outlet controlled filters to keep constant filtration rates. However, in inlet controlled filters, once the desired rate is set, frequent flow adjustments are not necessary. The rising supernatant water level as filtration progresses compensates for the developed head-losses.

(d)Under-drain system and support gravel

The even abstraction of filtrates from slow sand filters was enhanced by a system of under-drains comprising perforated (10 mm diameter holes @ 10 cm spacing) one inch GI pipes. A 20 cm layer of gravel, to support the filter media and also aid in even collection of filtrates, was placed on top of the collecting drains. This gravel was designed not to permit the wash-out of the fine sand. Following the design procedures described by *Huisman* (1989), the following characteristics of the support gravel were selected:

⇒ Bottom layer 1: Size = 19.1-38 mm, 10 cm thickness

⇒ Middle layer 2 : Size = 6-12 mm, 5 cm thickness

⇒ Top layer 3 : Size = 1.5-4 mm, 5 cm thickness

(e)Filter media

Local sand was used as filter media. Figure 3.4-7 presents results of the sieve analysis for both the unwashed sand (UWSand) and washed sand (Wsand).

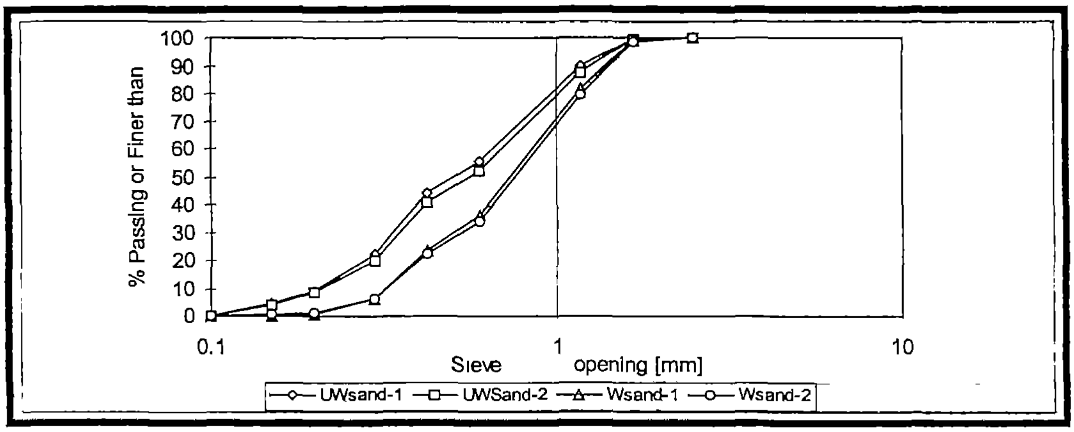


Figure 3.4-7: Sieve analysis for SSF sand

The sieve analysis showed that the unwashed sand (d_e = 0.21 mm, UC = 3.35) satisfied the recommended sand specifications for SSF. However, the sand was visibly dirty (clay) and required washing. Dirty sand causes high turbidity filtrates until all the clay is washed out. *Rietveld* and *Matsinhe* (1993) report of their case in which unclean SSF sand took over three months to begin producing filtrates of acceptable turbidity. In this study, the dirty sand was washed, dried and graded to avoid such a situation. The washed sand had a reduced UC value of 2.80 and the effective diameter increased to about 0.33 mm, both parameters still remained acceptable.

A filter-bed depth of 80 cm was selected, which falls within the acceptable limits (see Table 2.2-1). This depth allowed the operation of the SSF units through the period of investigations without reaching the recommended minimum depth due to cleaning.

(f) Supernatant and free-board depths

Since the height of the SSF units was 2 m, the 20 cm support gravel and 80 cm filter-bed left 1.0 m for the supernatant water and free-board depth. The maximum initial supernatant depth was set at 90 cm and free-board at 10 cm.

(g) Outlet line

The outlet line for SSF unit comprised one inch GI pipe systems and a drainage valve (see Figure 3.4-8).

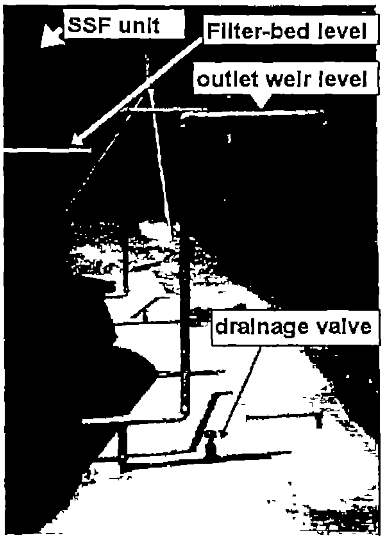


Figure 3.4-8: Outlet lines for pilot plant *Iolanda* slow sand filters

The outlet weir level was set above the sand surface level to prevent below atmospheric air pressures. The drainage valve was used to drain the water level in the sand to about 10-15 cm below sand surface to facilitate cleaning by scraping.

(h)Scaling down effects

To check against the effects of short-circuiting along the side-walls, the ratio of the SSF unit diameter to the effective diameter of the filter-media was determined. A ratio of 2700 was found, far much larger than the recommended minimum of 25. Therefore short-circuiting along the side walls was assumed negligible.

3.4.4 Layout of pilot plant *Iolanda*

(a)Raw water supply system

Raw water for pilot plant *Iolanda* was abstracted from an existing tapping on one of the raw water mains for LWSC's *Iolanda* Water Works (see Figure 3.4-9).

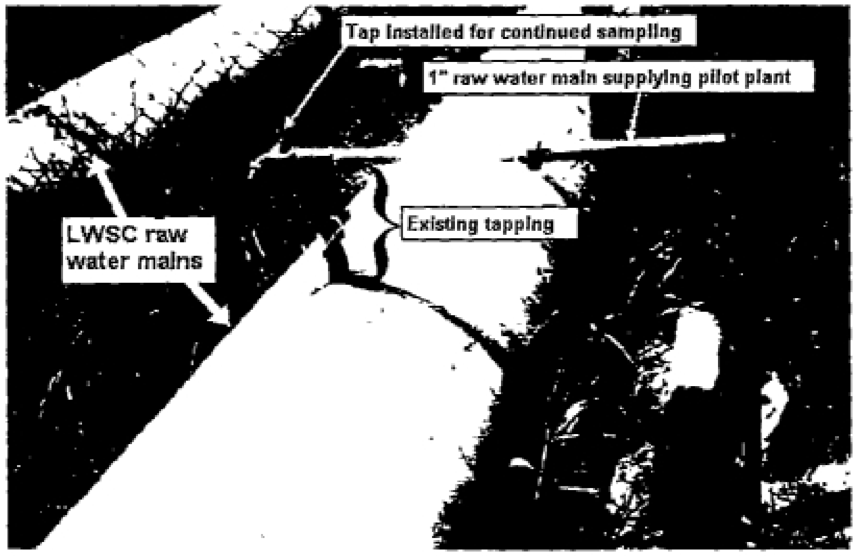


Figure 3.4-9: Raw water abstraction for pilot plant *Iolanda*

The pressure within the LWSC raw water mains managed to discharge into two elevated raw water tanks located about 7 m high from the abstraction point. The layout and construction of the raw water tanks allowed taking one out of operation, with the other tank still supplying the filter units (see Figure 3.4-10). Settling within the raw water tanks was minimized by setting the outlet at the bottom of the tanks (see Figure 3.4-10).

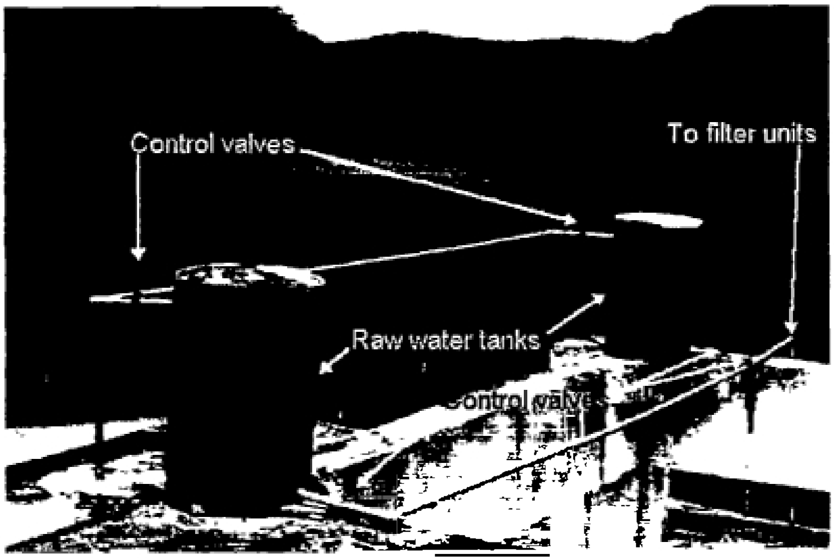


Figure 3.4-10: Layout of pilot plant *Iolanda*'s raw water tanks

A float valve in each raw water tank was installed to maintain constant water level so that the hydraulic head delivering water to the filter units was constant, hence constant flows. Changes in water levels could have caused flow adjustment problems.

(b) Filter units

The two URFL units and two SSF units made two production lines, each consisting one URFL and one SSF (see Figures 3.4-11 and 3.4-12). The interconnections between the URFL outlet lines ensured continuous supply to slow sand filters. It was possible for one URFL to supply both SSF units when the other was out of operation. The construction of two production lines allows adequate evaluation (*Thompson,* 1982).

Flow from the raw water tanks through the filter units was by gravity (see Figure 3.4-13). Gravity flow eliminated the need for costly pumping. Filtrates from URFL units were in excess of the capacities of slow sand filters. Therefore, URFL outlet boxes maintained a constant hydraulic head, which delivered pre-filtered raw water to slow sand filters, by means of a fixed overflow. This ensured steady flows to SSF units.

(c) Drainage systems

The drainage systems of the pilot plant collected and directed all overflows, SSF filtrates and URFL wash-water safely to an existing drainage system.

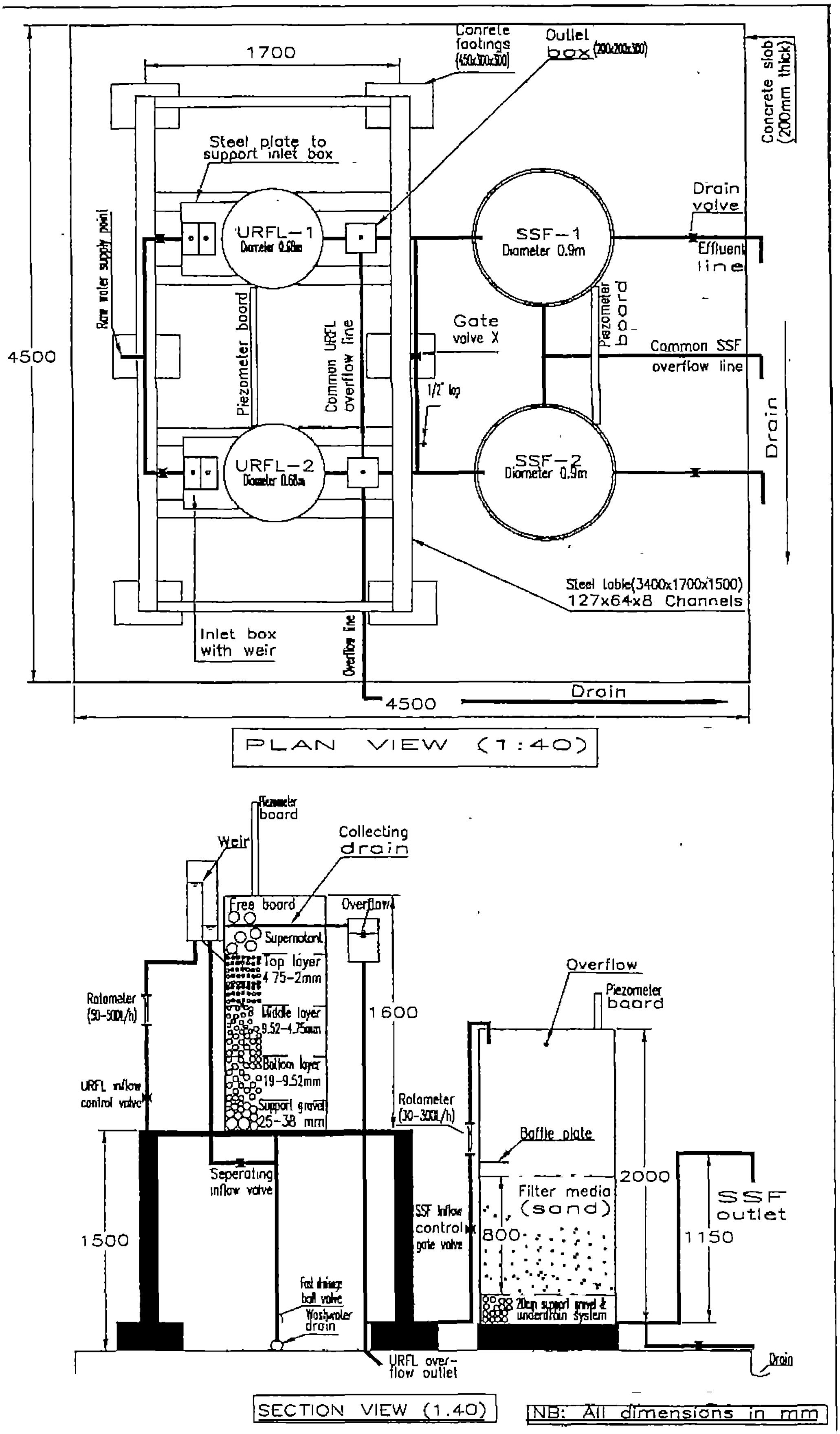


Figure 3.4-11: Schematic layout and design of pilot plant *Iolanda*

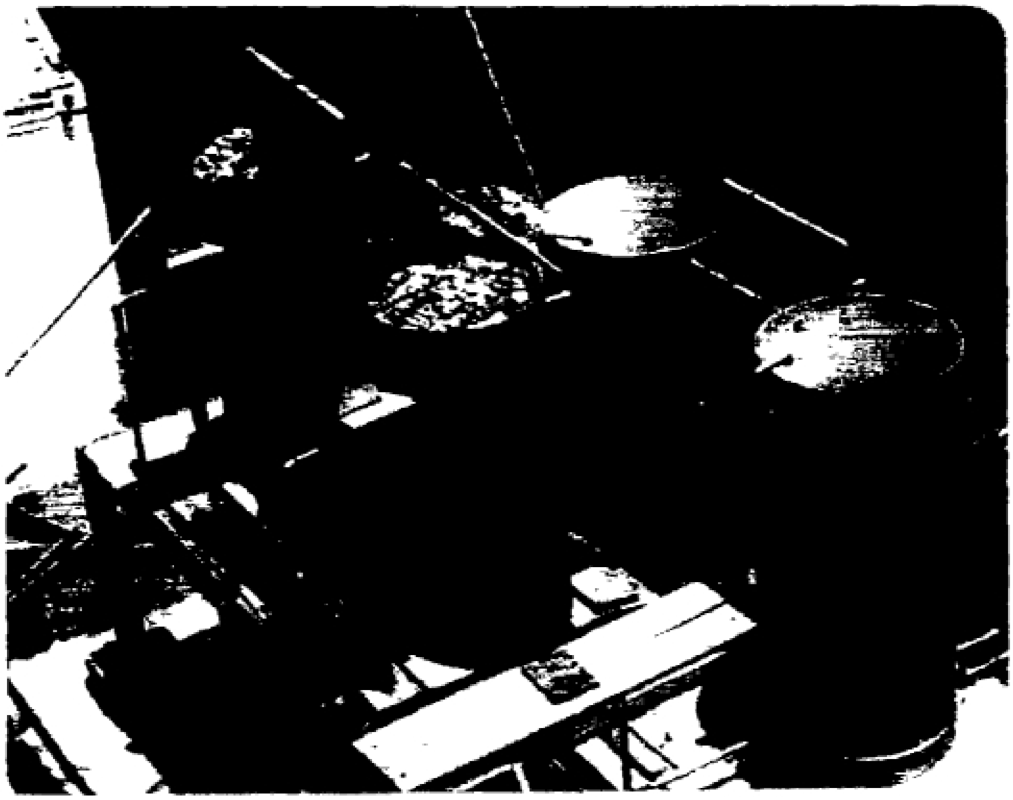


Figure 3.4-12: Picture of the complete pilot plant *Iolanda*

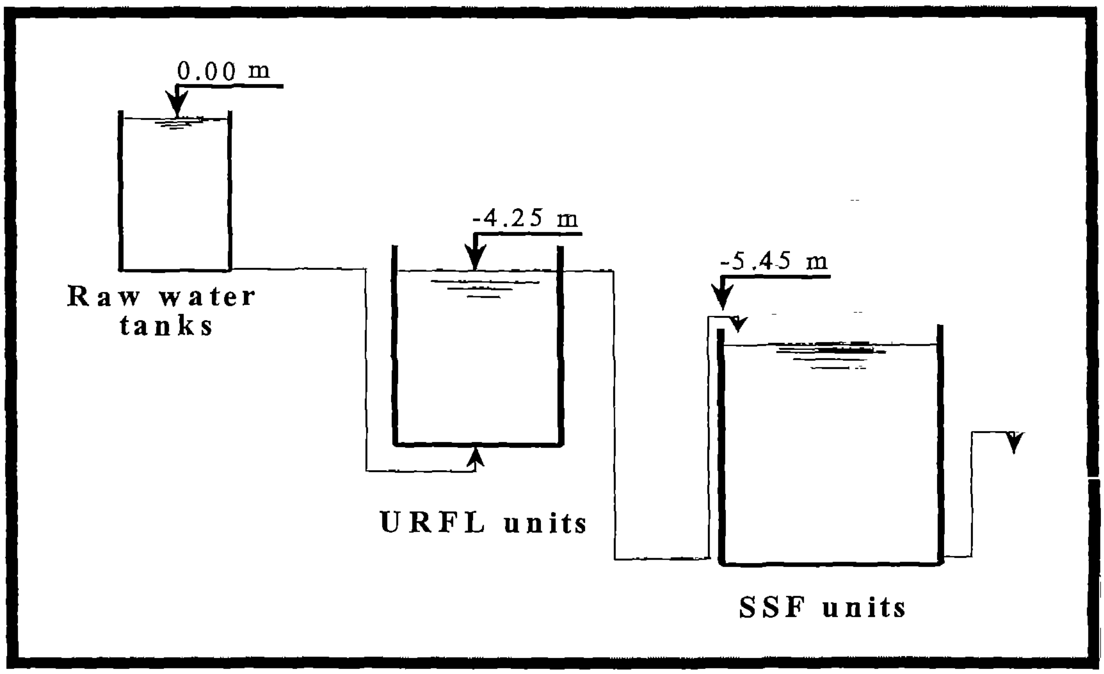


Figure 3.4-13: Hydraulic profile of pilot plant *Iolanda*

3.5 Investigations on pilot plant *Iolanda*

3.5.1 Objectives

The overall objective of the investigations on pilot plant *Iolanda* was to evaluate the effectiveness of a combination of up-flow roughing filtration in layers and slow sand filtration as a potential alternative to conventional surface water treatment methods in Zambia. Therefore, the treatability of the surface raw water by URFL-SSF systems, suitability of the local filter materials used, and the operation and maintenance aspects of URFL-SSF systems were investigated. The investigations also aimed to establish confidence in URFL-SSF systems to promote their application in Zambia, and possibly elsewhere.

3.5.2 Operating period and conditions

(a)Operating period

The operation period ranged from February 28, 1997 to May 31, 1997. This period did not entirely cover the wet season in Zambia which starts from November to March the following year. Initially, the operation period was planned to cover the rain season period when adverse raw water qualities are expected. But this was not possible due to unforeseen logistical problems. The recommendations on the period of water treatment pilot plant operation state that the period should cover all conditions under which the full-scale plant is expected operate. Hence, the need to simulate wet season raw water quality was inevitable.

(b)Operating conditions

(i) Raw water quality

Raw water was tapped from the LWSC raw water mains which transport raw water abstracted from *Kafue* River (see section 3.4-4 a)). *Kafue* River is characterized by low turbidity during dry seasons (<10 NTU monthly averages) and occasional daily peaks ranging from 30-250 NTU during wet seasons. The wet season turbidity was simulated using clay settled along the *Kafue* River banks. The clay suspension was prepared in a 200 L container and was allowed to settle for at least one hour to remove easily settleable solids. The supernatant of the suspension, mainly containing colloidal particles, was dosed for simulation. Initially, small electrical dosing pumps were used,

but they were giving operation problems and could not simulate high turbidities. Gravity dosing was later designed. The supernatant of the clay suspension was fed to 20 L containers, supported on top of each URFL unit, from which flexible plastic tubes (diameter 4 mm) dosed by gravity into the URFL inlet boxes.

The raw water simulations were done from 07:00 hours to 18:00 hours Zambian time. The typical raw water quality during the period of investigations is given in table 3.5-1.

Table 3.5-1: Typical characteristics of the raw water fed to Pilot plant *Iolanda*

Water Quality parameter	**Raw water**	
	***Kafue* river**	**simulated**
⇒ Turbidity NTU (daily averages)	<5	<300
⇒ Faecal coliforms per 100 ml	<200	<4000
⇒ Total suspended solids (mg/L)	<5	<2000
⇒ Temperature	18-31 °C	18-31 °C

Note: Turbidity was measured daily from 07:00 to 18 00 hours, but is reported as daily average

(ii)Filtration rates

URFL filtration rates of 0.4, 0.5, 0.75, 1.0 and 1.25 m/h were tested as in Table 3.5-2.

Table 3.5-2: Applied filtration rates and influent turbidity ranges on URFL

Trial	Filtration rate (m/h) $v_{f(average)}$	URFL-1		URFL-2	
		Run time: days, (dates)	Raw water turbidity range- NTU (daily average)	Run time days, (dates)	Raw water turbidity range- NTU (daily average)
1	0.40	25, (2-26/03/1997)	1.04 - 10.67*	25, (2-26/03/1997)	1.04 - 10 67*
2	0.75	20, (27/03-15/04/1997)	1.48 -12.85**	20, (27/3-5/4/1997)	1.48 - 12.85 **
3	0.50	17, (16/04-02/05/1997)	1.37 - 3.83	17, (16/4-2/5/1997)	[15 - 260]***
4	0.75	26, (04-30/05/1997)	1.41 - 3.11, [30-101] ***	26, (04-30/05/1997)	[22 - 123]***
5	1.0	31, (31/05-30/06/1997)	1.40 - 2.82, [25-156]***	31, (31/5-30/6/1997)	[24 - 220]***
6	1.25	18, (01-18/07/1997	[47 - 240]***	10, (01-10/07/1997)	[54 - 299]***
7	0.50	13, (19-31/07/1997)	[71 - 245]***	21, (11-31/07/1997)	[67 - 277]***

<u>NOTE:</u>

* ⇨ 2 days in this range recorded 9.68 & 10.67 NTU, the rest had < 5 NTU; suspected runoff upstream of *Kafue* River on one day, and raw water tanks were cleaned on the other(depositions in the pipe system may have raised turbidity.

**⇨ Only 1 day recorded 12.85 NTU after cleaning the raw water tanks, the rest had <5 NTU

[ ]*** ⇨ simulated turbidity

During Trial 1, both URFL and SSF units were not shaded. This was deliberately done to evaluate the algae growth. From Trial 2 till 7, the filters were shaded since it was observed in Trial 1 that algae caused rapid clogging of slow sand filters. URFL units were shaded by filling the supernatant and free-board depths with coarse gravel (25-50 mm), while SSF units were covered with timber boards.

Investigations on 0.75 m/h were repeated in Trial 4 for simulated high turbidities since Trial 2 (0.75m/h) ran under low turbidity raw water. This is the same reason for having repeated investigation on 0.50 m/h in Trial 7.

Rotameters for slow sand filters were set at 150 L/h (filtration rate of 0.24 m/h). Volumetric measurements on the outlets revealed the lowest filtration rates of 0.08m/h at the end of the filter- run (since the filter media are more clogged then).

3.5.3 Operation and maintenance procedures

(a)Start-up of pilot plant operation

Before starting slow sand filters, they were back-filled from the bottom as described in section 2.2.4 (a). A flexible hose pipe was secured for back-filling using drinking water from an existing tap within the pilot plant site. It is important to use potable water for back-filling so that the filter-bed is not contaminated if raw water was used. Back-filling was done at very low flows (50-100 L/h: 0.08-0.15m/h) to ensure that all the air within the sand was driven out as recommended from literature. Entrapped air may cause short circuiting during filtration, and also impair the filtration rates.

Before supplying raw water to the pilot plant from the elevated raw water tanks, it was necessary to drive out all the entrapped air within the raw water pipe system to prevent air-locks. The effects of air-locks were experienced at the beginning: no flow reached the pilot plant filters even when the raw water tanks were filled and their outlet valves fully open. The air-locks were cleared by shaking the pipes until water flowed into the URFL inlet boxes. After clearing the air-locks supply to the pilot treatment plant was started. The first URFL filtrates were visibly dirtier than the raw water, due to the self-washing of gravel. These filtrates were filtered to waste.

(b)Filter-bed cleaning and restarting procedures

(i) Up-flow roughing filters in layers

The cleaning of the URFL filter media was necessary before starting each filter-run so that at least the filter-bed was brought back to a clean state. Additionally, cleaning of URFL is necessary when the filter resistance reaches the maximum allowable head-loss of about 30 cm [*Wegelin,* 1996] or when the filtrate quality deteriorates beyond the desired level; normally daily average turbidity greater than 10 NTU are not acceptable. However, in this study non of these head-loss and filtrate quality criteria were reached. This was probably because of the intermittent simulation of high turbidity (only day times).

Both URFL were washed at the end of Trial 1 (27-03-97) before starting Trial 2. Thereafter, the filters were not washed at the end of Trial 2. At the end of Trial 3, URFL-1 was not cleaned since the effluent was still acceptable (<3 NTU), but URFL-2 was cleaned (02-05-97) because during this trial it was fed with highly turbid raw water(simulated) than URFL-1, and must have accumulated appreciable amounts of suspended solids. At the end of Trial 4, both URFL were not cleaned since the filtrate quality and head-loss were still acceptable. At the end of Trial 5, URFL-2 was cleaned and within Trail 6 (18-07-97) both URFL units were cleaned.

The filter gravel for URFL was cleaned by complete drainage of the units. The following procedure was followed for each URFL cleaned (refer to Figure 3.4-11):

⇒ the valve connecting the two URFL outlet pipes (Valve X) was opened so that the remaining URFL unit supplied both SSF units.

⇒ then the URFL outlet point was sealed by a cloth so that the supernatant water level was raised to maximum free-board level (to increase the wash water volume)

⇒ the URFL inflow control valve was closed to isolate the incoming flow.

⇒ the URFL separating valve was closed to prevent the drained wash-water from back-flowing into the URFL inlet box.

⇒ the fast drainage ball valve was suddenly fully opened to completely drain the filter unit. Draining washed out suspended solids within the filter-bed.

After cleaning the URFL unit, it was restarted as follows:

⇒ the fast drainage and separating valves were closed and opened, respectively. The URFL outlet was also opened by removing the cloth.

⇒ then the URFL inflow control valve was opened to set low flow rates not more than 150 L/h (0.4m/h) so that remaining solids were not re-suspended. Initial attempts to fill the units quickly by setting the inflow rate to about 500 L/h resulted in highly turbid filtrates, which were filtered to waste until they became clear.

⇒ after the URFL was refilled, the valve separating the two URFL outlet lines (valve X) was closed so that each roughing filter supplied one SSF..

(ii) Slow sand filters

Slow sand filter media were cleaned after each filter attained the maximum head-loss: when supernatant water level reached the overflow point (see Figure 3.4-11). The cleaning procedure was as follows (refer to Figure 3.4-11):

⇒ the SSF inflow control valve was closed to isolate the incoming flow.

⇒ the supernatant water was drained by means of the supernatant manometer connection which was at about 10 cm above the initial filter-bed surface.

⇒ the filter-bed was slowly drained by the SSF drainage valve on the outlet to lower the water level to at least 20 cm below the sand surface. Water levels were checked by manometer connections along the filter-bed depth.

⇒ the top dirty layer of the sand (about 1-2 cm) was scraped using a flat shovel (with short handle) and the sand surface was evened out afterwards. Scraping was done while standing on the baffle plate.

The just cleaned SSF unit was back-filled with filtrates from the adjacent SSF unit. A flexible hose pipe was used to connect the outlet of the filling SSF unit to the outlet of the SSF unit which was being back-filled. After back-filling raised the supernatant water to at least 15 cm above the outlet weir level, normal SSF operation was restored by opening the SSF inflow control valve. This valve was set to low filtration rates (<0.1m/h) which were increased to the desired average rate of 0.24 m/h after at least a day.

3.5.4 Data collection and analytical procedures

(a)Data collection

The collected water quality data included that of turbidity, total suspended solids, faecal coliforms, head-losses and filtration rates. A summary of the collected data and the respective point and frequency of collection are given in Table 3.5-3.

Table 3.5-3: Monitoring program for pilot plant *Iolanda*

Parameter	Up-flow Roughing Filter in Layers		Slow sand filter	
	Influent (raw water)	*Effluent*	*Influent (pre-filtered water)*	*Effluent*
1. Flow (filtration) rate	daily		daily	daily
2. Turbidity	daily	daily	daily	daily
3. Total suspended solids	weekly	weekly	-	-
4. Faecal coliform	weekly	weekly	weekly	weekly
5. Head-loss	Daily along the filter-beds			

Rotameters installed on inlet lines of the filter units were used to read flow rates. Volumetric measurements (beaker and timer) were used to determine effluent flows rates. This was done for SSF units but not for URFL units because the effluent point could not facilitate volumetric measurements. Flow rates were read (measured) once a day.

Turbidity measurements were done daily, at least on an hourly basis from 07:00 to 18:00 hours Zambian time. Analysis of TSS was only done during turbidity simulation periods when appreciable TSS levels were common from Trial 3. Water samples for analysis of TSS and faecal coliforms were collected and analyzed at the University for Zambia (*Lusaka*), at the Environmental Engineering laboratory. URFL wash-water samples were also collected for TSS analysis on four of the hydraulic cleaning occasions.

Head-losses were monitored on peizometer tubes (manometers) installed along the depth of each filter unit. The tubes were vertically fixed to a timber board for easy reading.

(b)Analytical procedures

(i) Water sampling and water quality analysis

The water sampling and water quality analysis procedures were done in accordance with the standard methods for the examination of water and waste water [APHA *et al.,* 1995]. Grab samples were collected for turbidity, TSS and Faecal coliform analysis. Composite sampling was not feasible because the samples would have required refrigeration on site, which was not possible, otherwise sample characteristics can be altered if stored under normal temperature. The sampling was done manually. A portable HATCH 2000 Turbidimeter was used for measuring turbidity on site.

(ii) Data analysis

Turbidity was reported as daily averages although measurements were done only during the day time. It was not possible to monitor turbidity for 24 hours per day since it was feasible to acquire online measuring equipment. A log-scale was used for the vertical turbidity scale on the turbidity versus time plots for URFL because of the wide variations between the raw water and filtrate turbidity levels. A normal plot could not clearly distinguish the raw water and filtrate turbidity lines. Standard deviations (%) of the daily turbidity values were also calculated and indicated in the plots.

Total suspended solids and faecal coliform samples were usually analysed in duplicate to increase the precision of the results. The former are presented in tables and the latter in block diagrams, since they were not monitored on a daily basis.

3.6 Manning of pilot plant Iolanda

From the date of commissioning, the plant was monitored by the author and one plant operator. The operator was one of the local personnel engaged during the construction of the pilot plant and had established a good understanding of the pilot plant details. He was given adequate on the job training on how to operate and maintain the pilot plant, and how to measure turbidity, with the portable Turbidimeter. To motivate and stimulate the operator, he was given a monthly allowance. In his absence, usually at night, the LWSC guards at the

Iolanda Water Works intake area assisted in manning the plant. The author used to visit the plant at least three days a week while the pilot plant operator was there every day from 07:00 - 18:00 hours Zambian time. The overall tasks of the operator are summarized in Table 3.6-1.

Table 3.6-1: Responsibilities of the operator of pilot plant *Iolanda*

Frequency	**Activity**
Daily	• keeping the pilot plant area tidy • check flow to each unit through Rotameters and adjust to desired values • clean Rotameters to ensure correct readings • measure turbidity levels in both influents and effluents of each filter unit • check and record head-losses in each filter
Weekly	• Clean inlet and outlet boxes of the URFL units. The operator ensured that the wash water overflowed to drain. • Clean raw water tanks. • Clean SSF rotameters

The cleaning of the URFL and SSF filter media was entirely done by the author with the help of the operator because pertinent observations and sampling, beyond the capability of the operator, were necessary.

Chapter four

RESULTS AND DISCUSSIONS

4.1 General

This chapter presents and discusses results of the investigations on pilot plant *Iolanda*, with reference to the literature reviewed. The main purpose of URFL is to lighten the turbidity and suspended solid loads on the subsequent SSF, hence these water quality parameters were emphasised. The removal of turbidity along the filter-bed of URFL was analysed at a filtration rate of 0.50 m/h to study the performance of each gravel layer. The experiences with the operation and maintenance aspects of pilot plant *Iolanda* are also presented and discussed.

4.2 Turbidity and total suspended solids reduction

The data on turbidity monitoring is presented graphically in this section. The numerical data is given in Appendix B for all the trial results. All TSS data is presented in form of tables.

4.2.1 Up-flow roughing filters in Layers

a) Trial one [02-26 March 1997]: filtration rate, $v_f = 0.40$ m/h

For turbidity analysis results in raw water and URFL filtrates, see in Figures 4.2-1 & 4.2-2.

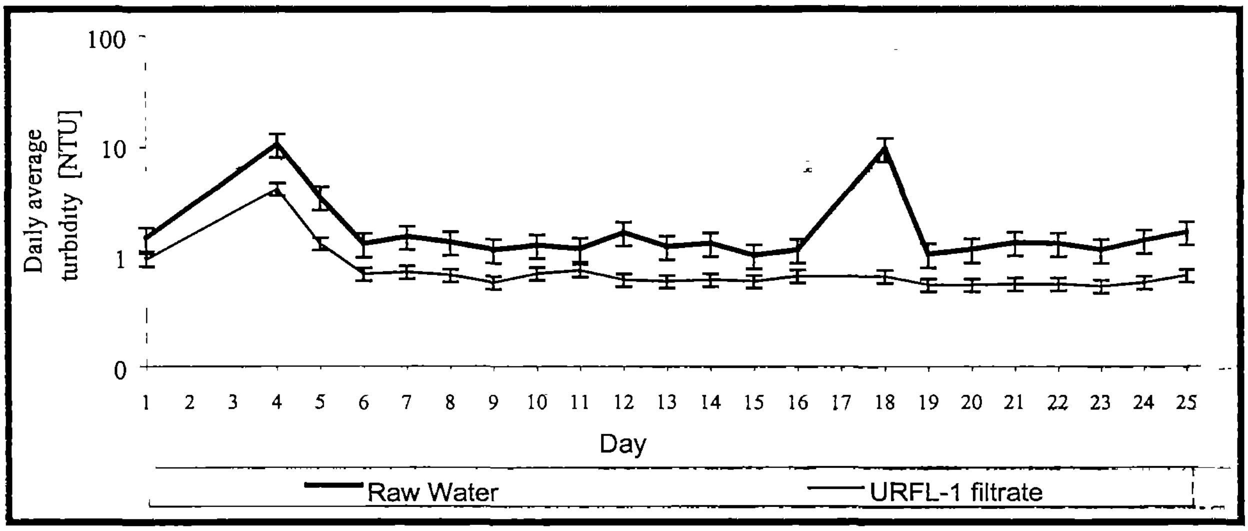


Figure 4.2-1: Trial 1- Turbidity levels in raw water and URFL-1 filtrate (v_f=0.4m/h)

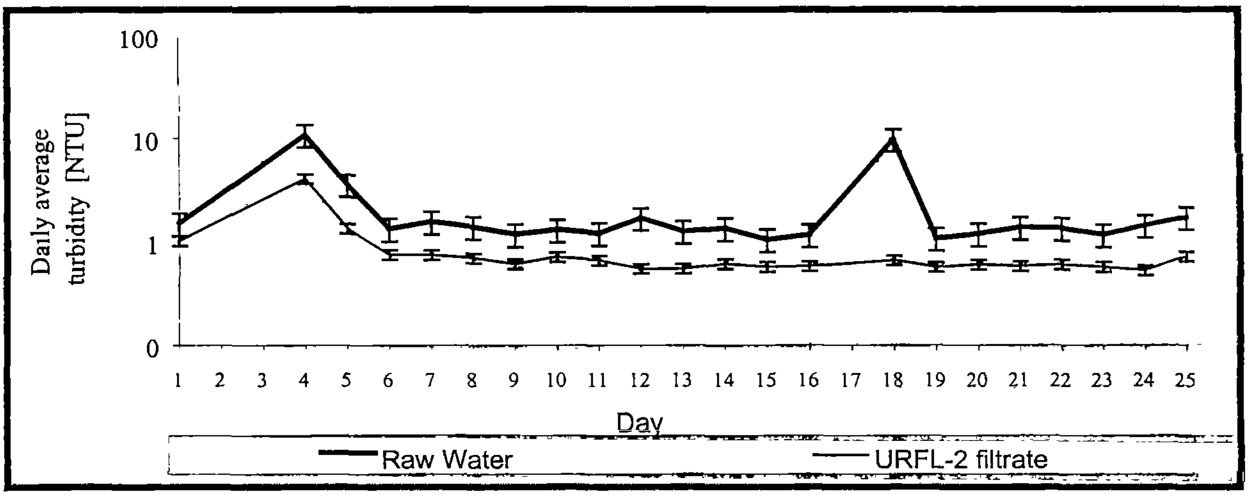


Figure 4.2-2: Trial 1- Turbidity levels in raw water and URFL-2 filtrate(v_f= 0.4m/h)

Both URFL units received unsimulated raw water (*Kafue* River). On days 2, 3 and 17, no measurements were taken due to problems with the turbidimeter. The higher raw water turbidity levels on day 4, were due to suspected run-off up-stream of the Kafue river. However, raw water turbidity levels became stable after day 6. On day 18, the higher turbidity occurred after cleaning the raw water tanks. It was possible that sediments, not completely washed out, within the pipes caused this increase.

The removal efficiencies of turbidity generally ranged from 41-62% and 43-67% for URFL-1 and URFL-2, respectively. However, on the first day, URFL-1 and URFL-2 recorded the lowest removal efficiencies of 36% and 32% respectively. These initial low removal efficiencies can be attributed to the fact that the filter-media were still undergoing self-cleansing since the filters were run for the first time. It is was not practically possible to use filter-media which were 100% clean. Despite the sharp increase in raw water turbidity on day 18, the filtrate turbidity from both filters was consistent with previous levels and a highest removal of 93% was recorded on this day. This may indicate the ability of URFL to handle sharp loads of turbidity, and a fact that the process is stable. For chemical pre-treatment processes, their performances are usually dependent on raw water quality. Variations in raw water quality for these systems causes operation problems since chemical dosages would then need adjustments.

b) Trial Two[27$^{Th.}$ March-15$^{Th.}$ April 97]: filtration rate; $v_f = 0.75$ m/h,

Figures 4.2-3 & 4.2-4 show turbidity levels in raw water and URFL filtrates during Trial-2.

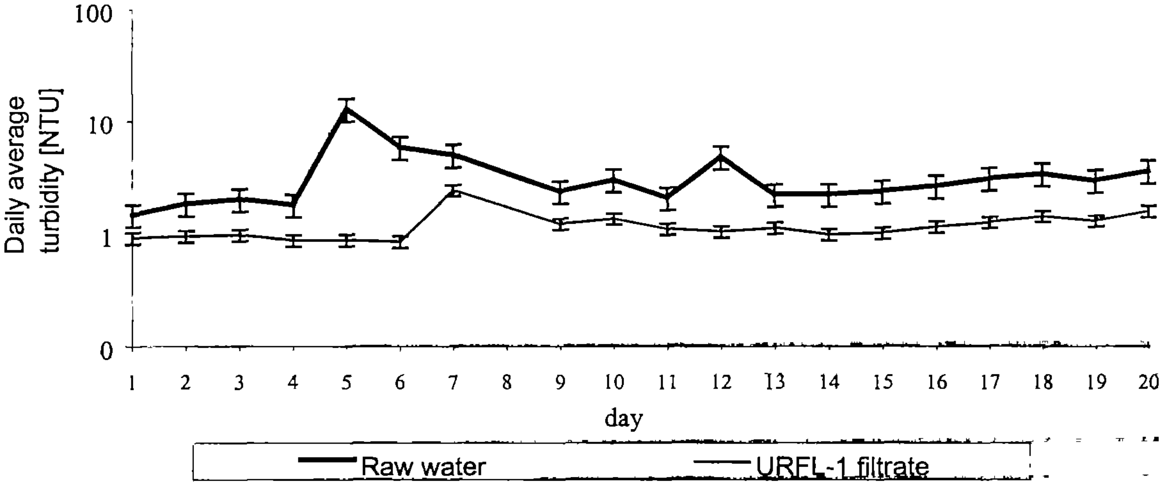


Figure 4.2-3: Trial 2- Turbidity levels in raw water and URFL-1 filtrate(v_f= 0.75m/h)

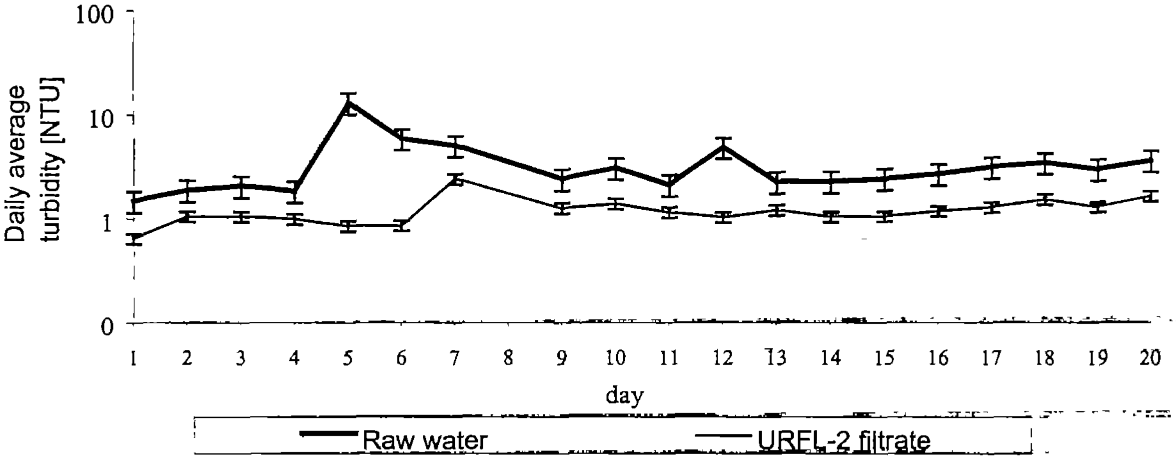


Figure 4.2-4: Trial 2- Turbidity levels in raw water and URFL-2 filtrate(v_f= 0.75m/h)

Removal efficiencies ranged from 38-93% and 44-93% for URFL-1 and URFL-2, respectively. On day 5, raw water turbidity increased after cleaning the raw water tanks. Two days after day 5 (see day 7 in both Figures 4.2-3 and 4.2-4), filtrate turbidity increased and after day 9 it became stable again. This phenomenon could not be explained scientifically. However, operation problems maybe attributed to this strange observation even though the pilot plant operator did not report any. A mistake in measurement was ruled out because filtrate turbidities on day 7 were consistently greater than 2 NTU during

the period of monitoring. The only possibility was that the filtration rate might have been set at a slightly higher rate than before. This can cause deep penetration of colloidal particles and their breakthrough.

c) Trial Three [16$^{Th.}$ April- 2nd May 1997]: filtration rate: $v_f = 0.50$ m/h

URFL-1 and URFL-2 were fed with unsimulated and simulated raw water respectively.

i) Turbidity simulations were started for the raw water fed to URFL-2. Turbidity levels in the raw water and URFL filtrates are shown in Figures 4.2-5 and 4.2-6.

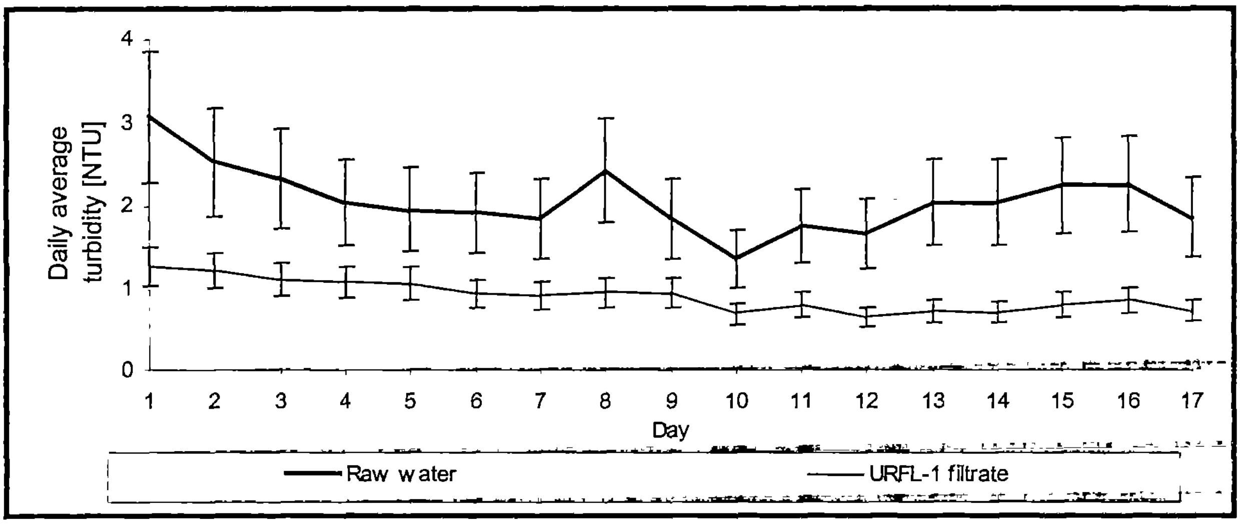


Figure 4.2-5: Trial 3- Turbidity levels in raw water and URFL-1 filtrate (v_f = 0.5m/h)

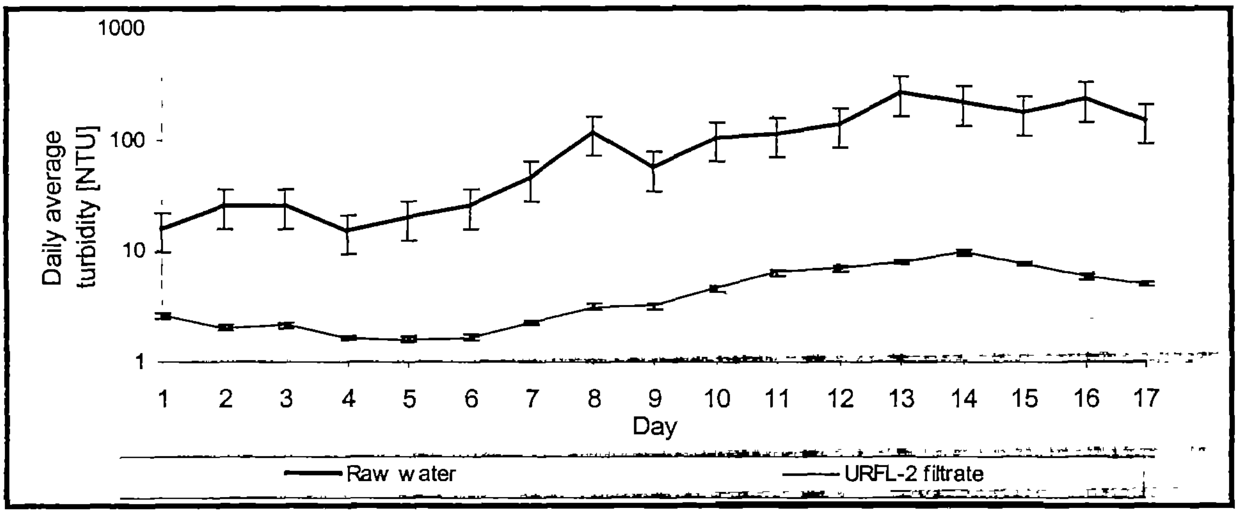


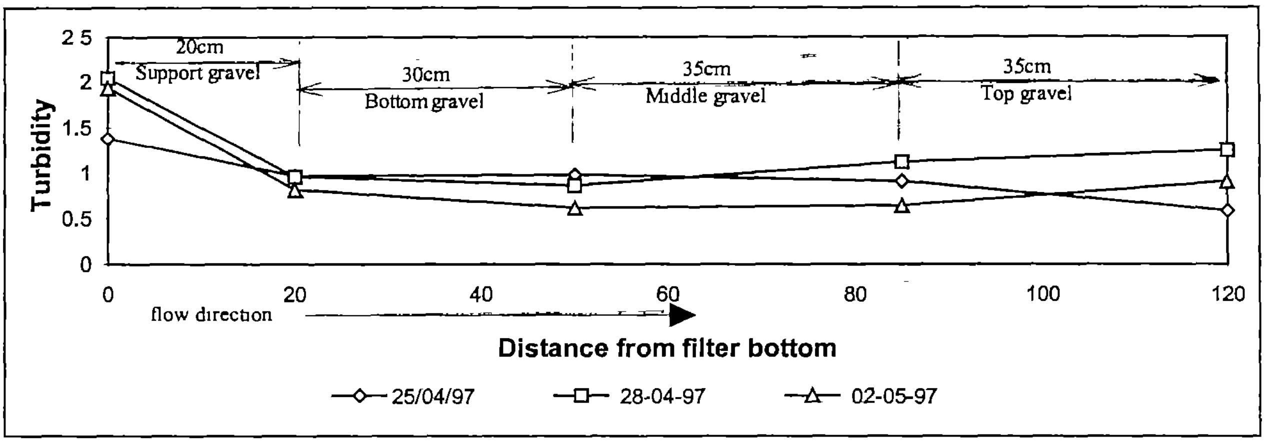
Figure 4.2-6: Trial 3- Turbidity levels in raw water and URFL-2 filtrate(v_f = 0.50m/h)

URFL-1 and URFL-2 reduced raw water turbidity by 45-73 % and 83-97 % respectively. The different removal efficiencies are attributed to the different raw water quality: URFL-2 was fed with simulated raw water. The high removal efficiencies recorded by URFL-2 do not mean better filtrate quality. URFL-2 filtrate turbidities were higher than those of URFL-1 although the filters were run at the same filtration rates. This reveals how filter performance relies on the raw water quality. These results indicate that high turbidity raw water is likely to cause turbidity breakthroughs faster than low turbidity raw water. The filtrate turbidity of URFL-2 was increasing with increasing raw water turbidity (see Figure 4.2-6). The capability of URFL in treating raw water turbidities from 150-350 NTU is shown in Figure 4.2-6, from day 13.

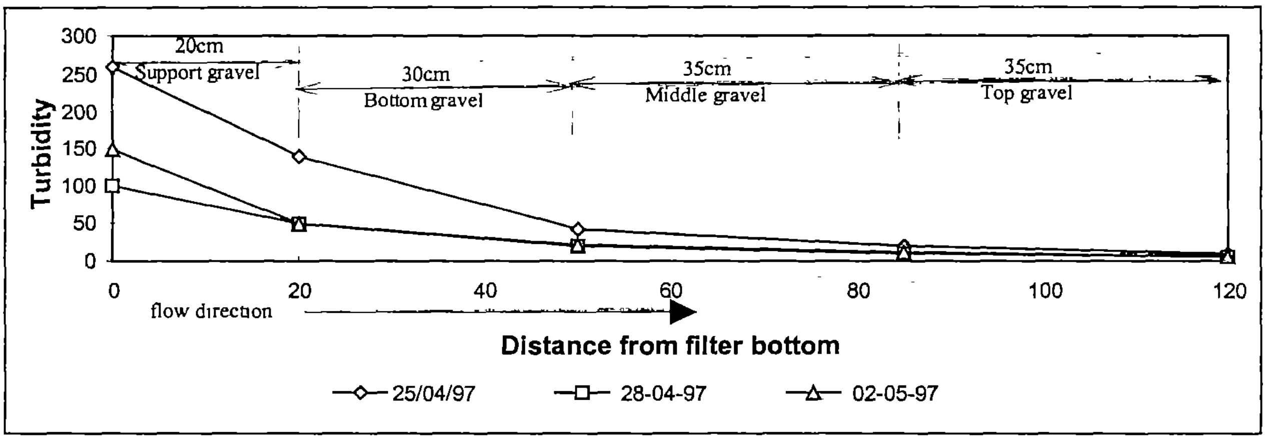
Turbidity levels through URFL filter-beds were evaluated (see Table 4.2-1 and Figure 4.2-7). This evaluation was done to have an idea of how each gravel layer reduces turbidity.

Table 4.2-1: Trial 3- Turbidity levels and removals along URFL filter-beds

Date	Turbidity (NTU)									
	Low turbidity raw water(URFL-1)					High turbidity raw water(URFL-2)				
	Raw Water	Support Gravel effluent	Bottom gravel effluent	Middle gravel effluent	Top gravel effluent	Raw Water	Support Gravel effluent	Bottom gravel effluent	Middle gravel effluent	Top gravel effluent
25/4/97	1.37	0.96	0.98	0.91	0.58	259	140	41.7	19.1	9.61
28/4/97	2.04	0.95	0.86	1.12	1.24	101	48.9	20.1	9.77	5.43
02/5/97	1.93	0.81	0.62	0.64	0.91	150	48.8	20.5	10.8	6.12
Turbidity removal range (%) →		**30 to 60**	**-2 to 23**	**-30 to 7**	**-42 to 36**		**45 to 70**	**60 to 70**	**50 to 55**	**40 to 50**



(a) Low turbidity raw water (<2.5 NTU): URFL-1



(b) High turbidity raw water (100-260 NTU): URFL-2

Figure 4.2-7: Turbidity reduction along URFL filter-beds

The results in Table 4.2-1 and Figure 4.2-7 reveal that each gravel layer plays a role in improving the raw water quality. From Figure 4.2-7(a), it was deduced that for low turbidity raw water (< 2.5 NTU in this case), the support gravel removes most of the turbidity and subsequent layers hardly remove turbidity. For highly turbid raw water (100-260 NTU in this case), again the support gravel showed remarkable turbidity reduction, but not to levels acceptable by SSF. Subsequent bottom and middle gravel layers further reduced turbidity, while the top layer merely acted as a polishing layer. This kind of performance corresponds to what *Wegelin* (1996) reports: each gravel layer lightens the turbidity and suspended solids load to the subsequent layer. These results also revealed that; despite the large gravel size of the support gravel layer, it does not just support the bottom gravel but also plays a significant role in reducing turbidity, and most likely total suspended solids (measurements not taken) as well. Although most of the suspended solids

which easily settle were removed within the raw water simulation tank (by allowing for at least one hour settling before simulating), the fact that the support gravel shows higher removals due to high levels of easily settled solids can not be ruled out. It is definite that with highly colloidal particles in raw water, the support layer can show lower turbidity reductions because of the high porosity gravel in this layer.

ii) After applying simulated raw water to URFL-2, levels of TSS in the raw water and URFL-2 filtrates were evaluated since TSS levels in the raw water were then appreciable (see Table 4.2-2).

Table 4.2-2: Trial 3- Total suspended solids reduction by URFL-2 ($v_f = 0.50$)

Date	**Influent TSS (mg/L)**	**Effluent TSS (mg/L)**	**% Reduction**
16.04.97	25.5	0	100
18.04.97	98.5	1.3	99
21.04.97	47.5	2.5	95
25.04.97	171.2	2.2	99
28.04.97	552.3	5.7	99

TSS were reduced to levels suitable for SSF. The results in Table 4.2-2 generally meet the upper TSS limit (5 mg/L) recommended by *Wegelin* (1996) except for the April 28, 1997 result (see Table 4.2-2). Nevertheless, these results are comparable to results reported in Colombia (see Table 2.4-3) and demonstrate that the performance of URFL can be compared to that of URFS, HRF and DRFS. TSS removals in Table 4.2-2 are higher than those obtained in the study by *Rietveld* and *Matsinhe* (1993) who report 50-90% for URFL. However in their study, raw water TSS level ranged from 5-40 mg/L compared to pilot plant *Iolanda* levels which went up to ~ 600 mg/L. This performance difference maybe due to the fact that *Rietveld* and *Matsinhe* (1993) used coarser gravel for URFL (5-38 mm) compared to general recommendations (1.6-25 mm). Additionally, their filter media were not supported by any coarser gravel, which is capable of removing part of TSS as was evidenced in this study.

d) Trial Four [4$^{Th.}$ - 30 $^{Th.}$ May 1997]: filtration rate: $v_f = 0.75$ m/h

i) For turbidity analysis results in raw water and URFL filtrates, see Figures 4.2-8 & 4.2-9.

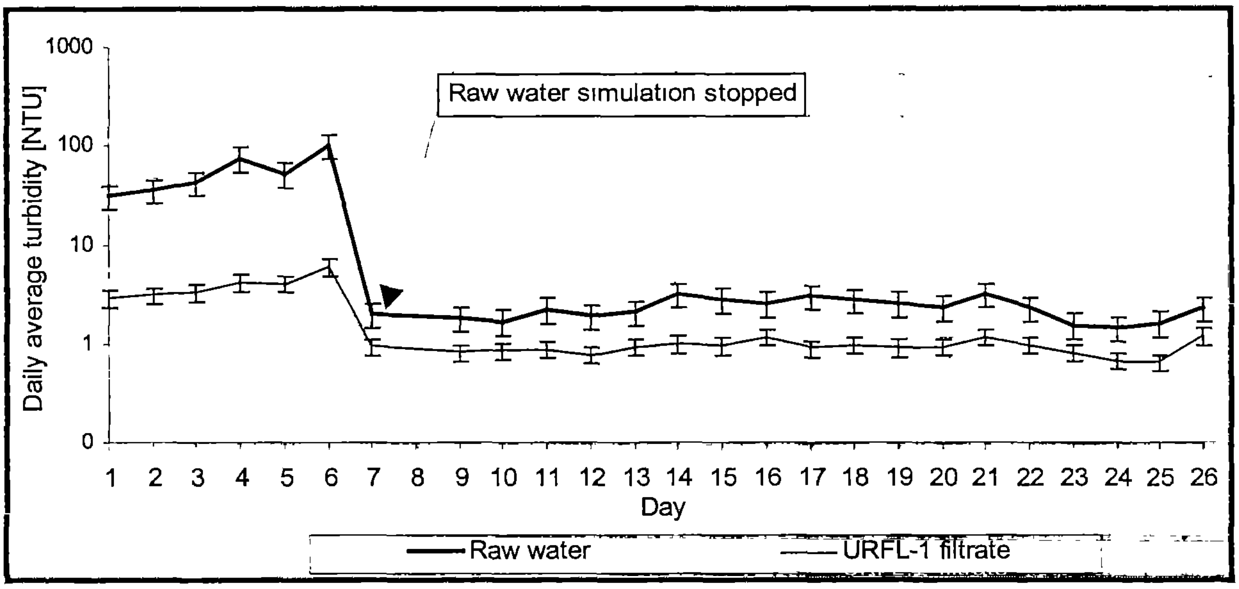


Figure 4.2-8: Trial 4- Turbidity levels in raw water and URFL-1 filtrate(v_f = 0.75m/h)

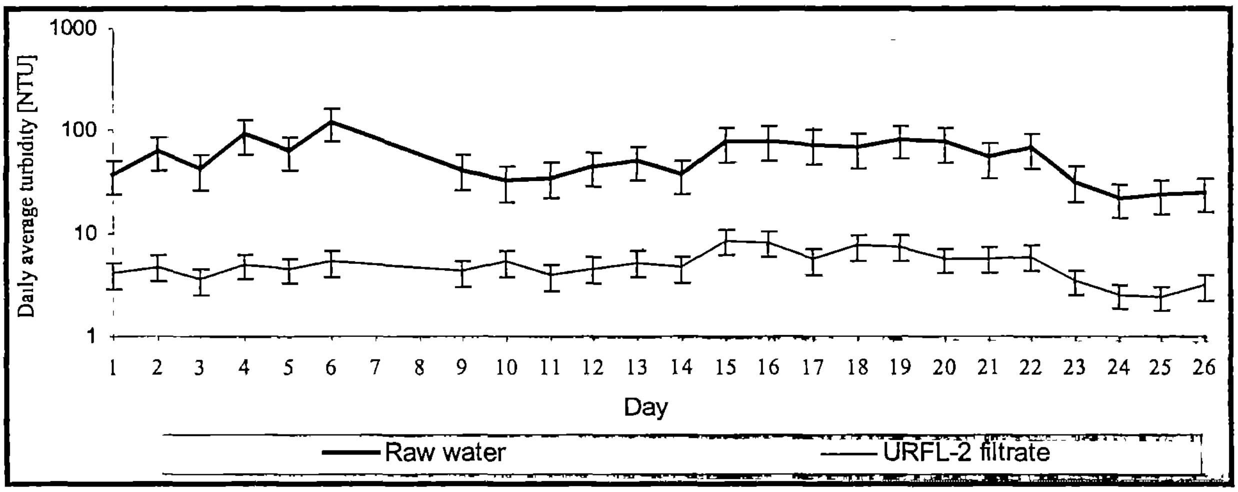


Figure 4.2-9: Trial 4- Turbidity levels in raw water and URFL-2 filtrate(v_f = 0.75m/h)

During Trial 4, the high turbidity simulation pump to URFL-1 broke down on Day 6, thereafter *Kafue* River water was fed to URFL-1(Figure 4.2-8). The sharp drop in raw water turbidity after stopping simulation(Figure 4.2-8), corresponded to sharp drops in URFL-1 filtrate turbidity. This shows how the raw water quality can affect filtrate quality. In Figure 4.2-8, high turbidity raw water (30-101 NTU) was reduced by 91-95 % and low

turbidity raw water (1.41-3.11 NTU) was reduced by 48-70%. Despite the difference in the removal efficiencies, all URFL-1 filtrates had turbidity less than 10 NTU, acceptable for SSF. Turbidity of the simulated raw water (22-123 NTU) fed to URFL-2 was reduced by 84-96%, with all filtrates having turbidity less than 10 NTU. Here, the process stability was demonstrated by the stable filtrate quality despite fluctuating raw water turbidity.

ii) TSS reductions were also analysed on three days. Removal efficiencies above 98% were recorded (see Table 4.2-3). URFL filtrates had less than 5 mg/L TSS, acceptable for SSF.

Table 4.2-3: Trial 4- Total suspended solids reduction by URFL-2 (v_f = 0.75m/h)

Date	Influent TSS(mg/L)	Effluent TSS(mg/L)	% Reduction
22.05.97	48. 7	0.5	99
28.05.97	98.5	1.3	99
30.05.97	47.5	2.5	98

e) Trial Five [31st May - 30Th June 1997]: Filtration rate, v_f = 1.0. m/h,

i) For turbidity analysis results in raw water and URFL filtrates, see Figures 4.2-10 & 4.2-11.

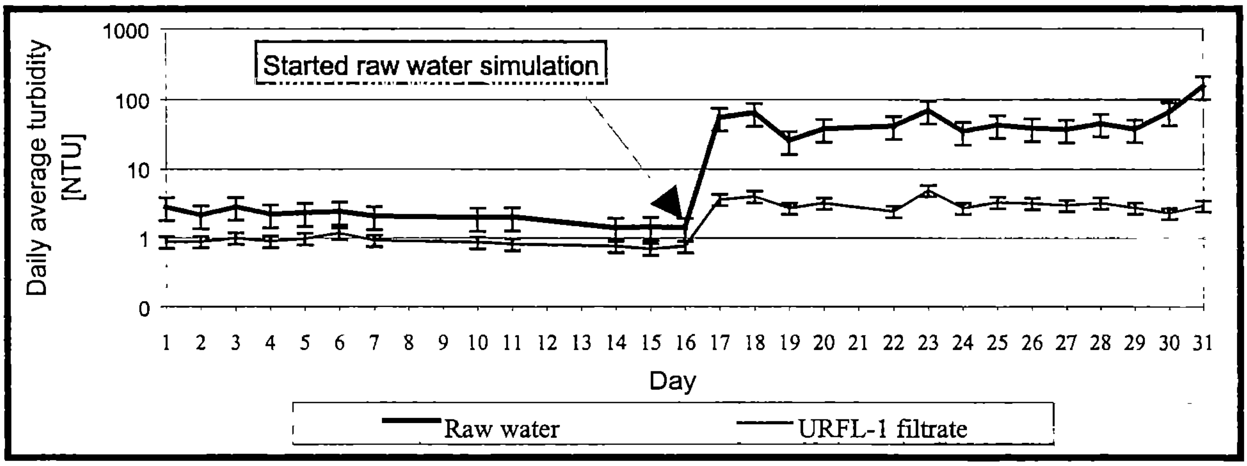


Figure 4.2-10: Trial 5- Turbidity levels in raw water and URFL-1 filtrate(v_f =1.0 m/h)

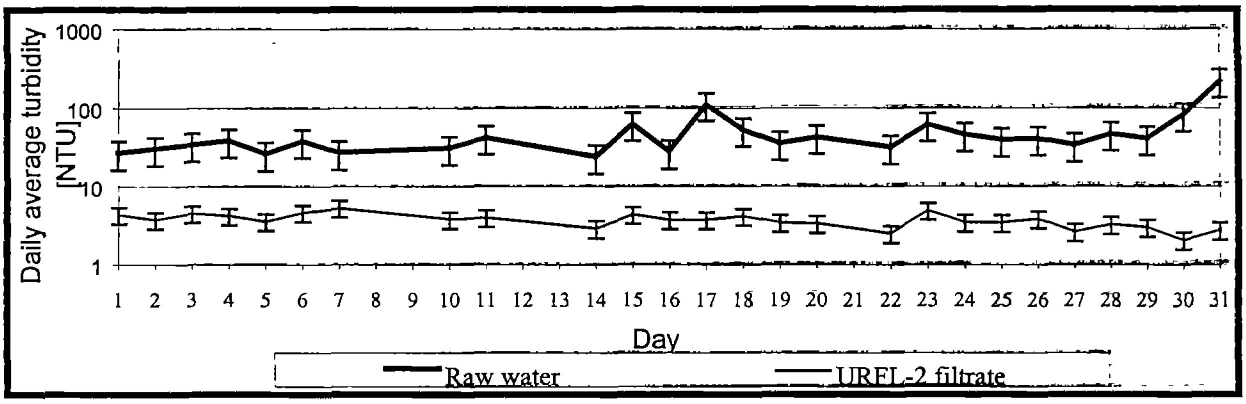


Figure 4.2-11: Trial 5- Turbidity levels in raw water and URFL-2 filtrate(v_f =1.0 m/h)

For URFL-1, the removal efficiency with the actual *Kafue* River water (1.4-2.82 NTU) was 45 - 68 % and with the simulated raw water (25-156 NTU) it was 89-98%. Turbidity removals by URFL-2 (Figure 4.2-11) ranged from 80-99%. In both filters, filtrate turbidity was less than 5 NTU, suitable for SSF.

ii) Total suspended solids reductions were also analysed (see Table 4.2-4). URFL-1 and URFL-2 removal efficiencies ranged from 83.3 to 98.6 % and 89.8 to 99.8 % respectively. All URFL filtrates had less than 5 mg/L TSS, acceptable for SSF.

Table 4.2-4: Trial 5- Total suspended solids reduction by URFL (v_f = 1.0m/h)

Date	URFL-1			URFL-2		
	Influent	Effluent	% Reduction	Influent	Effluent	% Reduction
04/06/97	5.500	0.167	97.0	58.833	4.600	92.2
09/06/97	not taken	- not taken	-	178.500	1.300	99.3
13/6/97	- not taken	- not taken	-	149.250	0.500	99.7
16/6/97	46.667	- not taken	-	58.000	0	100.0
20/6/97	16.800	2.800	83.3	17.600	1.800	89.8
23/6/97	73.750	1.000	98 6	- not taken	not taken	-
25/6/97	57.750	2.400	95.8	50.200	1.200	97.6
27/6/97	150.500	3.200	97.9	302 200	4.800	98.4
30/6/97	122 000	2.200	98.2	212.000	0.400	99.8

f) Trial Six [1^{st}-$18^{Th.}$ May 1997]: filtration rate, $v_f = 1.25$

i) For turbidity analysis results in raw water and URFL filtrates, see Figures 4.2-11 & 4.2-12.

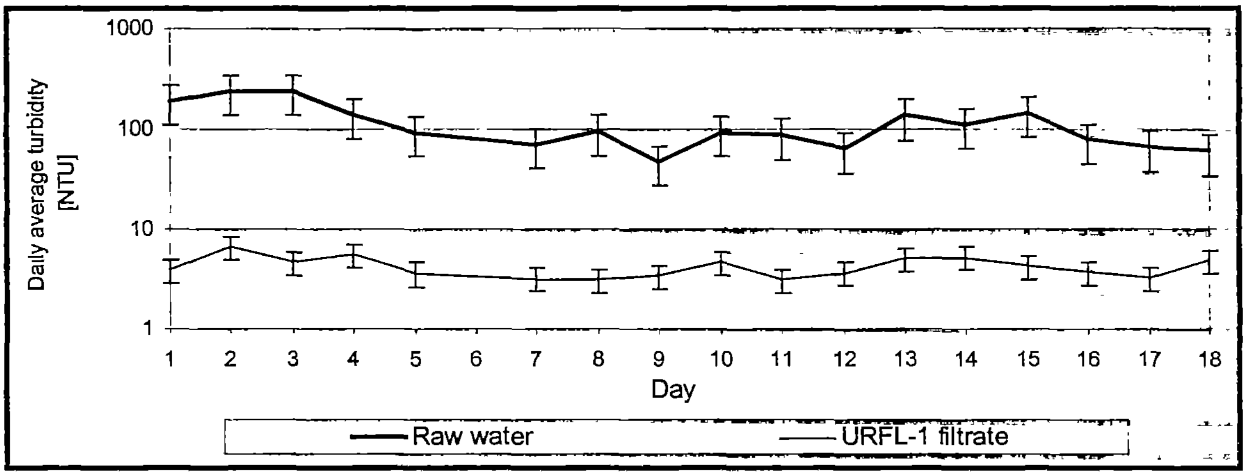


Figure 4.2-12: Trial 6- Turbidity levels in raw water and URFL-1 filtrate(v_f=1.25m/h)

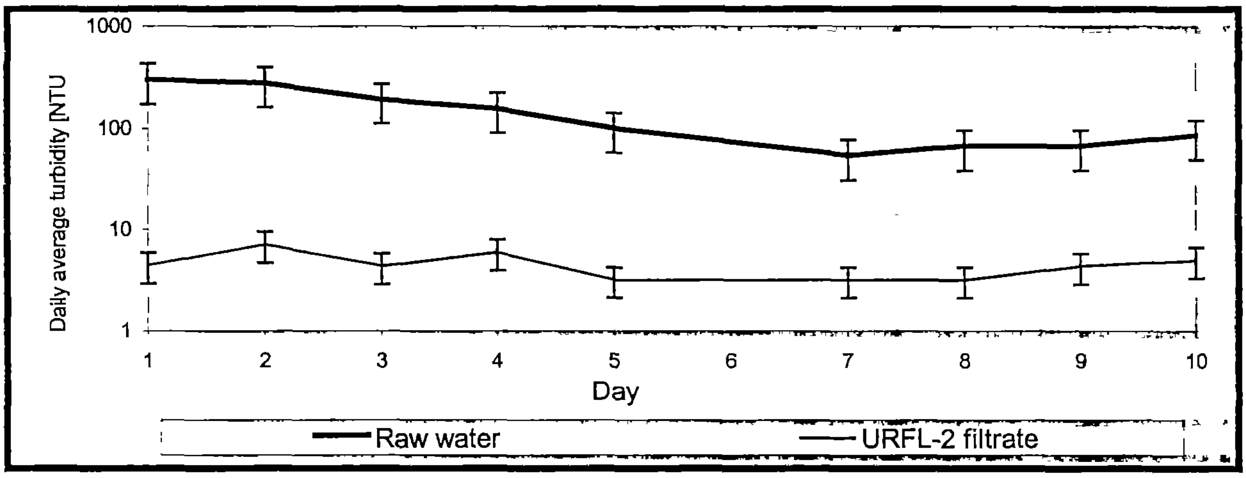


Figure 4.2-13: Turbidity levels in raw water and URFL-2 filtrate (v_f = 1.25m/h)

Turbidity removal efficiencies in Figures 4.2-12 and 4.2-13 range from 92-98% and 94-98%, respectively. The daily average turbidities of the filtrates ranged from 3-7 NTU which was acceptable for SSF. Although URFL generally employs rates up-to 1m/h (*Wegelin,* 1996; *Galvis et al.,* 1993), the comparable performances of the two URFL units at 1.25 m/h indicate that URFL can also perform at rates higher than 1.0 m/h.

ii) Analysis results of TSS are given in Table 4.2-5.

Table 4.2-5: Total suspended solids reduction by URFL(v_f=1.25m/h)

Date	URFL-1			URFL-2		
	Raw water TSS (mg/L)	Filtrate TSS (mg/L)	% Removal	Raw water TSS (mg/L)	Filtrate TSS (mg/L)	% removal
02/07/97	606.7	8.8	98 6	1684.0	11.0	99.4
04/07/97	442.0	16.2	96.3	482.0	20.6	95.7
07/07/97	166.5	8.8	94.7	144.8	12.8	91.2
11/07/97	72.4	3.8	94.8	-not taken	- not taken	-
16/07/97	140.5	1.3	99.1	- not taken	- not taken	-
18/07/97	76.5	1.4	98.2	- not taken	- not taken	-

In some samples, filtrate TSS levels were higher than the recommended upper limit of 5 mg/L, although removal efficiencies were high (91-99%). Hence, URFL cannot perform effectively at filtration rates higher than 1 m/h. Such filtration rates are likely to cause breakthrough of suspended solids because of the reduced retention times.

g) Trial Seven [19$^{Th.}$ - 31st May 1997]: filtration rate, v_f = 0.5m/h.

i) URFL were tested again in treating higher turbidity levels than in Trial-3. Analysis results of raw water and filtrate turbidity are given Figures 4.2-14 and 4.2-15.

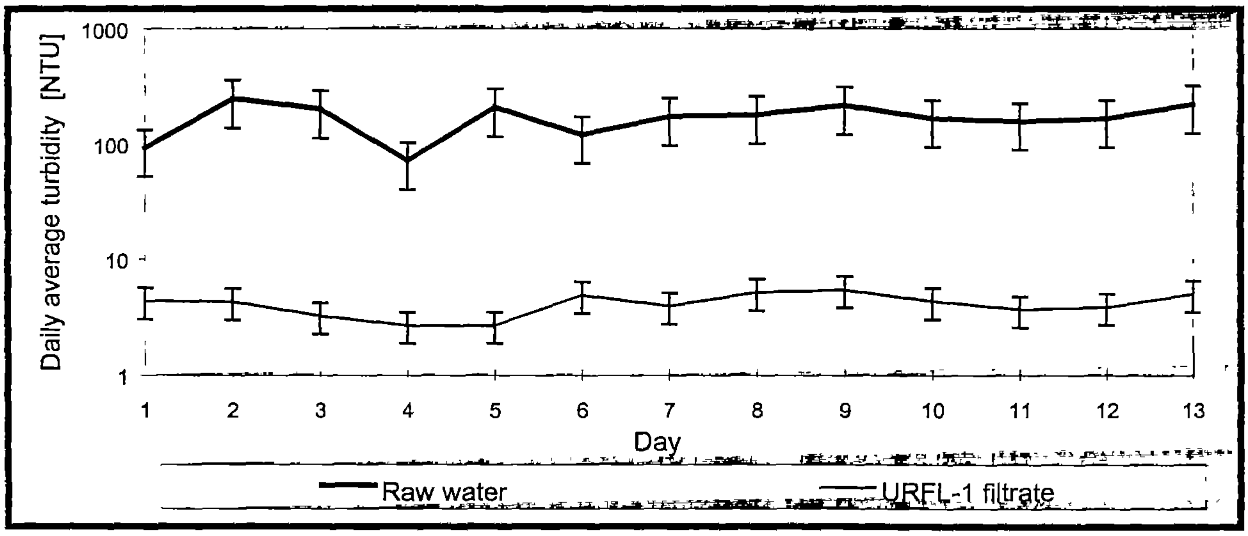


Figure 4.2-14: Trial 7- Turbidity levels in raw water and URFL-1 filtrate(v_f=0.5m/h)

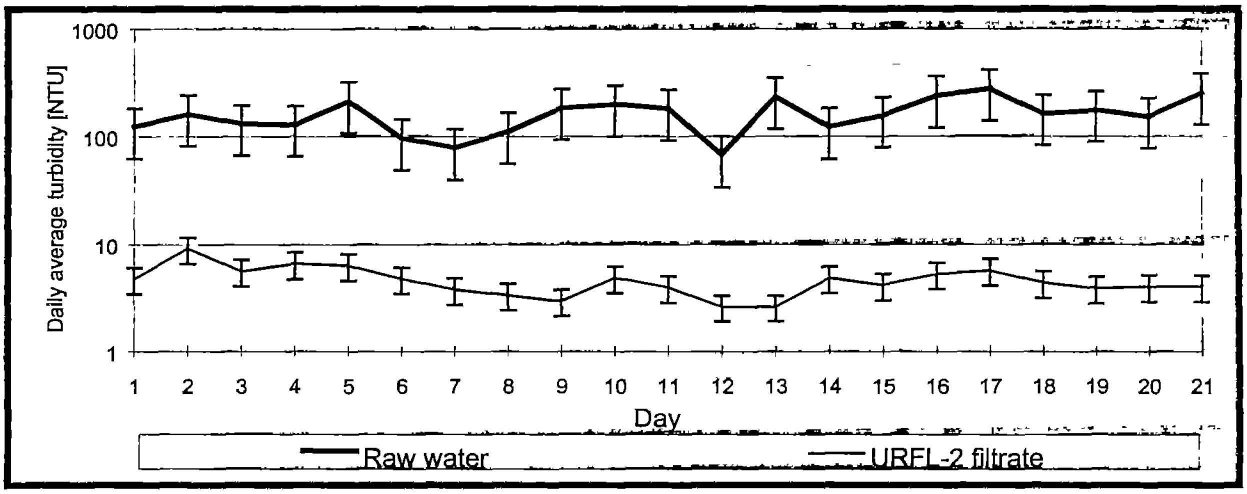


Figure 4.2-15: Trial 7- Turbidity levels in raw water and URFL-2 filtrate(v_f=0.5m/h)

Turbidity removal efficiencies in Figures 4.2-14 and 4.2-15 range from 94-98% and 94-99% respectively, with filtrate turbidity ranging from 3-9 NTU. Both URFL units show similar and acceptable performances, despite the raw water being above 100 NTU most of the time. These results reveal the ability of URFL to handle high turbidity raw water.

ii) Analysis results of TSS in raw water and URFL filtrates are given Table 4.2-6,

Table 4.2-6: Trial 7- Total suspended solids reduction by URFL-2(v_f = 0.50)

Date	URFL-2		
	Raw water TSS (mg/L)	Filtrate (mg/L)	% Removal
11/07/97	84.5	6.8	92.0
14/07/97	309.3	17.3	94.4
16/07/97	539.5	1.2	99.8
18/07/97	408.0	8.3	98.0
21/07/97	643.5	1.0	99.8
23/07/97	330.0	0.8	99.8

TSS levels in raw water were reduced to below 5 mg/L in 50 % of the samples taken (see Table 4.2-6). The higher than 5 mg TSS /L in the other samples could be attributed to the no-washing of the filter before starting on trial 7. Hence, re-suspension of previously retained solids was likely in this case.

h) Overview of turbidity removal efficiencies by URFL

The performance of pilot plant *Iolanda* with respect to turbidity removal at the various filtration rates is summarised in Tables 4.2-7 and 4.-2-8.

Table 4.2-7: URFL turbidity removal efficiencies (actual *Kafue* River water)

Filtration rate (m/h)	Raw water turbidity (NTU)		Filtrate turbidity (NTU)		Removal efficiency(%)	
	URFL-1	URFL-2	URFL-1	URFL-2	URFL-1	URFL-2
0.40	1 04-10.67	1.04-10.67	0 55-4.21	0 53-4.05	36-93	32-93
0.50	1.48-5.84	1 48-5.84	0 85-2.45	0 64-2.39	39-85	44-85
0.75	1.37-12 85	not done	0 66-1 27	not done	45-73	-
1.0	1 40-2.82	not done	0.70-1 17	not done	45-68	-

Table 4.2-8: URFL turbidity removal efficiencies (simulated raw water)

Filtration rate(m/h)	Raw water turbidity (NTU)		Filtrate turbidity (NTU)		Removal efficiency(%)	
	URFL-1	**URFL-2**	**URFL-1**	**URFL-2**	**URFL-1**	**URFL-2**
0.50	not done	15-260	not done	1.58-9.61	-	83-97
0.50[1]	71-245	67-277	2.67-5.42	2.62-9.07	95-99	94-99
0.75	30-101	22-123	2.82-5.85	2.39-8 42	91-93	84-96
1 0	25-156	24-220	2.22-4.49	2.06-5.28	89-98	80-99
1.25	27-240	54-299	3.02-6 65	3.23-7.13	93-98	94-98

From Tables 4.2-7 and 4.2-8, it is clear that URFL is able to improve both low and high turbidity raw water at filtration rates 0.4-1.25 m/h under the conditions of investigations. Throughout the period of investigations, filtrate turbidities were below 10 NTU, the general upper limit for raw water turbidity appropriate for SSF. These results are very comparable with those reported in literature. These results are better than those of chemical pre-treatment systems in most township water supply in Zambia. Most of these systems are reported to pre-treat raw water to turbidity greater than 10 NTU [*Holzhaus* and *Versteeg*, 1993]. However, for well operated chemical pre-treatment systems in Zambia, they can consistently produce pre-treated raw water having turbidity less than 5 NTU. For instance, the *Iolanda* Water Works (LWSC) usually pre-treats turbid raw water to less than 5 NTU turbidity throughout the year.

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[1] Trial 7 results: second investigation on $v_f = 0.5 m/h$

There was little difference in URFL turbidity removal efficiencies at different filtration rates. The filtrate quality still remained acceptable for SSF when pre-treating both low and high turbidity raw water.

The ability of URFL to pre-treat low turbidity raw water is an important aspect when compared to the use of chemical pre-treatment. Chemical pre-treatment of low turbidity raw water is usually more difficult and expensive. In practice, the efficiency of chemical pre-treatment to treat low turbidity raw water maybe improved by adding suitable clay to increase the turbidity. In most cases, more chemical dosages are usually applied instead, to compensate for the low particle concentration [*van Breemen,* 1994].

Some noticeable differences in turbidity removal efficiencies (even filtrate turbidity) at different filtration rates were expected when URFL were fed with simulated high turbidity raw water, but this was not so. From Table 4.2-8, the filtrate quality was acceptable for SSF and it cannot be pinpointed that one filtration rate performance was better than the other. Although it is reported in literature that there is little difference in performance at filtration rates less than 0.6m/h, the trend shown in Table 4.2-8 is probably due to the intermittent simulation. It is therefore likely that if simulation was 24 hours per day, a clear distinction in performance between filtration rates less and greater than 0.6 m/h could have be drawn. With increasing filtration rates, suspended solids are expected to penetrate the filter-bed more and affect the filtrate quality.

4.2.2 Slow sand filters

Turbidity analysis results in URFL filtrates (fed to SSF units) and SSF filtrates are presented in Figures 4.2-16 and 4.2-17 respectively. Most of the high turbidity simulations were done on URFL-2 which most of the time fed SSF-2. Comparatively, URFL-2 produced relatively higher filtrate turbidity than URFL-1.

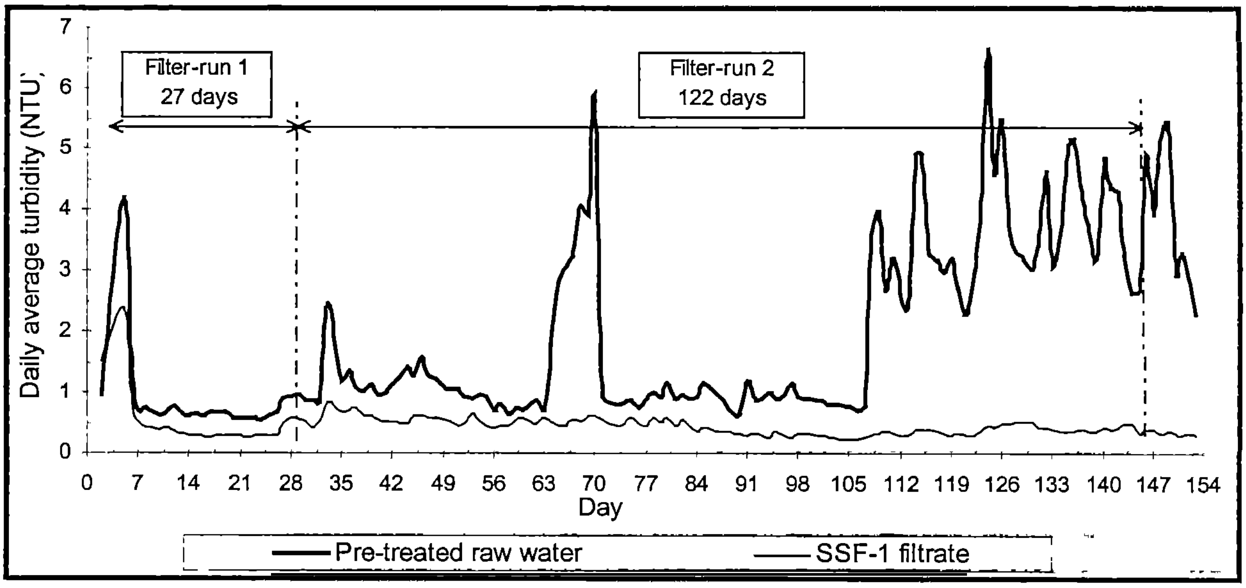

Figure 4.2-16: Turbidity levels in pre-treated raw water and SSF-1 filtrate

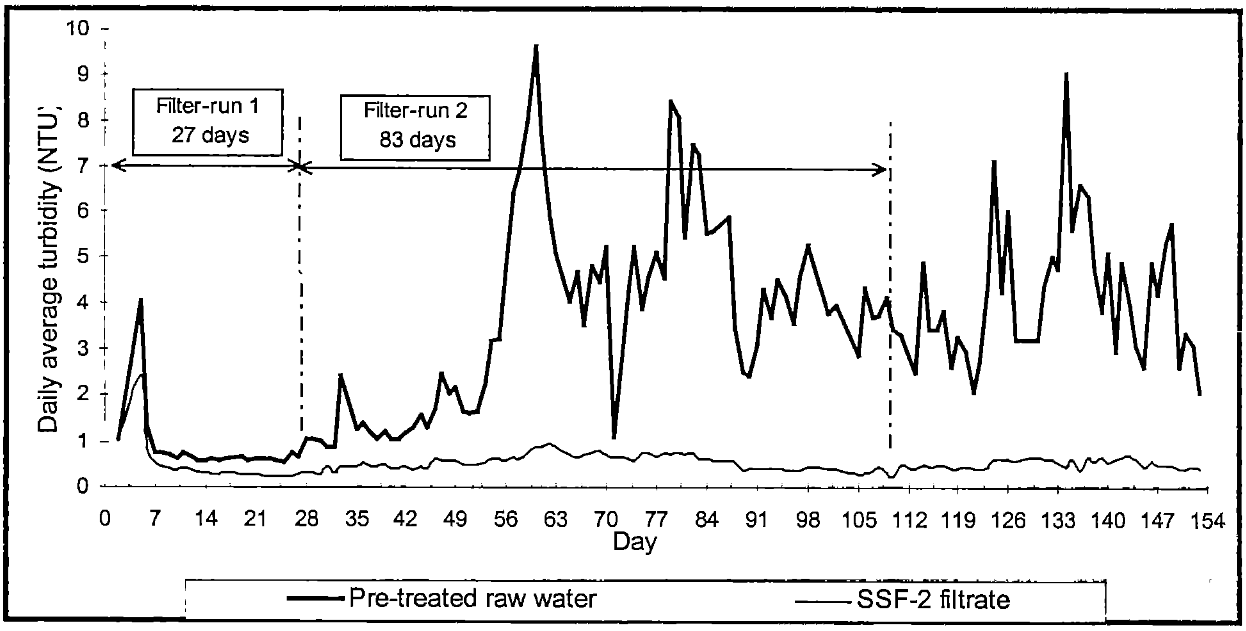

Figure 4.2-17: Turbidity levels in pre-treated raw water and SSF-2 filtrate

During the first four days of SSF operation, filtrate turbidities exceeded the upper limit of 1 NTU, recommended by WHO (1984) for effective disinfection by chlorination. This may have been a result of the fact that, after commissioning a slow sand filter, it is likely that the new sand was not very clean and that it tended to wash itself at the start of the filter.

However, four days later, the filtrate turbidity was reduced to less than 1 NTU. The period of self-washing of the filter-media will depend on how well the sand was cleaned before use. The four days achieved with pilot plant *Iolanda* can be considered acceptable compared to some studies done in Mozambique by *Rietveld* and *Matsinhe* (1993). Despite using very fine sand (d_e = 0.10 mm), they experienced self-washing periods of over three months and suspected that the used sand was not sufficiently washed. This is a clear testimony of the need to thoroughly wash sand meant for SSF before use.

The removal of turbidity by the SSF units is very acceptable. Filtrate turbidities were usually less than 1 NTU, meeting the WHO upper limit for effective disinfection. Compared to slow sand filters applied in some townships in Zambia, the performance of pilot plant *Iolanda* was better. This can be attributed to the adequate pre-treatment by URFL and the use of good filter media. The media used in most townships in Zambia is usually of poor quality and not graded [*Holzhaus* and *Versteeg,* 1993]

Both slow sand filters showed complete removal of suspended solids. The removal of turbidity and suspended solids took place almost entirely within the top 1-3 cm layer of the filter-bed. The mechanism responsible for this kind of removal was straining because the fine filter media did not allow deep penetration of turbidity and suspended solids. However, truly colloidal particles, smaller than the pore openings of the sand may penetrate the filter-bed [*Huisman*, 1989]. This is probably why the removal of turbidity by SSF was not 100%.

4.3 Head-loss development and filter-runs

4.3.1 Up-flow roughing filters in layers

a) Head-loss development

The maximum head-loss in both URFL units were below the maximum allowable (30 cm) throughout all trials (see Table 4.3-1).

Table 4.3-1: Head-loss development in up-flow roughing filters in layers

Trial No., URFL	Run time (days)	Filtration rate (m/h)	Head-loss (cm)
1, URFL-1	25	0.4	0-0.4
1, URFL-2	25	0 4	0-1.1
2, URFL-1	20	0.75	0-0.3
2, URFL-2	20	0.75	0-0.3
3, URFL-1	17	0 5	0-0.4
3, URFL-2	17	0.5	0-0.4
4, URFL-1	26	0 75	0-0.5
4, URFL-2	26	0.75	0-0.5
5, URFL-1	31	1.0	0-1.7
5, URFL-2	31	1.0	0-1.7
6, URFL-1	18	1.25	0-3.2
6, URFL-2	10	1.25	0-3 5
7, URFL-1	13	0.5	0-0 8
7, URFL-2	21	0.5	0.1-2.8

The highest head-losses in both filters occurred during Trial 6. These were 3.2 cm and 3.5 cm for URFL-1 and URFL-2, respectively. The low head-losses experienced in this study can be attributed to the raw water quality, since high turbidities and TSS were only applied by simulation during day time. If high turbidity and TSS raw water was continuously fed as is usually the case during rain seasons, higher head-loss developments could have been experienced resulting in noticeable filter-runs.

b) Filter-runs

The maximum head-loss or deterioration of filtrate to undesirable quality indicates the end of a filter-run. In this study, non of these criteria were met. The trial periods investigated are probably shorter than the actual filter-runs of URFL with respect to the conditions under which the study was done. It is likely that continuous feed of high turbidity raw water to URFL could have effected one of the final filter-run indicators. Filter-runs of about one week can be experienced under continuous high turbidity raw waters [*Wegelin,* 1996].

4.3.2 Slow sand filters

a) Head-loss development

Slow sand filters showed fluctuating head-losses. However, it was increasing with time due to progressive clogging of the filter-bed (see Figure 4.3-1).

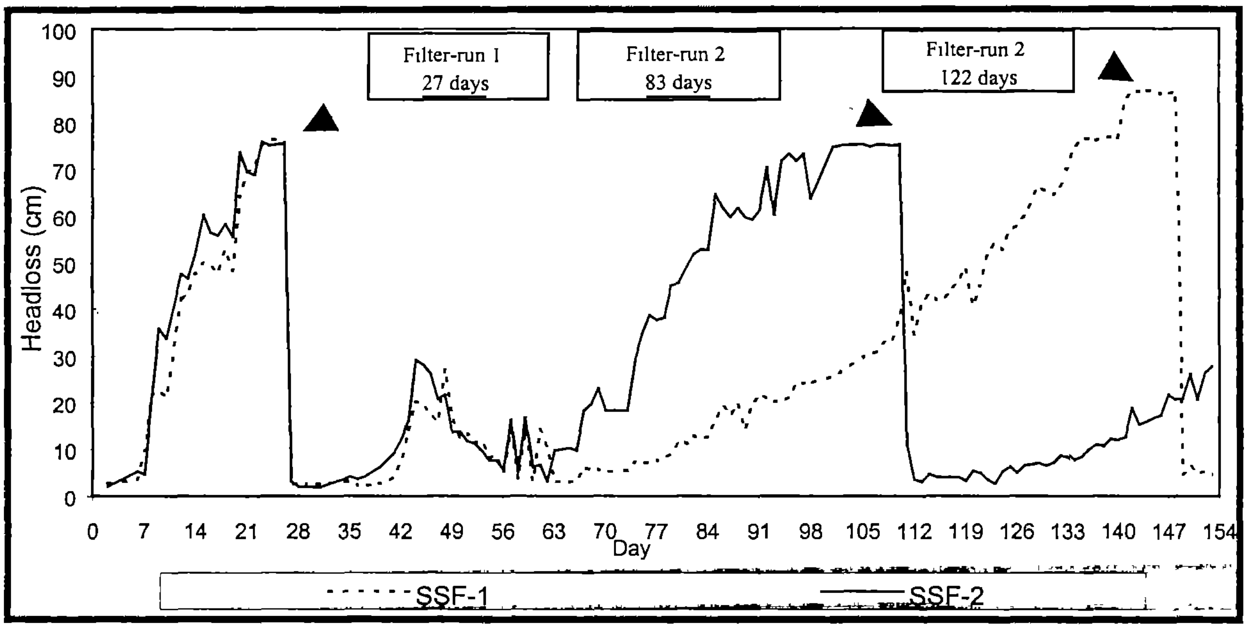

Figure 4.3-1: Head-loss development in pilot plant *Iolanda* SSF units

Initial head-losses ranged from 2.8 to 3.5 cm. Head-loss in both SSF units at the end of filter-run 1 was about 77 cm. In filter-run 2, SSF-1 and SSF-2 recorded 87 cm and 76 cm as maximum head-losses, respectively. The end of a filter-run was indicated by the supernatant water level reaching the set overflow point (see Figure 3.4-11).

The higher head-loss in SSF-1 at the end of filter-run-2 was due to the fact that even after the supernatant water level reached the set overflow point the filter was allowed to run for about two weeks since the filtration rate during this period was still acceptable (>0.1 m/h). The filter was taken out for cleaning after the filtration rate became less than 0.1 m/h (acceptable lower limit). Hence, when the supernatant water level in an inlet controlled slow sand filter reaches the set overflow, the filter may still run at acceptable rates.

Fluctuations in head-loss development could have been due to the frequent in-flow adjustment necessitated by algae and suspended solids depositions inside rotameters. Excessive

accumulations of these depositions slightly reduced inflow rates. Hence, rotameters had to be cleaned at least once a week. During cleaning, which took about 5 minutes, the supernatant water level was dropping leading to slight head-loss decreases.

b) Filter-runs

Filter-runs for the SSF units obtained in this study can be considered acceptable. The first filter-run for both slow sand filters was 27 days. The minimum recommended for optimal operation and maintenance is about one month (~30 days) [*Wegelin,* 1996]. The second filter-runs are also very acceptable: 83 days and 122 days for SSF-2 and SSF-1 respectively. The shorter filter-run 1, compared to filter-runs 2, for both filters was due to the rapid clogging caused by excessive algae growth during filter-run-1. During filter-run 1, SSF units were not covered and the sunlight which reached the supernatant water stimulated algae growth. However, during filter-run 2, the filters were shaded. This prevented excessive algae growth. SSF-1 showed a longer filter run-2 because it received less turbid influents, which were from URFL-1. Most of the simulations were done on URFL-2 and therefore, its filtrates were usually of higher turbidity than those of URFL-1.

Filter-runs for SSF were much higher than those reported for SSF applications in Zambia, which experience runs of not more than one month during the dry seasons and 2 weeks during the wet season (see Table 2.6-2). Some applications even have filter-runs as low as 3 days (see Table 2.6-2, Mansa Township). The high filter-runs obtained, compared to SSF applications in Zambia, are due to adequate pre-treatment provided by URFL.

4.4 Micro-biological performance

The micro-biological performance was assessed by analysing the levels of faecal coliforms (FC). Analysis results are tabulated in Appendix C.

4.4.1 Up-flow roughing filters in layers

Analysis results of FC in raw water and URFL filtrates are shown in Figures 4.4-1 and 4.4-2.

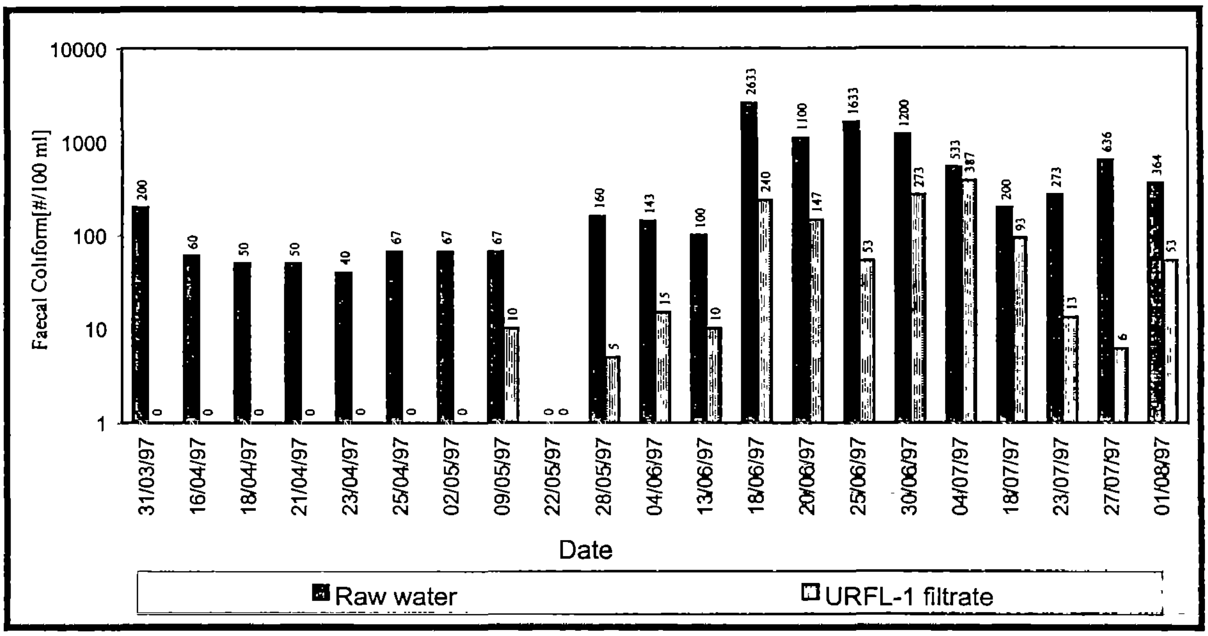

Figure 4.4-1: Faecal Coliform numbers/100 ml of raw water and URFL-1 filtrate

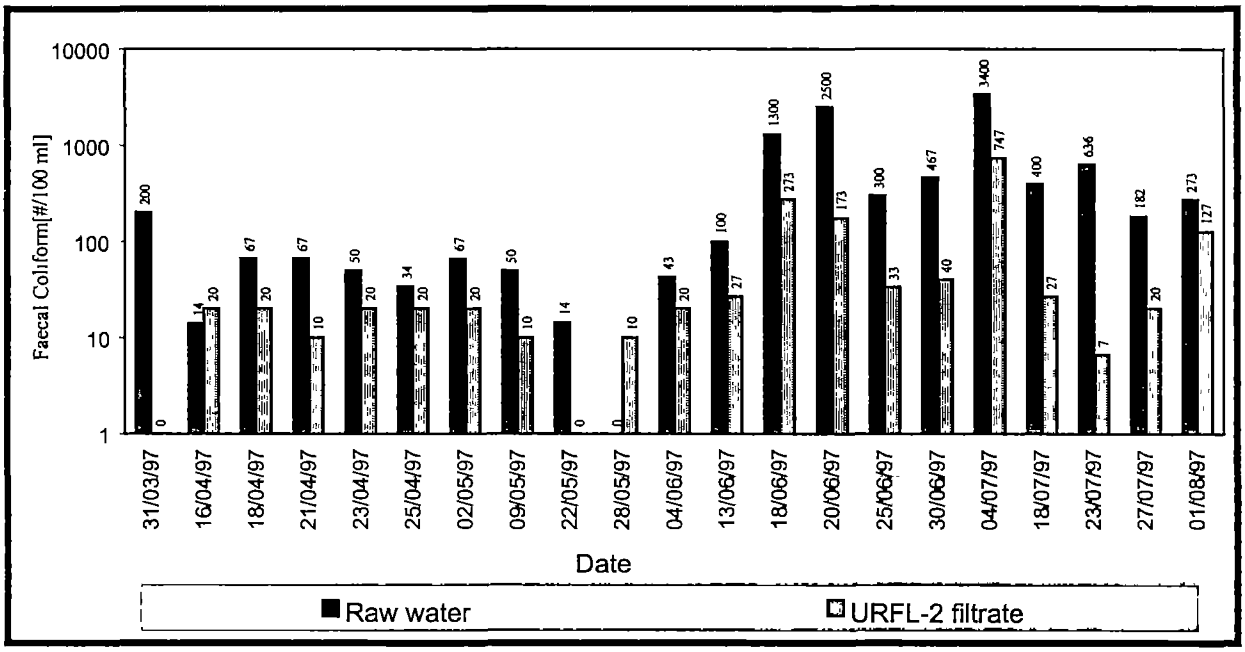

Figure 4.4-2: Faecal Coliform numbers/100 ml of raw water and URFL-2 filtrate

The results in Figures 4.4-1 and 4.4-2 are for average filtration rates of 0.5, 0.75, 1.0 and 1.25 m/h (see Table 3.5-2). The FC removal efficiencies by URFL at these filtration rates are summarised in Table 4.4-1. Results for URFL-2 on 16/04/97 and 28/05/97 are not included in

this table since the filtrate FC levels were greater than raw water levels. Therefore, an error either during sampling or analysis was suspected and the results on these dates were rejected.

Table 4.4-1: FC removal efficiencies by URFL at different filtration rates

Filtration rate(v_f)	**URFL-1**		**URFL-2**	
	Influent FC #/100 ml	**% reduction**	**Influent FC #/100 ml**	**% reduction**
1) 0.50	40 - 636	95-100	34 - 636	41.18-98.95
2) 0.75	67 - 200	85-98.95	14 - 200	80.00-100.00
3) 1.0	100 - 1633	77.22-96.73	43 - 2500	53.33-93.07
4) 1.25	200 - 533	27.50-78	273 - 3400	53.56-78.00

From Table 4.2-1, URFL show differences in FC removal efficiencies due to different FC levels in the raw water. Despite the different performances, both URFL-1 and URFL-2 produced effluents with FC levels below the maximum recommended level of 200 FC/ 100 ml by *Di Bernardo* (1991) for effective SSF. Only five out of the 42 URFL filtrate samples analysed had greater than 200 FC/100 ml. The corresponding raw water FC levels in these five samples had greater than 1000 FC /100 ml. This is an indication that effective micro-biological performance of URFL is also dependent on the contamination levels in the raw water, as reported in literature as well [Galvis et al., 1993]. Filtration rates of 1.0 and 1.25 m/h show relatively lower FC removal efficiencies. This could be as a result of the shorter retention times at these filtration rates compared to filtration rates less than 0.75 m/h. Higher retention times enhance FC removals since more time for the effective purification mechanisms to take place is provided. *Galvis et al.* (1993) report FC removal efficiencies for pilot and full-scale URFL plants ranging from 73.3 to 98.4 % for 0.3-0.75m/h filtration rates. The removal efficiencies in Table 4.4-1 for 0.5 m/h and 0.75m/h are comparable to these results.

4.4.2 Slow Sand Filters

FC analysis results in pre-treated raw water and SSF filtrates during filter-run 2 and afterwards are shown in Figures 4.4-1 and 4.4-2. FC analysis was not done during filter-run 1. SSF-1 was cleaned on July 27, 1997 and SSF-2 on June 18, 1997.

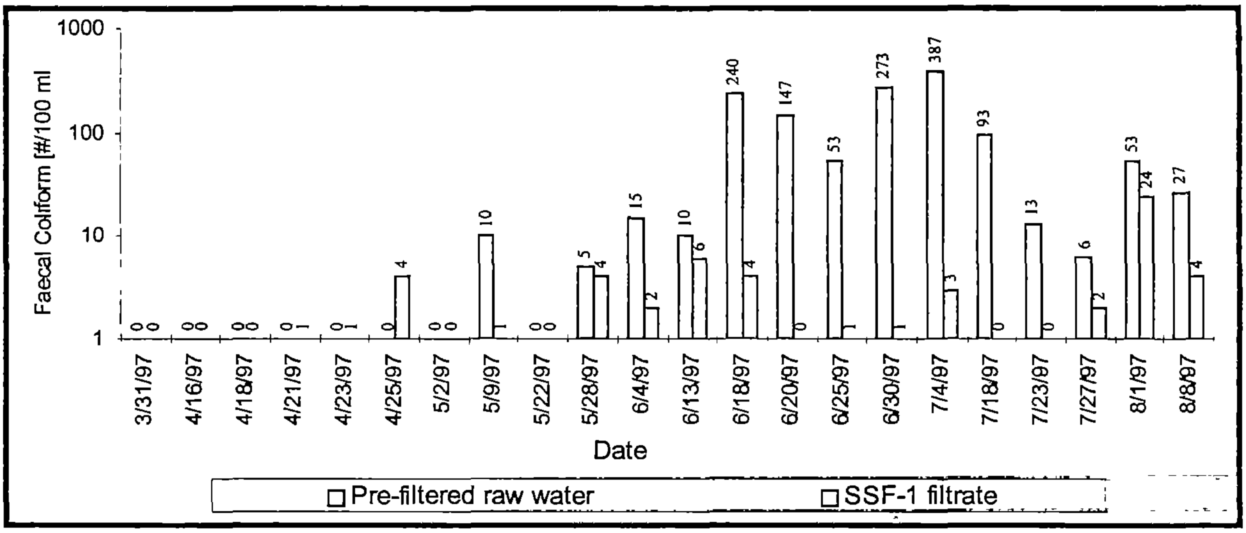

Figure 4.4-3: Faecal Coliforms in pre-filtered raw water and SSF-1 filtrate

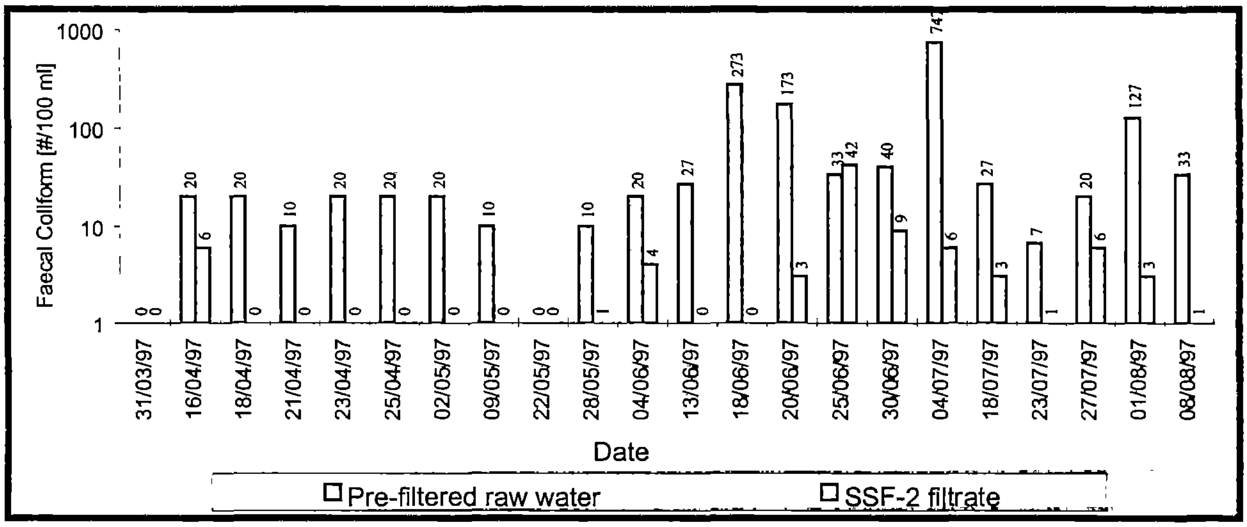

Figure 4.4-4: Faecal Coliforms in pre-filtered raw water and SSF-2 filtrate

From Figures 4.4-3 and 4.4-4, about 90% of the influent FC levels for both SSF units were below the maximum level of 200 FC /100 ml recommended by *Di Bernardo* (1991). This is due to the reduction of FC by URFL . However, it should be mentioned that about 50% of the

FC analysis results of raw water samples revealed less that 200 FC/100 ml, consequently, most URFL filtrate samples had less than 200 FC/100 ml.

The average FC/100 ml for SSF-1 and SSF-2 filtrates before end of filter-run 2 were 1.6 and 1 respectively. WHO recommends zero FC/100 ml in drinking water. Therefore, these SSF filtrates would still require disinfecting to guarantee supply of potable water.

After cleaning each SSF unit at the end filter-run 2, there was an increase in FC/100 ml SSF filtrate. The high FC/100 ml after cleaning verifies that the scraping removes the *Schmutzdecke* layer. This is an indication that the top dirty layer greatly enhances FC reductions. Therefore, after cleaning a filter, it should be filtered to waste for a period of at least 24 hours within which the *Schmutzdecke* is allowed to re-develop [*Graham,* 1988]. Usually, a filter-bed with a fully developed *Schmutzdecke* should produce filtrates with zero FC/100 ml. After cleaning such a filter, the ripening period is normally less than a few days to a week. The 'ripening period' is reached when bacteriological analysis of SSF filtrates show zero FC/100 ml. This was not achieved, and a much longer ripening period was experienced (about two weeks for SSF-1 and four weeks for SSF-2). This can be attributed to the high initial filtration rates (~0.25 m/h) experienced after putting the filter back to service, which consequently might have caused FC breakthroughs. Usually, it is recommended that a SSF filter should be put back to service at low filtration rates (<0.10m/h) to promote quick ripening.

The high initial filtration rates experienced, even when it was attempted to reduce SSF inflow rates to less than 65 L/h (<0.10m/h), could have been due to the fact that the filters were started with the supernatant water level slightly above the outlet weir level. This meant that even if the inflow to slow sand filter units was set at less than 65 L/h (0.1m/h), the already available hydraulic head above the outlet weir caused filtration rates higher than 0.1 m/h.

Before cleaning SSF-2, at the end of Filter run 2, its filtrate had 0 FC/ 100 ml. After cleaning FC levels increased gradually, and over a period of about four weeks decreased to about one FC/100 ml (see Figure 4.4-4). In practice, it is therefore necessary to apply adequate disinfection during longer ripening periods because FC levels in filtrates could be

unacceptable. The decreasing FC after cleaning indicates the re-ripening of the filter-bed, and hence the development of the *Schmutzdecke.*

4.5 Operation and maintenance aspects

Two Operation and maintenance aspects were distinguished: daily routine tasks carried by the operator, and the major tasks carried out by the author with the help of the plant operator.

4.5.1 Routine tasks

a) **Adjustments of flow rates**

The control of raw water flow to URFL was done nearly daily due to the algae growth and suspended solids depositions inside the rotameters. When one rotameter of an URFL unit was being cleaned, continuous supply to slow sand filters was ensured by opening valve X the interconnection the two production lines(see Figure 3.4-11).

Rate of SSF (controlled from the inlet side) were set at the beginning of each filter-run and no further adjustments were required. This is the advantage of inlet-controlled filters compared to outlet controlled filters in which daily adjustments are required to compensate for head-loss. The problem of depositions in SSF rotameters was less pronounced since they received pre-treated water.

b) **Cleaning of raw water tanks, filter units and URFL inlet and outlet boxes**

Depositions of suspended solids, and growth of algae occurred within the raw water tanks and URFL inlet and outlet boxes, and had to be cleaned occasionally. The growth of algae in the supernatant water of all filter units was excessive during filter-run 1 when the filters were not shaded, and had to be fished out daily. The initial low supernatant water level of slow sand filters was difficult to reach for algae removal. This could be big a problem in full-scale plants as it is reported to be one disadvantage of inlet controlled filters [*Galvis et al.,* 1993]. A plastic mesh with small openings was cut into a circular shape around which a wire was tied. The wire was attached to a long stick to reach and fish out the algae.

The grown of algae can be minimised by raw pre-chlorination or micro-straining and shading the filter units. The former is expensive for developing countries, but shading is more economical especially for small to medium treatment plants. Hence, algae problems were minimised by covering raw water tanks, filter units, and URFL inlet and outlet boxes.

Settling in raw water tanks was minimised by locating the outlets at the bottom of the tanks (see Figure 3.4-10).

4.5.2 Cleaning of the filter-bed media

a) **Up-flow Roughing Filters in Layers**

Cleaning of the URFL filter media was strictly supposed to have been done before commencing investigations in each trial run. In this way, the filter-bed is brought back to a clean state. URFL cleaning is due when the allowable head-loss is attained or when filtrate quality becomes unacceptable. Non of these criteria were attained in this study. Therefore, the cleaning intervals were due to the limitation on the period of investigations.

Both URFL were cleaned at the end of Trial 1 (27-03-97) before starting Trial 2. Thereafter, the filters were not washed at the end of Trial 2. At the end of Trial 3, URFL-1 was not cleaned since the effluent was still acceptable (<3 NTU), but URFL-2 was cleaned (02-05-97) since it had been fed with highly turbid raw water (simulated) and filtrate turbidity was approaching 10 NTU(acceptable upper limit, see Figure 4.2-6). At the end of Trial 4, both URFL were not cleaned (effluent quality and head-loss were acceptable). At the end of Trial 5, URFL-2 was cleaned. Within Trail 6 (18-07-97), both URFL units were cleaned.

Theoretically, if the filter media were not washed before each trial, removal efficiencies during the subsequent trial may either improve or reduce depending on the quantity of suspended solids retained. If retained solids are still less than what the filter-bed can accept before breaking through, these retained solids will enhance physical filtration mechanisms (adsorption, attachment, screening and interception) and improve removal efficiencies. However, if the filter bed cannot store any more solids, removal efficiencies will drop and effluent quality will deteriorate due to solids breakthrough. Either cases was not noticeable in this study. It is possible that between the trials when the filter media was not washed, the amount of accumulated solids was not enough to affect high or low removal efficiencies.

Visual observations on the quality of the wash water during hydraulic cleaning of the URFL filter media showed removal of suspended solids. Cleaning was done at least twice on each occasion. When cleaned for the second or third time, wash water was more clarified.

During four of the cleaning occasions, grab samples were collected and analysed for suspended solids contents. Analysis results are shown in Figures 4.5-1 & Appendix D.

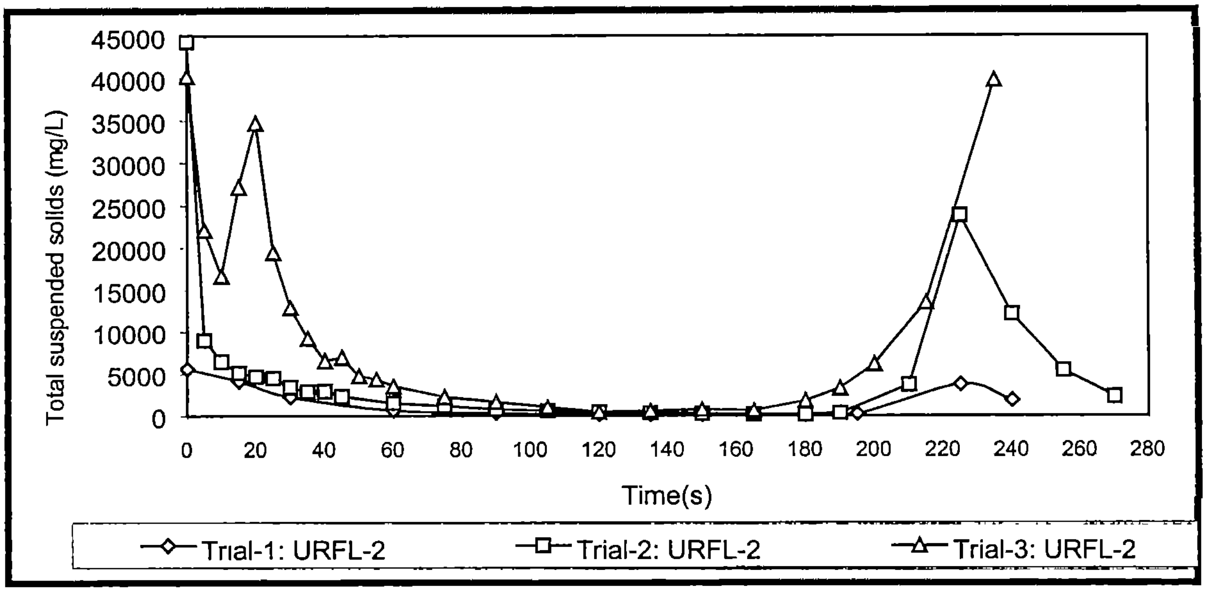

Figure 4.5-1: TSS concentration in URFL hydraulic cleaning wash water

From Figure 4.5-1, it is seen that there were high TSS at the start of the cleaning. This indicates that most suspended solids were retained near the filter bottom. High TSS near the end of the draining could be due to low velocities (due to the low water levels in the filter unit then) which allowed flow of solids (retained near the filter walls, between under-drain openings and between lateral drains) towards the outlet of the filter unit. This trend is what *Wegelin* (1996) obtained in his investigations of the hydraulic cleaning as well. Theoretically, the concentration of TSS levels in the wash water is supposed to be decreasing with time of draining.

Wolters (1988) suggests that "shock loading" (instantaneous closure and opening of the fast drainage valve during draining) enhances the dislodgement and removal of solids. By opening the fast drainage valve and then suddenly closing it, water hammer effects are initiated to aid in dislodging suspended solids from the filter media grains. The shock loading effect was tried once on URFL-1 in Trial 6 (see Figure 4.5-2).

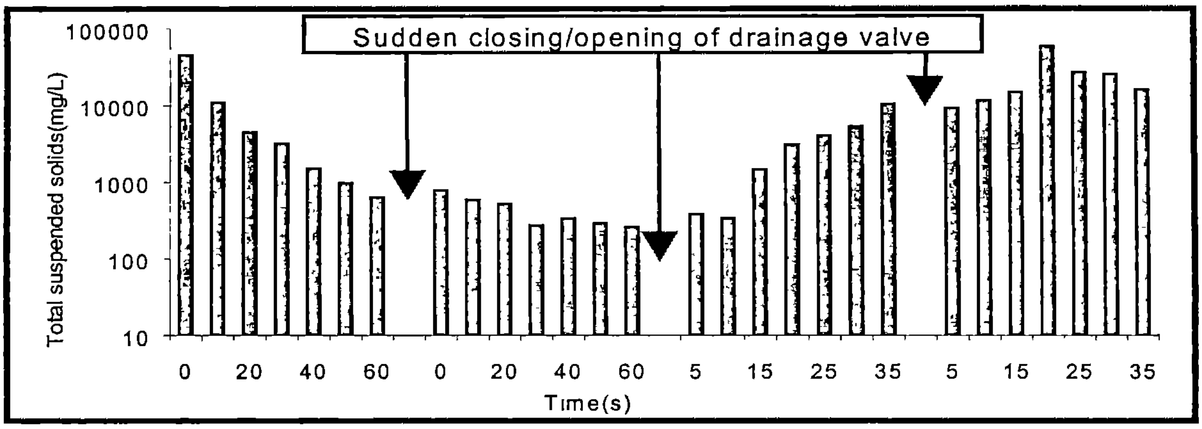

Figure 4.5-2: TSS concentration in URFL wash- water during "shock loading"

According to *Wolters* (1988), TSS peaks are supposed to occur between the intervals of shock loading. This would then illustrate that suspended solids were dislodged. The peaks should then decrease with increasing cleaning/draining time. However, in the trial done (Figure 4.5-2) these peaks did not occur. This could be attributed to the inadequacy of the under-drain system, which in his case was only coarse gravel. The of design criteria of RF under-drain system for effective filter washing has not been fully developed, only preliminary guidelines exist to date [*Galvis et al.,* 1993].

b) Slow sand filter filter-bed

SSF media were cleaned by scraping off the top 1-2 cm of top layer (*Schmutzdecke)* until relatively clean sand was reached. After cleaning, the sand surface was levelled to prevent formation of puddles of water when the filter is drained for cleaning the next time.

A just cleaned SSF unit was put back to service by first re-filling the unit through the under-drain with filtrate from the adjacent filter unit. After re-filling raised the supernatant water to about 15 cm above the effluent weir level, the filter was put back to service.

After putting the filter back to service, higher filtration rates were common. This was as a result of refilling the supernatant water level to above the outlet weir level. Hence, when the filter is started, the already existing hydraulic head above the weir level initiated high filtration rates than those set on the rotameters.

Chapter five

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The potential for the use of roughing and slow sand filtration systems, as alternatives to conventional methods, in treating surface water in Zambia, have been revealed through the critical literature review and the attendant pilot plant investigations. Pilot plant investigations revealed simplicity in operation and maintenance associated with these systems, compared to the operation and maintenance of conventional systems reported in literature. Final filtrates of these systems are of very high physical and micro-biological quality. The results of the study provide the first basis for designing roughing and slow sand filtration systems in Zambia based on local practical investigations.

The specific conclusions drawn include:

a) Ability of URFL to treat raw water to quality acceptable for SSF

It was concluded that URFL are able to pre-treat raw water to physical and bacteriological quality acceptable for slow sand filters. Turbidity, total suspended solid and faecal coliform levels were reduced to less than 10 NTU, 5 mg/L and 200 FC/100ml, respectively.

b) Treatability of the Kafue river water by URFL-SSF systems

The *Kafue* River water was found to be treatable by URFL with respect to turbidity, faecal coliforms and suspended solids removal. However, the actual high turbidity and total suspended solid levels common in the rain seasons were not studied since the plant was commissioned after the rain season was almost over. The simulation of high turbidity raw water using clay from the *Kafue* River banks provided an indicative capability of URFL to treat raw water common during rain seasons. URFL were able to reduce average daily turbidities from about 300 NTU to below 10 NTU. However, the algae content of *Kafue* River water, although not measured, poses problems related to clogging filters. This was confirmed by the short first filter-runs of both pilot SSF units. The filters clogged due to algae blooms before they could be prevented by shading.

c) Filter runs of up-flow roughing filters in layers and slow sand filters

URFL filter-runs were not established, either with respect to effluent quality or head-loss development. The operation periods of URFL ranged from 10-31 days, with the highest (31 days) occurring when both URFL units were run at 1.0 m/h. It is therefore likely that for filtration rates less than 1.0 m/h, URFL filter-runs could exceed four weeks. Because of the low turbidity raw water and intermittent simulations of high turbidity, head-loss development was very low and could not be used as an indicator of the end of a filter-run. However, there was an indication of filtrate turbidities increasing with time. This can be a reasonable criteria for indicating the end of a filter-run. In literature, filter-runs of about a week are reported with heavy turbidity and suspended solid loads common in wet seasons. It could have been possible to experience such filter-runs if highly turbid raw water was fed to pilot plant *Iolanda* continuously.

Obtained SSF filter-runs(at least 4 weeks) were acceptable and comparable with reported values in literature for well operated SSF(more than 1 month). It is possible that without pre-treatment, filter-runs of SSF could have been shorter. These acceptable filter-runs are attributed to the adequate pre-treatment provided by URFL. The filter-runs obtained in this study are much higher than those reported by *Versteeg* and *Holzhaus* (1993) for SSF applications in Zambia (3 days-2 weeks) which receive chemically pre-treated or raw surface water.

d) Suitability of local filter media for URFL and SSF

Local filter media used in SSF and URFL units are suitable, and can readily be employed in full-scale installations as is evident from the good performance of pilot plant *Iolanda.* The suitability of local filter media can definitely reduce capital costs since importing large quantities of filter media could prove very expensive. However, thorough washing and grading is very necessary before use.

e) Influence of investigated URFL filtration rates on performance of URFL

URFL filtration rates of less than 1.0 m/h did not show marked difference in turbidity reduction, TSS, and faecal coliforms. However, an average filtration rate of 1.25 m/h indicated reduced performance with respect to faecal coliforms removals. Since the main purpose of roughing filters is usually to reduce turbidity and suspended solids which may rapidly clog slow sand filters, the filtration rate of 1.25 m/h can still be applied as long as it

is able to reduce levels of these parameters to acceptable quality for SSF. Faecal coliforms can still be removed by terminal disinfection.

f) Operation and maintenance of URFL-SSF systems

Operation and maintenance of URFL-SSF systems compared to conventional water treatment systems is simpler. No daily expert supervision was necessary. Operation and maintenance of pilot plant *Iolanda* was done by a local person (operator) who was easily trained on site.

The non-chemical pre-treatment by roughing filtration means lower operation costs compared to conventional methods which demand continuous use of chemicals. The absence of mechanical/electrical components (used for back-washing in RSF and chemical preparations and dosing) imply less operation and maintenance problems.

The hydraulic cleaning of URFL by rapid draining was easy and required neither pumping nor extra labour. It was effective in removing accumulated solids. However, after cleaning the filter, it is better to refill it using low rates (<0.5 m/h) to prevent re-suspension of dislodged solids which were not washed out. Attempts to quickly refill the filter at high rates (>1.0 m/h) can result in high turbidity filtrates.

5.2 Recommendations

The following recommendations for the operation, maintenance, design and possible future investigations on URFL-SSF systems have been drawn based on the critical literature review done and experiences with pilot plant *Iolanda.*

5.2.1 Operation and maintenance

a) To prevent the proliferation of algae and secure plant hygiene, URFL and SSF should be shaded. For URFL, this is achieved by filling the supernatant depth, including the collecting drains, with coarse gravel (>25 mm), while SSF units can be roofed. For economic reasons, it may be appropriate to shade only URFL, which may remove most of the algae. The use of pre-chlorination or micro-straining to prevent algae blooms could be very costly for small and medium community water supplies in developing countries.

b) To achieve effective hydraulic cleaning of URFL, the draining should be done at least twice, successively. After cleaning, the filter should be put back to service at low filtration rates(~<0.50 m/h). High turbidity break-through can occur if the filters are refilled quickly at higher filtration rates, and this would lead to clogging of the subsequent SSF units if the filtrates are not sent to waste. Attempts to fill the filters at high rates and then filter to waste until the filtrate is acceptable to SSF, may result in increased down-time because the experience with pilot plant *Iolanda* indicated that it can take several hours of filtering to waste before the filtrate becomes acceptable.

c) When a SSF is taken out for cleaning, it should not be completely drained and dried, as practised in most SSF installations in Zambia, because the developed micro-biological life within the filter-bed is killed. Re-development of the micro-biological fauna requires time to adjust to new conditions. Re-filling and re-charging of the filter should be done at low filtration rates(<0.1m/h) to allow effective development of the *schmutzdecke*.

After cleaning an inlet controlled slow sand filter, it should not be back-filled to above the effluent weir level. Back-filling should only raise the supernatant water level to the effluent weir level. If the initial supernatant water level is above the effluent weir crest and the inflow rate is set to the recommended low starting rate (<0.10m/h), the available hydraulic head above the effluent weir crest level can cause higher than 0.1 m/h rates. This was experienced with pilot plant *Iolanda.* The high filtration rates in a just cleaned slow sand filter can result in faecal coliform breakthroughs, since the *Schmutzdecke* layer is still not fully developed.

d) Filtration rates in SSF are best controlled from the inlet side as experienced with pilot plant *Iolanda.* Outlet-controlled SSF could have required frequent adjustments of the effluent control valve (nearly daily) to compensate for increasing head-loss. The advantages of inlet-controlled SSF are that regular adjustment of the flow control valve is not necessary, and the rising water level is an obvious indicator that the filter is clogging.

e) URFL and SSF should be operated with minimal fluctuations of the filtration rates. In URFL, fluctuating filtration rates can cause re-suspensions of the retained impurities

leading to their breakthrough. For SSF, constant filtration rates are essential for consistent bacteriological performance.

f) Because of the low head-loss development in URFL, filter resistance may not always be a decisive operational criteria for cleaning the gravel. Increasing turbidity of the filtrates up to undesired levels (daily averages ~ >10 NTU) is a possible alternative for indicating the end of a filter-run. Where turbidimeters cannot be available, standard clay suspensions with turbidity around 10 NTU can be prepared and used to compare filtrate clarity.

5.2.2 Design aspects

a) Use of intake or dynamic filters to protect URFL against very high turbidity loads which occur in rain seasons should be considered in the design of URFL-SSF systems. During the study on pilot plant *Iolanda,* there were indications of increasing URFL filtrate turbidity with increasing raw water turbidity during the daily simulation periods. It is thus likely that high turbidity raw water for at least a day or more could reduce URFL efficiencies. Intake or dynamic filters can protect the plant against such high turbidity loads.

b) Literature suggest that URFL give best results at filtration rates below 1.0 m/h. There is not much performance difference at filtration rates less than 1.0 m/h. However, filtration rates of 1.25m/h can also be applied as experienced with pilot plant *Iolanda.* Higher rates could be possible only for short periods of time when one filter is out of operation for maintenance.

c) The inclusion of a support gravel in URFL is recommended. Besides the supporting role, it can also contribute to the storage capacity of the filter. It may also be essential during hydraulic cleaning since the large porosity there provides good drainage. However, the performance of the support gravel maybe affected by the raw water characteristics.

d) Flow to URFL units should preferably be by gravity as this facilitates easy monitoring of head-loss developments and permit installation of hydraulic flow measuring facilities.

e) Existing structures, like sedimentation basins in conventional pre-treatment systems, can easily be reconstructed to URFL. Large SSF units can be reconstructed to include URFL.

5.2.3 Future research

a) Up-flow Roughing filters in layers

i) Although hydraulic cleaning of URFL showed that it removes part of the accumulated solids, design criteria for the under-drain system and efficiency of the cleaning process need more research, preferably using full-scale demonstration plants. The **mass balance** analysis of total suspended solids would be the best tool to ascertain the efficiency of the hydraulic cleaning. The decreasing water level in the filter units is an interesting aspect since the drainage velocity also decreases. Possibilities of additional wash water and sloping filter bottoms should be considered.

ii) URFL filter-runs need further investigations with respect to raw water quality. This study was limited to simulated high turbidities. A study in the rain season when continuously high turbidity is common and over investigations periods greater than the ones used in this study, would be interesting.

iii)With regard to URFL filter media, low depths need to be considered especially where low turbidity raw waters are common. Monitoring of turbidity reductions through the three gravel layers of pilot plant *Ioalnda's* URFL units revealed that for low turbidity raw water, the last two layers hardly reduced turbidity. Suggestions by *Wegelin* (1996) that depths of the bottom, middle and top gravel layers in URFL can be designed in the ratio of 3:2:1 can definitely reduce amounts of gravel media used and the overall size of the plant, thus giving economical benefits.

iv)The performance of pilot plant *Iolanda* with regard to the removal of COD, colour, iron and manganese, need to be investigated so that the extent of purification mechanisms is known. These parameters are also reported to be limiting factors to the performance of slow sand filters.

b) Slow sand filtration

i) The ripening period of the SSF filter-bed, with respect to faecal coliform removal, using local sands need further investigations. If the ripening period is known, it is possible to minimise on safety chlorination especially in rural and township areas in *Zambia*, and possibly elsewhere, where disinfectants are difficult to get.

ii) If slow sand filters are fed with well pre-treated raw water, then it should be possible to increase production by applying higher filtration rates than those experienced with pilot plant *Iolanda* (average 0.24 m/h). Then, the corresponding filter resistance, and turbidity and faecal coliform removals need evaluation at higher rates under the Zambian conditions. *Kors et al.* (1996) report yearly average filtration rates of 0.48 m/h for slow sand filters at the *Amsterdam* Water Works (The *Netherlands*) with a design capacity of 0.65 m/h because they are fed with well pre-treated raw water.

iii) Local sources of SSF filter media need to be explored to avoid costly importation of sand. Most of the existing water treatment plants in Zambia use imported sand. The need to explore and study various sands is important because different sands are reported to perform differently. Pilot plant studies are vital in establishing the suitability of unknown sands.

iv) Although shading or covering SSF has been recommended as a method of minimising algae growth, enhancing filter-run length and securing plant hygiene, research is still required on quantifying the cost and productivity benefits of shading.

v) There is still some considerable uncertainty as to an acceptable minimum filter-bed depth of sand. *Huisman* (1989) recommends 0.70 m, *Visscher et al.* (1987) suggest 0.50m, *Rachwal et al.* (1988) indicate that a lower value of 0.3 m is permitted for the *London* slow sand filters, and a minimum depth of 0.4 m for algae removal have been suggested by *Di Bernardo et al.* (1991). The minimum depth is likely to depend on operational conditions such as influent quality, sand size, filtration rate, and water temperature [*Graham et al.,* 1994]. According to *Graham* (1994), recent pilot plant studies have suggested that bacterial removal is not very sensitive to filter depth, even with the depth reduced to 0.20m. Certainly, investigations are required concerning the minimum filter-bed depth, using local materials in Zambia, since it has a cost implication, especially where large quantities of sand are required.

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Appendix A: Effects of filter-bed depth in slow sand filtration on operation period before re-sanding, head-loss and filter run-time.

Useful relationship:

The years of operation before re-sanding can be calculated as follows

$$Y = (H_i - H_m) / (H_s * f) \quad \text{.......} \; 1$$

where:

- ⇒ H_i is the initial filter bed depth
- ⇒ H_m is he minimum filter-bed depth before re-sanding is needed
- ⇒ H_s is the depth of sand scraped after each filter-run
- ⇒ **f** is the frequency of cleaning per year

The relationship of the filtration rate, head-loss and filter depth is given by the Darcy's Equation

$$v = - k\,(dH / dZ) \quad \text{.......} \; 2$$

where:

- ⇒ **dH** is the head-loss available across the filter-bed
- ⇒ **dZ** flow distance through media or filter-bed depth (m)
- ⇒ **k** hydraulic conductivity of porous media
- ⇒ **v** is the superficial velocity synonymous with the hydraulic loading rate (m/h)

Example one: Effect of filter-bed depth on bed life

GIVEN DATA:

⇒ filter-bed depths of 1.3m and 1.0m

⇒ H_s 1.5 cm per scraping

⇒ $f = 6$ scrapings per year

⇒ $H_m = 50$ cm

CALCULATION

⇒ FOR $H_i = 1.3$m and using equation (1)

$Y = (130-50)/(1.5 * 6) = 9$ years

⇒ FOR $H_i = 1.$m and using equation (1)

$Y = (100-50) /1.5 * 6) = 5.5$ years

Example two: Effects of filter-bed depth on head-loss and run time

Given data:

⇒ Filter-bed depths of 1.3m and 1.0m

⇒ filtration rate V = 0.2m/h

⇒ k =5.05 * 10^{-7} m/s (assuming Temperate = 10°C)

⇒ filter run time 60 days

⇒ maximum allowable head-loss 1.5 m

Applying Darcy's law (equation 2) to solve for the available head-loss for the clean filter-bed

Filter-bed depth of 1.3m gives **dH** = 0.14 m

Filter-bed depth of 1.0m gives **dH** = 0.11 m

Discussions

A filter-bed depth of depth of 1.3m gives a bed life of 9 years, where as a 1.0 m bed gives a bed life of only 5.5 years. The bed life increases by 3.5 years merely by adding an additional 30cm of filter-bed.

A filter-bed of 1.3 m gives a clean bed head-loss of 14 cm, where as a 1.0m bed gives a clean bed head-loss of 11 cm. The head-loss increases only by 3 cm by increasing the filter-bed depth by 30 cm.

Assuming a linear head-loss development with time and an allowable terminal head-loss of 1.5m over a filter run of 30 days for the 1.0m filter-bed would mean the filter-run would drop by of 4 days if the 1.3m filter-bed is applied. Weighed against this is the additional 3.5 years bed life before re-sanding. This shows that the trade-offs of increasing the filter-bed could be smaller than the benefits, although in this theoretical example the additional cost aspects of the side-wall are not taken into account and whether the foundation soil would accommodate the additional pressures.

APPENDIX B (i): Turbidity (NTU) measurements in Up-flow roughing filters in layers

Note: STDEV (%) means standard deviation (percentage)

Trial 1

Up-flow roughing filter in layers No. 1

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Raw Water	Turbidity	1 50			10 67	3 54	1 32	1 54	1 37	1 17	1 29	1 20	1 67	1 25	1 33	1 04	1 16		9 68	1 07	1 18	1 36	1 33	1 16	1 42	1 70
	STDEV (%)	2 36			84 94	63 83	13 20	31 86	7 11	9 44	14 90	6 32	46 28	12 08	17 59	6 17	0 00		121 73	9 65	12 80	18 01	14 08	9 57	18 93	35 30
Filtrate	Turbidity	0 96			4 21	1 33	0 71	0 74	0 69	0 60	0 72	0 77	0 63	0 61	0 63	0 61	0 68		0 68	0 57	0 57	0 58	0 58	0 55	0 60	0 69
	STDEV(%)	8 14			8 05	16 00	13 87	11 38	8 91	9 81	13 24	17 65	12 07	12 96	18 12	10 57	0 00		31 92	10.28	9 38	9 18	9 49	10 60	16 40	25 26
Turbidity reduction(%)		36 12			60 57	62 43	46 21	51 95	49 64	48 72	44 19	35 83	62 28	51 20	52 63	41 35	41 38		93 18	46 73	51 69	57 35	56 39	52 59	57 75	59 41

Up-flow roughing filter in layers-2

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Raw water	Turbidity	1 50			10 67	3 54	1 32	1 54	1 37	1 17	1 29	1 20	1 67	1 25	1 33	1 04	1 16		9 68	1 07	1 18	1 36	1 33	1 16	1 42	1 70
	STDEV(%)	2 36			84 94	63 83	13.20	31 86	7 11	9 44	14 90	6 32	46 28	12 08	17 59	6 17	0 00		121 73	9 65	12 80	18 01	14 08	9 57	18 93	35 30
Filtrate	Turbidity	1 02			4 05	1 33	0 75	0 74	0 69	0 61	0 71	0 66	0 55	0 55	0 61	0 57	0 58		0 66	0 57	0 60	0 58	0 60	0 57	0 53	0 72
	STDEV(%)	3 48			4 41	16 47	8 07	13 06	4 88	14 47	16 58	17 45	12 06	13 65	13 33	5 44	0 00		9 21	8 59	10 33	6 36	12 88	8 09	7 82	23 59
Turbidity reduction(%)		32 11			62 07	62 43	43 18	51 95	49 64	47 86	44 96	45 00	67 07	56 00	54 14	45 19	50 00		93.18	46 73	49 15	57 35	54 89	50 86	62 68	57 65

Trial 2

Up-flow roughing filter in layers No. 1

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Raw water	Turbidity	1 48	1 87	2 54	2 23	12 65	5 84	5 00		2 39	3 04	2 10	4 79	2 24	2.25	2 40	2 66	3 11	3 41	2 98	3 61
	STDEV(%)	1 79	8 11	7 32	8 41	171 49	17 28	16 02		15 56	19 06	17 30	10 41	14 42	28 38	13 42	30 45	30 77	14.29	4 64	3 90
Filtrate	Turbidity	0 91	0 95	0 97	0 87	0 88	0 85	2 45		1 22	1 36	1 10	1 04	1 12	0 98	1 01	1 14	1.26	1 42	1.29	1 58
	STDEV(%)	37 76	6 14	7 91	3 74	36 78	11 16	16.25		10 74	19 00	8 48	3 41	5 76	28 38	2 92	7 44	8 81	5 66	8 85	10 30
Turbidity reduction(%)		38 51	49 20	61 81	60 99	93 15	85 45	51 00		48 95	55 26	47 62	78 29	50 00	56 44	57 92	57 14	59 49	58 36	56 71	56 23

Up-flow roughing filter in layers No. 2

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Raw water	Turbidity	1 48	1 87	2 54	2 23	12 85	5 84	5 00		2 39	3 04	2 10	4 79	2 24	2 25	2 40	2 66	3 11	3 41	2 98	3 61
	STDEV(%)	1.79	8 11	7 32	8 41	171 49	17 28	16 02		15 56	19 06	17 30	10 41	14 42	28 38	13 42	30 45	30 77	14 29	4 64	3 90
Filtrate	Turbidity	0 64	1 05	1 05	0 99	0 85	0 86	2 39		1 26	1 39	1 15	1 03	1 21	1 04	1 05	1 18	1 29	1 53	1 30	1 66
	STDEV(%)	23 38	15 91	4 52	8 61	47 61	10 44	8 61		9 01	14 87	12 78	7 98	14 81	8 20	1 79	9 71	12 10	8 28	7 31	7 85
Turbidity reduction(%)		56 76	43 85	58 66	55 61	93 39	85 27	52 20		47 28	54.28	45 24	78 50	45 98	53 78	56 25	55 64	58 52	55 13	56 38	54 02

Trial 3

Up-flow roughing filter in layers No. 1

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Raw water	turbidity	3 08	3 83	2 34	2 04	1 96	1 92	1 85	2 43	1 85	1 37	1 76	1 67	2 04	2 04	3 01	2 27	1 87
	STDEV(%)	10	24	21	12	20	17	15	31	39	20	39	25	30	40	57 54	22	14
Filtrate	turbidity	1 27	1 22	1 11	1 08	1 07	0 94	0 91	0 96	0 95	0 70	0 81	0 66	0 73	0 71	0 81	0 86	0 74
	STDEV(%)	11 53	7 74	12 71	22 12	30 71	15 16	16 52	34 62	20 00	17 00	18 00	8 00	16 00	18 00	19 00	17 00	1 35
Turbidity reduction(%)		58 77	68 15	52 56	47 06	45.41	51 04	50 81	60 49	48 65	48 91	53 98	60.48	64.22	65 20	73 09	62 11	60 43

Trial 3

Up-flow roughing filter in layers No. 2

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Raw water	turbidity	15.76	25.68	25.34	15.26	20.25	26.17	45.31	115.83	56.65	101.08	111.78	137.75	259.33	216.00	177.03	234.00	149.67
	STDEV(%)	42.03	27.36	42.56	34.56	44.16	51.83	17.95	45.94	27.82	48.58	40.05	49.28	38.74	34.08	62.58	18.23	25.67
Filtrate	Turbidity	2.64	2.01	2.13	1.63	1.58	1.65	2.25	3.18	3.23	4.67	6.43	6.93	7.98	9.61	7.61	5.92	5.09
	STDEV(%)	33.65	26.76	25.20	22.05	20.26	21.49	22.18	36.97	27.48	41.00	37.00	28.00	26.00	29.00	8.00	71.63	2.39
Turbidity reduction(%)		83.25	92.17	91.59	89.32	92.20	93.70	95.03	97.25	94.30	95.38	94.25	94.97	96.92	95.55	95.70	97.47	96.60

TRIAL 4

Up-flow roughing filter in layers No 1

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Raw water	turbidity	30.45	35.05	42.26	74.58	51.34	100.83	1.93		1.76	1.67	2.19	1.86	2.05	3.09	2.74	2.51	2.99	2.65	2.50	2.29	3.11	2.22	1.51	1.41	1.59	2.22
	STDEV(%)	20.44	36.15	34.93	44.30	58.91	63.95	6.23		23.76	11.97	28.75	34.17	16.40	24.19	27.90	23.21	24.24	50.61	20.65	31.32	40.26	15.44	8.33	15.26	13.89	13.37
Filtrate	Turbidity	2.82	3.06	3.23	4.08	3.93	5.85	0.92		0.81	0.85	0.87	0.76	0.90	0.99	0.94	1.15	0.89	0.96	0.90	0.92	1.16	0.95	0.80	0.66	0.64	1.19
	STDEV(%)	18.66	12.06	10.49	40.89	52.42	47.77	16.03		22.75	6.45	14.67	8.60	7.23	12.96	18.28	18.26	12.77	13.51	3.33	8.30	17.41	15.99	16.60	17.64	18.56	31.43
Turbidity reduction(%)		90.7	91.3	92.4	94.5	92.3	94.2	52.1		53.9	49.0	60.4	59.3	56.1	68.1	65.8	54.1	70.3	63.8	64.0	59.8	62.7	57.3	47.3	53.3	59.6	46.7

Up-flow roughing filter in layers No 2

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Raw water	turbidity	37.48	62.55	41.67	91.60	63.52	122.60			40.96	32.17	34.50	44.31	50.86	37.08	77.29	79.57	72.93	67.27	82.65	76.43	53.78	67.23	31.62	21.99	23.94	24.98
	STDEV(%)	58.3	78.8	23.5	9.9	44.5	95.7			50.7	18.5	22.0	24.0	54.7	17.3	18.1	16.2	55.4	18.8	16.2	15.7	45.0	24.1	76.7	42.9	30.9	55.1
Filtrate	turbidity	4.03	4.67	3.54	4.83	4.46	5.26			4.19	5.22	3.87	4.55	5.11	4.57	8.42	8.05	5.46	7.48	7.27	5.55	5.57	5.86	3.42	2.50	2.39	3.08
	STDEV(%)	33.46	18.96	18.46	40.92	45.83	48.65			35.05	27.97	24.85	18.44	47.22	14.50	24.09	17.23	32.71	9.40	18.99	35.01	25.79	15.85	39.55	13.97	15.90	51.02
Turbidity reduction(%)		89	93	92	95	93	96			90	84	89	90	90	88	89	90	93	89	91	93	90	91	89	89	90	88

Trial 5

Up-flow roughing filter in layers No. 1

	Day	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25	26	27	28	29	30
Raw water	Turbidity	2.78	2.13	2.82	2.19	2.31	2.41	2.06			1.96	1.99			1.41	1.45	1.40	54.64	64.16	25.08	37.60	41.14	69.18	34.25	42.51	38.37	36.76	44.84	37.12	65.73	156.11
	STDEV(%)	30.30	43.68	61.89	31.93	10.99	21.17	22.39			23.00	41.93			7.00	17.29	10.56	23.13	38.56	21.18	50.93	67.18	30.07	44.09	44.95	38.05	27.56	38.70	43.98	53.98	101.31
Filtrate	turbidity	0.88	0.89	1.00	0.90	0.98	1.17	0.92			0.86	0.82			0.77	0.70	0.76	3.59	3.98	2.69	3.18	2.41	4.89	2.70	3.27	3.17	2.96	3.20	2.72	2.28	2.93
	STDEV(%)	17.50	14.97	16.19	11.94	20.78	27.44	11.60			12.23	24.92			13.48	13.82	17.79	12.02	10.57	16.84	27.24	13.54	15.78	25.26	37.27	17.73	21.03	15.21	15.00	14.24	40.80
Turbidity reduction(%)		68.5	58.3	64.5	59.1	57.6	51.5	55.4			55.9	59.1			45.4	51.8	45.5	93.4	93.8	89.3	91.5	94.1	92.9	92.1	92.3	91.7	92.0	92.9	92.7	96.5	98.1

Up-flow roughing filter in layers No 2

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Raw water	Turbidity	26.64	29.99	33.99	38.09	26.00	37.50	26.86			30.80	41.56			23.94	61.68	27.56	110.56	52.46	35.27	42.32	31.47	60.55	45.36	39.12	40.39	33.71	46.38	40.88	81.85	220.20
STDEV(%)		27.27	48.56	45.03	17.10	17.12	60.82	20.21			19.27	40.56			18.57	45.33	13.79	48.02	38.52	48.02	59.86	43.46	24.06	70.39	48.45	48.24	20.63	31.97	30.50	51.67	74.10
Filtrate	turbidity	4.30	3.70	4.49	4.17	3.55	4.61	5.28			3.76	3.96			2.86	4.35	3.71	3.72	4.13	3.42	3.32	2.48	4.89	3.45	3.43	3.82	2.62	3.24	2.97	2.06	2.73
	STDEV(%)	28.36	10.37	12.01	18.62	17.34	24.89	20.48			28.94	25.31			2.94	18.75	21.57	55.44	14.32	52.80	27.02	12.36	41.23	23.64	35.09	22.44	18.92	21.49	21.57	24.39	30.43
Turbidity reduction(%)		83.9	87.7	86.8	89.1	86.3	87.7	80.3			87.8	90.5			88.0	93.0	86.6	96.6	92.1	90.3	92.2	92.1	91.9	92.4	91.2	90.5	92.2	93.0	92.7	97.5	98.8

TRIAL 6

Up-flow roughing filter in layers No 1

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Raw water	Turbidity	191.21	236 90	239 40	136 78	92.42		71 17	94 84	46 62	93 24	86 49	62 66	135 72	111 01	143 53	78 33	65 60	60.28
	STDEV(%)	61 07	42 91	41 09	53 92	19 00		34 05	49 13	25 64	14 05	48.27	51 93	63 18	47 57	37 14	50 88	43.27	42 58
Filtrate	Turbidity	3 82	6 65	4 58	5 48	3 59		3 15	3 02	3 43	4 60	3 11	3 60	5 05	5 17	4 20	3 74	3 19	4 82
	STDEV(%)	12 39	30 11	25 80	76 24	24 06		30 46	20 03	20 41	15 90	6 89	27 02	20 49	20 77	14 75	36 48	15 59	53 06
Turbidity reduction (%)		98 0	97.2	98 1	96 0	96 1		95 6	96 8	92 6	95 1	96 4	94 3	96 3	95 3	97 1	95 2	95 1	92 0

Up-flow roughing filter in layers No.2

	Day	1	2	3	4	5	6	7	8	9	10
Raw water	Turbidity	299 40	277 10	191 76	156 45	99 05		53 90	66 95	67 11	84 63
	STDEV(%)	67 96	39 01	23 84	57 65	44 58		40 11	54 68	31 65	19 90
Filtrate	Turbidity	4 47	7 13	4 40	6 03	3 23		3 23	3 24	4 39	5 04
	STDEV(%)	11 64	51 80	24 69	99 31	17 48		32 61	26 09	24 01	13 19
Turbidity reduction (%)		98 5	97 4	97 7	96 1	96 7		94 0	95 2	93 5	94 0

TRIAL 7

Up-flow roughing filter in layers No. 1

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13
Raw water	Turbidity	92 45	245 43	200 33	71 12	206 50	119 52	171 18	177 68	214 60	165 36	156 24	166 03	221 50
	STDEV(%)	50 14	91 25	70 02	47 09	10 13	55 60	20 63	44 79	40 34	37 73	49 99	27 27	25 91
Filtrate	Turbidity	4 37	4 30	3.23	2 67	2 67	4 88	3 92	5 14	5 42	4 31	3 64	3 85	5 00
	STDEV(%)	13 91	49 69	36 84	34 16	17 33	50 09	9 22	28 56	42 12	36 69	43 60	13 39	17 50
Turbidity reduction %		95 3	98 2	98 4	96.2	98 7	95 9	97 7	97 1	97 5	97 4	97 7	97 7	97 7

Up-flow roughing filter in layers No. 2

	Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Raw water	Turbidity	122 29	160 75	130 71	128 81	212 93	96 43	78 23	110 74	183 87	198 04	180 93	67 12	232 70	122 50	155 63	239 47	276 58	162 67	175 00
STDEV(%)		53 32	38 44	53 43	33 13	51 59	60 02	36 06	73 17	65 45	68 80	59 58	39 53	30 19	59 99	47 42	62 34	63 38	34.26	45 97
Filtrate	Turbidity	4 78	9 07	5 64	6 61	6 36	4 81	3 80	3 37	2 97	4 91	3 97	2 62	2 62	4 88	4 19	5 31	5 73	4 42	3 91
	STDEV(%)	35 00	41 17	29 39	41 48	33 12	17 21	10 19	43 88	13 05	31 72	15 11	16 25	14 90	39 87	15 42	39.25	35 76	37 15	40 76
Turbidity reduction %		96 1	94 4	95 7	94 9	97 0	95 0	95 1	97 0	98 4	97 5	97 8	96 1	98 9	96 0	97 3	97 8	97 9	97 3	97 8

APPENDIX B (ii): Turbidity (NTU) reduction by slow sand filters (Pilot plant Iolanda)

{Note: ND means no data}

Date (March 1997)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1 SSF-1 Influent	ND	0.96	ND	ND	4.21	1.33	0.71	0.74	0.69	0.60	0.72	0.77	0.63	0.61	0.63	0.61	0.68	ND	0.68	0.57	0.57	0.58	0.58	0.55	0.60	0.69	0.91	0.95	0.97	0.87	0.88
2 SSF-1 Effluent	ND	1.52	ND	ND	2.40	0.81	0.52	0.43	0.43	0.40	0.42	0.35	0.32	0.30	0.29	0.27	0.25	ND	0.29	0.30	0.28	0.27	0.28	0.28	0.30	0.29	0.47	0.57	0.56	0.53	0.42
Þ% Reduction		-58.64			42.95	39.10	26.76	41.89	37.68	33.33	41.67	54.55	49.21	50.82	53.97	55.74	63.24		57.35	47.37	50.88	53.45	51.72	49.09	50.00	57.97	40.00	40.00	42.27	39.08	52.27
1 SSF-2 Influent	ND	1.02	ND	ND	4.05	1.33	0.75	0.74	0.69	0.61	0.71	0.66	0.55	0.55	0.61	0.57	0.58	ND	0.66	0.57	0.60	0.58	0.60	0.57	0.53	0.72	0.64	1.05	1.05	0.99	0.85
2 SSF-2 Effluent	ND	0.97	ND	ND	2.42	0.80	0.52	0.44	0.37	0.35	0.39	0.35	0.31	0.28	0.26	0.26	0.29	ND	0.26	0.27	0.25	0.23	0.22	0.23	0.20	0.21	0.24	0.29	0.30	0.27	0.42
Þ% Reduction		4.43			40.20	39.85	30.67	40.54	46.38	42.62	45.07	46.97	43.64	49.09	57.38	54.39	50.00		60.61	52.63	58.33	60.34	63.33	59.65	62.26	70.83	62.50	72.38	71.43	72.73	50.59

Date (April 1997)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1 SSF-1 Influent	0.85	2.45	ND	1.22	1.36	1.1	1.04	1.12	0.98	1.01	1.14	1.26	1.42	1.29	1.58	1.29	1.22	1.11	1.08	1.07	0.94	0.91	0.96	0.95	0.7	0.81	0.66	0.73	0.71	0.81
2 SSF-1 Effluent	0.53	0.83	ND	0.68	0.71	0.73	0.62	0.61	0.55	0.53	0.53	0.49	0.49	0.6	0.62	0.59	0.58	0.55	0.51	0.46	0.47	0.64	0.51	0.45	0.41	0.45	0.46	0.55	0.57	0.51
Þ% Reduction	37.65	66.12		44.26	47.79	33.64	40.38	45.54	43.88	47.52	53.51	61.11	65.49	53.49	60.76	54.26	52.46	50.45	52.78	57.01	50.00	29.67	46.88	52.63	41.43	44.44	30.30	24.66	19.72	37.04
1 SSF-2 Influent	0.86	2.39	ND	1.26	1.39	1.15	1.03	1.21	1.04	1.05	1.18	1.29	1.53	1.3	1.66	2.45	2.01	2.13	1.63	1.58	1.65	2.25	3.18	3.23	4.67	6.43	6.93	7.98	9.61	7.61
2 SSF-2 Effluent	0.32	0.45	ND	0.42	0.5	0.45	0.41	0.46	0.4	0.38	0.45	0.36	0.43	0.38	0.59	0.56	0.55	0.54	0.49	0.48	0.48	0.51	0.58	0.58	0.57	0.64	0.62	0.75	0.87	0.87
Þ% Reduction	62.79	81.17		66.67	64.03	60.87	60.19	61.98	61.54	63.81	61.86	72.09	71.90	70.77	64.46	77.14	72.64	74.65	69.94	69.62	70.91	77.33	81.76	82.04	87.79	90.05	91.05	90.60	90.95	88.57

Date (May 1997)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1 SSF-1 Influent	0.86	0.74	ND	2.82	3.06	3.23	4.08	3.93	5.85	0.92	ND	0.81	0.85	0.87	0.76	0.90	0.99	0.94	1.15	0.89	0.96	0.90	0.92	1.16	ND	0.95	0.80	0.66	0.64	1.19	0.88
2 SSF-1 Effluent	0.49	0.58	ND	0.46	0.46	0.54	0.53	0.61	0.62	0.54	ND	0.46	0.48	0.58	0.49	0.46	0.59	0.53	0.58	0.45	0.55	0.45	0.37	0.41	ND	0.35	0.34	0.33	0.31	0.29	0.32
Þ% Reduction	43.02	21.62		83.54	85.08	83.41	86.99	84.44	89.34	41.70		43.50	43.39	32.49	35.19	48.66	40.07	43.88	49.91	49.69	42.92	50.00	60.02	64.80		63.00	57.22	50.00	52.18	75.30	63.8
1 SSF-2 Influent	5.92	5.09	ND	4.03	4.67	3.54	4.83	4.46	5.26	1.07	ND	4.19	5.22	3.87	4.55	5.11	4.57	8.42	8.05	5.46	7.48	7.27	5.55	5.57	ND	5.86	3.42	2.50	2.39	3.08	4.30
2 SSF-2 Effluent	0.94	0.85	ND	0.68	0.65	0.70	0.74	0.76	0.68	0.64	ND	0.59	0.55	0.72	0.72	0.64	0.72	0.68	0.73	0.70	0.73	0.60	0.59	0.57	ND	0.56	0.51	0.36	0.37	0.37	0.40
Þ% Reduction	84.12	83.30		83.16	85.99	80.27	84.66	83.01	87.06	40.75		85.86	89.44	81.31	84.18	87.52	84.14	91.95	90.94	87.23	90.23	91.79	89.34	89.83		90.52	85.15	85.45	84.44	87.92	91

Date (June 1997)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1 SSF-1 Influent	0.89	1.00	0.90	0.98	1.17	0.92	ND	ND	0.86	0.82	ND	ND	0.77	0.70	0.76	3.59	3.98	2.69	3.18	ND	2.41	4.89	4.89	3.27	3.17	2.96	3.20	2.72	2.28	2.93
2 SSF-1 Effluent	0.29	0.26	0.37	0.28	0.26	0.31	ND	ND	0.29	0.27	ND	ND	0.23	0.22	0.27	0.29	0.32	0.35	0.32	ND	0.30	0.39	0.39	0.38	0.36	0.32	0.28	0.31	0.29	0.30
Þ% Reduction	67.7	73.9	58.8	70.9	77.5	66.3			66.0	66.4			70.1	68.0	65.1	92.0	92.0	87.2	89.8		87.8	92.1	91.9	88.5	88.5	89.0	91.3	88.6	87.4	89.8
1 SSF-2 Influent	3.70	4.49	4.17	3.55	4.81	5.28	ND	ND	3.76	3.96	ND	ND	2.86	4.35	3.71	3.72	4.13	3.42	3.32	ND	2.48	4.89	3.45	3.43	3.82	2.62	3.24	2.97	2.06	2.73
2 SSF-2 Effluent	0.39	0.37	0.36	0.35	0.32	0.42	ND	ND	0.37	0.39	ND	ND	0.28	0.31	0.33	0.41	0.32	0.23	0.48	ND	0.41	0.45	0.44	0.45	0.47	0.40	0.37	0.41	0.38	0.38
Þ% Reduction	89	92	91	90	93	92			90	90			90	93	91	89	92	93	86		84	91	87	87	88	85	89	86	82	86

Date(July 1997)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1 SSF-1 Influent	3.82	6.65	4.58	5.48	3.59	ND	3.15	3.02	3.43	4.60	3.11	3.60	5.05	5.17	4.20	3.74	3.19	4.82	4.37	4.30	3.23	2.66	2.67	4.87	3.92	5.14	5.42	2.96	3.28	2.80	2.28
2 SSF-1 Effluent	0.36	0.46	0.43	0.49	0.47	ND	0.52	0.53	0.41	0.43	0.40	0.35	0.36	0.34	0.39	0.36	0.36	0.42	0.40	0.43	0.47	0.49	0.32	0.39	0.40	0.32	0.37	0.32	0.28	0.31	0.29
Þ% Reduction	90.58	93.08	90.61	91.06	86.91		83.49	82.45	88.05	90.65	87.14	90.28	92.87	93.42	90.71	90.37	88.71	91.29	90.85	90.00	85.45	81.58	88.01	91.99	89.80	93.77	93.17	89.19	91.46	88.93	87.28
1 SSF-2 Influent	4.47	7.13	4.23	6.03	3.23	ND	3.23	3.24	4.39	5.04	4.78	9.07	5.64	6.61	6.36	4.81	3.80	5.12	2.97	4.91	3.97	3.11	2.62	4.88	4.19	5.31	5.73	2.62	3.36	3.11	2.06
2 SSF-2 Effluent	0.43	0.60	0.59	0.62	0.57	ND	0.65	0.66	0.62	0.61	0.51	0.43	0.62	0.35	0.66	0.55	0.66	0.53	0.62	0.64	0.68	0.62	0.41	0.54	0.47	0.46	0.48	0.40	0.37	0.41	0.38
Þ% Reduction	90.38	91.58	86.05	89.72	82.35		79.88	79.63	85.88	87.90	89.33	95.26	89.01	94.70	89.62	88.57	82.63	89.65	79.12	86.97	82.87	80.06	84.35	88.93	88.78	91.34	91.62	84.73	88.99	86.82	81.55

Appendix C: Analysis results of faecal coliforms (FC)

Date	U R F L - 1						SSF-1			U R F L - 2						SSF-2		
	Influent			Effluent (ssf-1 inf.)			Effluent			Influent			Effluent (ssf-1 inf.)			Effluent		
	Sam V(ml)	FC	FC/ 100ml	V(ml)	FC	FC/ 100ml	Sam V(ml)	FC	FC/ 100ml	Sam V(ml)	FC	FC/ 100ml	V(ml)	FC	FC/ 100ml	Sam V(ml)	FC	FC/ 100ml
3/31/97	1	2	200	1	0	0	5	0	0	1	2	200	1	0	0	5	0	0
4/16/97	5	9								5	2							
	10	0	60	20	0	0	*	*	*	10	0	14	20	4	20	100	6	6
4/18/97	1	0		10	0	0	100	0	0	1	0		10	2	20	100	0	0
	5	3	50							5	4	67						
4/21/97	1	1		10	0	0	100	1	1	1	1		10	1	10	100	0	0
	5	2	50							5	3	67						
4/23/97	5	2	40	10	0	0	100	1	1	1	0		10	2	20	100	0	0
										5	3	50						
4/25/97	1	0		5	0	0	100	4	4	1	0		5	1	20	100	0	0
	2	2	67							2	1	34			20			
5/2/97	1	1		10	0	0	100	0	0	1	0		10	2	20	100	0	0
	5	3	67			0				5	4	67			20			
5/9/97	1	1		10	1	10	100	1	1	1	2		10	1	10	100	0	0
	5	3	67							5	1	50						
5/22/97	2	0		10	0	0	100	0	0	2	0		10	0	0	100	0	0
	5	0	0			0				5	1	14			0			
5/28/97	5	8	160	20	1	5	100	4	4	5	0	0	20	2	10	100	1	1
6/4/97	2	3		20	3	15	100	2	2	2	0		20	4	20	100	4	4
	5	7	143							5	3	43						
6/13/97	1	1		10	1	10	100	5		1	1		5	1		100	0	0
	2	2	100				100	7	6	2	2	100	10	3	27			
6/18/97	1	35		5	19		100	1		1	12		5	41		100	0	0
	2	44	2633	10	17	240	100	6	4	2	27	1300	10	0	**273**			
6/20/97	1	15		5	6					1	31		5	16		100	3	
	2	18	1100	10	16	147				2	44	2500	10	10	173	100	2	3
6/25/97	1	12		5	3		100	1		1	3	300	5	2		100	42	
	2	37	1633	10	5	53	100	1	1				10	3	33	100	ntc	ntc
6/30/97	0.5	8		5	15		100	1		0.5	1		5	2		100	3	
	1	10	1200	10	26	273	100	1	1	1	6	467	10	4	40	100	14	9
7/4/97	0.5	3		5	23		100	1		0.5	36		5	55		100	0	
	1	5	533	10	35	387	100	4	3	1	15	3400	10	57	747	100	12	6
7/18/97	0.5	1		5	6		100	0		0.5	2		5	2		100	2	
	1	2	200	10	8	93	100	0	0	1	4	400	10	2	27	100	4	3
7/23/97	0.1	1		5	2		100	0		0.1	0		5	0		100	2	
	1	2	273	10	0	13	100	0	0	1	7	636	10	1	7	100	0	1
7/27/97	0.1	1		6.2	1		100	2		0.1	0		5	1		100	6	
	1	6	636	10	0	6	100	1	2	1	2	182	10	2	20	100	5	6
8/1/97	0.1	1		5	3		100	20		0.1	2		5	7		100	0	
	1	3	364	10	5	53	100	28	24	1	1	273	10	12	127	100	6	3
8/8/97				5	2		100	3					5	2		100	2	
				10	2	27	100	4	4				10	3	33	100	0	1

Appendix D: TSS Concentration in URFL wash water

Normal hydraulic cleaning

Time(S)	Trial-1	Trial-2	Trial-3
0	5626	44285	40160
5	ns	8950	22095
10	ns	6452	16645
15	4112	5130	27158
20	ns	4675	34702
25	ns	4478	19437
30	2260	3409	12882
35	ns	2900	9194
40	ns	2926	6548
45	ns	2326	6938
50	ns	ns	4763
55	ns	ns	4332
60	622	1539	3542
75	ns	1192	2254
90	293	779	1686
105	ns	577	1032
120	164	446	464
135	127	336	588
150	107	276	748
165	ns	197	622
180	83	152	1830
190	ns	350	3260
195	205	ns	ns
200	ns	ns	6170
210	ns	3678	ns
215	ns	ns	13510
225	3717	23775	ns
235	ns	ns	39675
240	1866	12130	ns
255	ns	5408	ns
270	ns	2321	ns

Shock loading effects

Time(S)	Trial-1
0	45970
10	10980
20	4460
30	3210
40	1510
50	985
60	633
0	785
10	584
20	518
30	273
40	334
50	291
60	261
5	378
10	338
15	1472
20	3064
25	4010
30	5280
35	10460
5	9180
10	11560
15	14960
20	58967
25	27340
30	25825
35	16300

Key:
ns – not sampled