water-e

Slow Sand Filters

About water-e

The **water-e** website provides building guidelines for water and sanitation technologies.

We provide practical information on how to build and run water and sanitation treatment works in places where high-tech solutions are unavailable, above all in the developing world.

The website is intended as a guide for NGOs, relief agencies and public utilities in the developing world, but all our information is freely accessible to anyone with an interest in this area and we hope you find it useful. Please respect references where you see them.

We have tried to keep the manual straightforward so that anyone can use it, and easy to navigate so you can go directly to the information you need if you have a specific question. On the homepage we ask you to select what scale of operation you are interested in so that we give you the information that is most relevant to you.

Currently we provide information only on slow sand filtration. We believe this technology has great potential in the developing world due to its relative simplicity. We hope to introduce more technologies in the future.

The **water-e** website is a joint initiative of:

- Centre for Environmental Health Engineering (CEHE) at the University of Surrey
- RWE Thames Water

Our objectives are:

- To put useful (free) information into the public domain regarding drinking water treatment, with an emphasis on developing country applications.
- To enhance the level of access to organisations active in developing world water (and sanitation) issues by providing useful links to appropriate websites.
- To provide guidelines on design, construction and operation of slow sand filters (more technologies will be availalbe in the future).
- To be user-friendly and accessible to those people without a scientific background, and to those who may only have access to relatively basic PCs operating through a dial-up Internet connection.

The water-e website can be found at:

http://www.surrey.ac.uk/water-e

1 Introduction

The information provided in this document describes a basic drinking water treatment technology (slow sand filtration). Slow sand filters (SSFs) have been used to treat water for 200 years and remain an appropriate method for treating drinking water today. They are relatively simple to construct and operate, using local materials and local labour. A SSF is primarily a biological treatment process and providing basic rules are followed when designing, constructing and operating SSFs, these can be very effective at removing disease-causing micro-organisms from water (98-99% removal rates, WHO, 1996).

Guidelines for the design, construction and operation of SSFs are provided in this document based on the research and operational experiences of others.

1.1 SSF Description

A slow sand filter (SSF) is a means of treating water for drinking water purposes and involves filtering water through a bed of 'media' (usually sand). It is simple in design, construction and operation. It consists of a tank inside of which lies a 'bed' of sand (i.e. media), supported by gravel, lying on a suitable under-drainage floor (Ellis, 1985). The filter is confined within a tank, typically rectangular or circular in shape and will be 2.5 to 4 metres deep (Figure 1.1). Water enters at the top of the tank, where it resides for a number of hours due to the slow percolation of water through the bed of sand beneath. Water then passes through a layer of gravel and the under-drainage. Systems downstream of the filter vary, but simple systems may comprise only a weir and clear water reservoir.

Treatment of water in a SSF is largely achieved by ecological processes. Micro-organisms colonise the surface areas of the sand grains and feed on impurities in the water as it filters passed. This process removes impurities from the water. The biological growth on the filter media and the material that is removed by the filter clogs the sand bed, particularly at the upper surface of the bed. Eventually the filter is too clogged for water to filter through it and it must be cleaned (e.g. by skimming). Periodically removing the top layer of sand by manual or mechanical 'skimming' (also known as scraping) allows the filter to continue to function efficiently. The time period between skimming is called a SSF 'run'. The requirement for skimming is usually demonstrated by an exponentially increasing headloss (e.g. due to clogging at the sand's surface) and an associated decline in SSF surface loading rate (achievable flow rate).

With each skim a thin layer of the sand bed is removed (typically 1-3cm). Eventually insufficient sand depth (usually 0.4-0.6m) will remain for effective treatment and the sand bed will need to be 're-instated', 'trenched' or 're-sanded'. After any of these operational procedures the filter is re-started but the initial water that filters through the bed may need to be discarded (run to waste). A so-called ‘ripening period’ is required before treated water meets the required water quality standards. This is because water treatment by the filter is primarily undertaken by the biological community established in the sand bed, and operational procedures such as skimming will have disturbed this community. Water monitoring during the ripening period is important in determining when treated water is of drinking water quality.

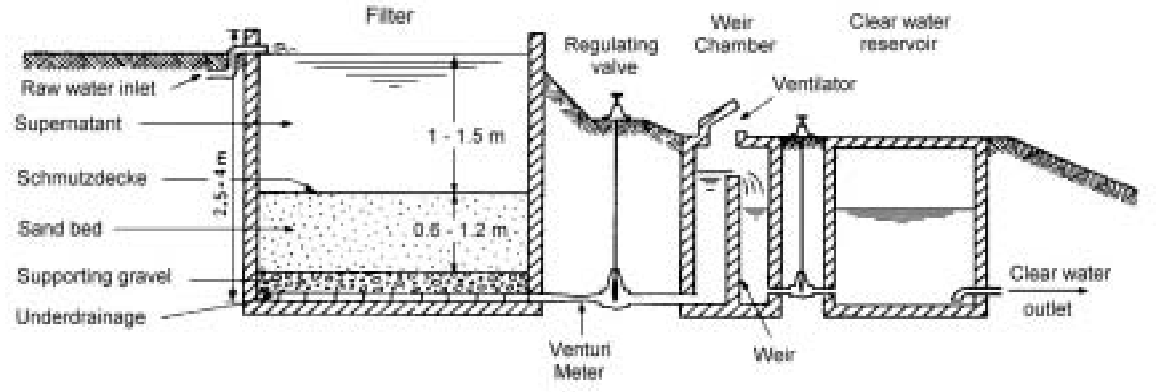


Figure 1.1: Sketch of a Slow Sand Filter (reprinted from Huisman & Wood, *Slow Sand Filtration*, Copyright (1974), with permission from the publisher, World Health Organisation, WHO)

Four basic components of the slow sand filter can be identified:

1. Supernatant, also known as the top water.
2. Filter bed, also known as the bed, media, or sand bed.
3. Under-drainage system.
4. Flow control systems (i.e. regulating valves, weir etc).

- Supernatant (Top Water)

The storage of water above the bed is called the supernatant. Its depth typically varies between 1 and 1.5m, which by selecting an appropriate filter area, constitutes between 3 to 24 hours of water supply (Huisman & Wood, 1974). The supernatant provides the driving head to push water through the media, under-drainage and flow control systems (Visscher *et al*, 1987).

The supernatant aids water treatment by sedimentation of heavy particulate matter, equalisation of influent water quality and some biological action such as bacterial die off (Fox *et al*, 1994). If the supernatant remains open to the atmosphere, then some degradation in water quality can be expected, for example due to contamination from wildlife (e.g. birds) and algal growth. Whilst these factors are unlikely to threaten the quality of the SSF treated water, algal growth in particular is an operational nuisance (Section 2.2.6).

- Filter Bed (media, sand)

The filter bed (also referred to as the ‘media bed’ or ‘bed’) usually comprises a uniform mixture of sand grains throughout its depth (Kiely, 1998). Its depth will typically vary between 0.6 and 1.2m (Huisman & Wood, 1974).

Most the water treatment in a SSF occurs within this bed of sand (Huisman & Wood, 1974). The sand grains are effective at capturing particulates. They provide a large surface area for attachment and microbiological growth, and the comparatively small interstitial spaces (pores, spaces between the sand grains) encourage sedimentation (Fox *et al*, 1994). The most microbiologically active zone is conventionally thought to be in the upper sand layers. The ‘schmutzdecke’ (literally translating as ‘dirty layer’ or ‘sludge blanket’) is a term given to the biological growth that occurs on the surface of the filter bed. Schmutzdecke growth assists in effecting treatment, however it is not essential to the treatment process and may cause clogging at the filter’s surface (Section 2).

- Under-drainage System

The under-drainage must be able to support the weight of the sand, the supernatant, and any maintenance procedures whilst enabling the free and even drainage of filtered water. Under-drainage systems can be built from perforated pipes, concrete tiles, bricks, porous concrete or other materials. Above the under-drainage system, gravel is laid to prevent sand from blocking the under-drainage orifices. An inappropriately designed under-drainage can result in water short-circuiting the filter bed, resulting in inefficient treatment and poor filtrate quality (Fox *et al*, 1994).

If skimming is manual then the weight of a man and wheelbarrow might be the greatest load it must support (Fox *et al*, 1994). For SSFs that are skimmed by vehicles, the under-drainage system will need to be capable of supporting greater loads.

- Flow Control Systems

The term ‘flow control systems’ refers to those aspects of the SSF design that allow operatives to control the SSF (e.g. to make sure that surface loading rates are uniformly applied, remain constant and are low in magnitude). On a household scale SSF this simply refers to the regulating valves and measures taken to maintain a constant head of water above the sand.

For larger (e.g. community) scale SSFs flow control systems will also comprise regulating valves and measures to maintain a constant head of water above the filter bed. Methods vary, for example community scale SSFs may use a weir within the outlet chamber. This ensures that the supernatant water level never drops below the filter’s media surface during operation (Huisman & Wood, 1974). This minimises air-binding problems (below atmospheric pressure in the filter bed) and avoids accidental bed drain-down, thus protecting the filter’s microbiological community from desiccation.

Flow control systems also permit water levels to be adjusted during operation, and enable backfilling to take place when a filter is recharged (refilled) after skimming. Additional functions are:

- Delivery of water into the supernatant.
- Removal of scum and floating debris from the supernatant.
- Supernatant drainage prior to filter skimming.
- Water level control within the SSF box.
- Control of surface loading rate (with respect to headloss).
- Re-circulation of water.
- Run to waste (RTW) of water.

(Huisman & Wood, 1974)

The design of a SSF's flow control systems will depend on whether it is controlled at the inlet (Figure 4.10) or the outlet (Figure 4.9). This is discussed in Section 4.2

1.2 Advantages of SSFs

SSF are a simple, reliable and effective means of achieving potable water treatment (Visscher, 1988, Boller, 1994, Lloyd, 1974). In 1974, Huisman & Wood stated that no other single process was thought to improve water quality physically, chemically and bacteriologically to the extent that slow sand filtration achieved. When operated properly, SSFs are an effective barrier against passage of pathogenic micro-organisms. They produce consistently high-quality treated water and provide a 'high safety factor', which reportedly cannot be matched by alternatives such as rapid filtration (Ellis, 1985). SSFs are also viewed as an effective barrier against *Giardia* cysts (Logsdon & Fox, 1988, Hendricks & Bellamy, 1991, Seelaus *et al*, 1986) and *Cryptosporidium* oocysts (Timms *et al*, 1994). The microbiological treatment achieved by SSFs is evident from examples taken from the time period before disinfection treatment was common-place, for example the frequently cited cholera outbreak in Elbe, in Hamburg (Shadwell, 1899, Kirkpatrick, 1917, Lloyd, 1974). Hamburg received unfiltered water from the River Elbe whilst the inhabitants of Altona (downstream of Hamburg) abstracted their water from the River Elbe but passed it through slow sand filters prior to supply. The 1892 cholera epidemic (due to infected water supply) caused thousands of infections in Hamburg. In contrast, not a single case was attributed to the Altona water supply (Lloyd, 1974).

Although there is evidence of biofilm growth in distribution pipes served by SSF treated water (McMath, 1998), this water is not thought to support microbiological re-growth in the distribution network to the same extent that treated water would in the absence of biological filtration (Huisman & Wood, 1974). This is particularly an advantage when water is not being chlorinated.

In areas that experience water shortages, SSFs are an appropriate means of treating water because there is little water wastage (Ellis, 1985). For examples SSFs do not require wash-water in the same way that rapid filters do (Huisman & Wood, 1974). Water that passes through a SSF immediately after skimming can be diverted to another mature filter for treatment. Furthermore, the relatively low surface loading rates (Section 2.2.2) result in considerable water storage (3-4 hours, Montiel *et al,* 1988). This may be useful for water treatment works where there is little upstream water storage. For example, in the case of short-term pollution of raw water the supply to the works can be temporarily stopped, but the supply of treated water to customers continued because the SSFs can continue to operate until their supernatant water is depleted. The large volume of supernatant water thus acts as a buffer (Montiel *et al,* 1988). Such water storage also enables consistency in SSF operation if influent water supply is interrupted for short periods. Consistent operating conditions are fundamental to ensuring effective treatment using SSFs (Section 2.2.2).

A slow sand filter is also a low energy-consuming process (Boller, 1994). The media removed from SSFs during skimming or re-sanding can be washed and re-used. No chemical dosing is required, mechanical equipment is limited and maintenance can be carried out by relatively unskilled labour (Shangarpawar & Kulkarni, 1994). There is also only low production of waste sludge (Ellis, 1985) and this is non-toxic. Furthermore, the media can be washed and re-used. SSFs are therefore a relatively environmentally friendly treatment technology.

Montiel *et al* (1988) described slow sand filtration as a microbiological barrier which is largely unaffected by human error. It is described by some as a ‘passive’ treatment process because it does not depend on active process control (Seelaus *et al*, 1986). They are easily constructed, and can be built using local resources, thereby ensuring minimal dependence on outside sources for any materials, goods or services (Seelaus *et al*, 1986). Such advantages render slow sand filtration an appropriate technology for many developing countries and small rural settlements (Visscher, 1988, Ryan, 1988, Poynter & Slade, 1977). By employing local labour there are also economic benefits (Seelaus *et al*, 1986).

The costs associated with SSF construction are relatively low (if land area is not an issue); therefore short design periods are usually possible. The cost of their operation lies primarily with filter skimming (60-80%, Rachwal *et al* 1988). SSFs are therefore a sustainable water treatment technology both economically and environmentally (Boller, 1994), however they have been abandoned or avoided by some in recent years due to the large space requirements and associated cost. For small rural settlements this is usually not an issue.

1.3 Limitations of SSFs

The high land requirements of slow sand filtration and associated construction costs may limit its suitability for water treatment plants located in and near urban areas (Huck 1989, Buffle 1984). Consequently, increased capital costs may outweigh the benefits of subsequently low operational costs.

The simplicity of slow sand filter operation is frequently highlighted as an advantage, however, with this approach there is a risk that SSFs are not given the necessary degree of attention to design and during operation (Ryan, 1988). Slow sand filtration is a relatively simple technology to operate, however, it requires operating conditions that remain constant (Buffle, 1984). This makes it less appropriate for raw waters that experience changes in quality (Shangarpawar & Kulkarni, 1994). Although, the composition of pre-treatment processes can be designed to cope with fluctuations in the quality of a specific raw water. Collins *et al* (1991) reported shortened filter runs when influent water turbidity and algal content exceeded relatively low levels. Therefore the inability to provide adequate pre-treatment may render slow sand filtration an inappropriate treatment process. Rapid headloss development and short filter runs are limitations causing SSFs in many developing country locations to have become inoperable and in need of rehabilitation (Boller, 1994). Evidence suggests, however, that these problems can be overcome (without need for chemical dosing) by deployment of pre-filtration processes (Boller 1994, Lloyd *et al*, 1988). Innovative measures (e.g. surface mats) have also been developed, and may be suitable for some applications (Mbwette & Graham, 1988, Graham *et al*, 1996).

SSF pre-treatment processes that employ the use of chemicals (e.g. ozone treatment) must be operated with care since biological systems (i.e. SSFs) can be prone to being ‘poisoned’ or damaged by the products of up-stream processes (Bates, 2000). If a chemical residual is carried over to a SSF this could adversely impact the filter’s microbiological community. A SSF’s vulnerability to irregularly operated pre-treatment processes (and thus influent water quality changes) can adversely impact upon SSF treatment. Thus appropriate pre-treatment ensures a SSF receives constant influent water quality, but it is vulnerable when these pre-treatment processes encounter problems.

SSF performance may be compromised in countries with a temperate climate, due to a seasonal decline in microbiological activity (during cold periods, Section 2.2.7), as well as due to problems associated with seasonal algal growth (e.g. during the spring and later summer, Section 2.2.6). Further disadvantages of slow sand filtration include loss of productivity during the relatively long filter skimming and ripening periods (Collins *et al*, 1991).

2 Theory

2.1 Removal Mechanisms

As water filters through the media, impurities in solution are brought into contact with the sand particles and are held there. Inert material captured in the upper sand layers is eventually removed by filter skimming, whilst that which is chemically or biologically degradable will first convert to simpler forms (Huisman & Wood, 1974). Physical, chemical and biological processes take place, although SSFs are predominantly biological systems. Before reviewing some of the transport, attachment and detachment mechanisms conventionally described when discussing filtration theory, the role of ‘biofilm’ and micro-organisms in SSF treatment is first discussed.

2.1.1 The Microbiological Community

The presence of a microbiological community in the bed of sand of a SSF is fundamental to achieving effective water treatment. Micro-organisms colonise and multiply on the sand’s surface and feed on bacteria, viruses and organic matter in the water as it filters passed (Brikké & Bredero, 2003).

Micro-organisms will inhabit the supernatant, biofilm and interstitial areas of the filter (pore spaces between the sand grains). As a biological system, these communities vary both spatially and temporally, and will grow, interact with one another, and hence dynamically change through the course of a SSF run. The behaviour of the micro-organisms will largely be governed by the environmental conditions provided within the SSF, which in turn will be controlled by natural factors (e.g. climate) and operational control parameters (e.g. surface loading rate). For example, the majority of the micro-organisms inhabiting a filter bed are conventionally thought to be located in the top 0.3-0.4m, however they will move deeper if the environment is suitable, for example when higher surface loading rates carry the supply of food and dissolved oxygen (DO) deeper in the bed (Huisman & Wood, 1974). By drawing attention to the complexity of such a system, the importance of maintaining consistency with regards to a SSF’s operation is highlighted. When steady-state conditions are not maintained then the microbiological community must adapt to the changing environment and this makes its treatment less effective. A SSF is a relatively robust water treatment process, but it is vulnerable to factors that adversely affect the microbiological community.

Microbiological population size, species composition and its depth distribution will change with time during a SSF run. Some of these changes will be induced by environmental factors such as the substrate (‘food’), nutrient and DO content of the filtering water, exposure to sunlight and temperature (Characklis *et al*, 1990). Initially if a SSF is started with a new bed of sand, or if it has had a large proportion of its microbiological community removed through skimming, then water treatment may be less effective due to the lack of a microbiological community. Efficient SSF treatment requires the relatively rapid (1-2 days) colonisation of clean media by micro-organisms and their persistence at high population densities throughout the filter run (Lloyd, 1974). Microbiological populations are subsequently thought to increase with time into a SSF run, due to ‘conditioning’ of the media surfaces and the development and growth of so-called ‘biofilm’.

The presence of a biological community in a SSF leads it to exhibit its own individual characteristics based on a number of environmental and operational variables (e.g. climate, raw water quality, surface loading rate etc). The biological community will adapt to any changes in these conditions. The SSF should therefore be thought of as an ecosystem of living organisms rather than a machine (Huisman & Wood, 1974). In order to keep this system performing effectively (i.e. producing good quality filtrate) all environmental and operational parameters should be kept as constant as possible.

2.1.2 Biofilm

"*Biofilm consists of living cells, dead cells, and the cell debris in a matrix of extracellular polysaccharide (glycocalyx) attached to a surface*" (Bishop *et al*, 1995).

Hence biofilms consist of two important components:

- Micro-organisms within the biofilm.
- Extracellular polysaccharides (EPS).

(Characklis *et al*, 1990)

In simple terms, biofilm can be described as a biologically active film that covers the sand grains of a SSF bed, which is inhabited by micro-organisms and which assists in removing impurities from the filtering water. EPS is a substance produced by some micro-organisms to protect against adverse conditions (e.g. desiccation, starvation). The presence of biofilm within a SSF is important in achieving optimum water treatment. A biofilm provides protection to micro-organisms which otherwise would not exist in the filter. The biofilm's support for a varied microbiological population allows for the degradation of a variety of different organic substrates (Bishop, 1997). Furthermore, the nature and growth of the biofilm itself has been shown to amplify attachment mechanisms (i.e. it improves removal rates and hence filtrate quality).

2.1.3 Filtration Theory

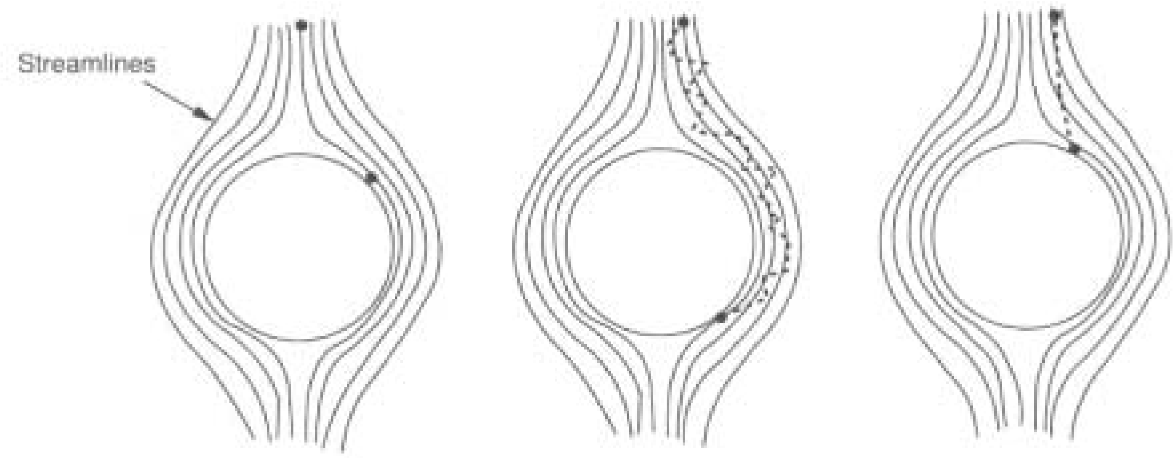
Filtration theory is conventionally described in terms of three processes:

1. Transport mechanisms
2. Attachment mechanisms
3. Detachment mechanisms

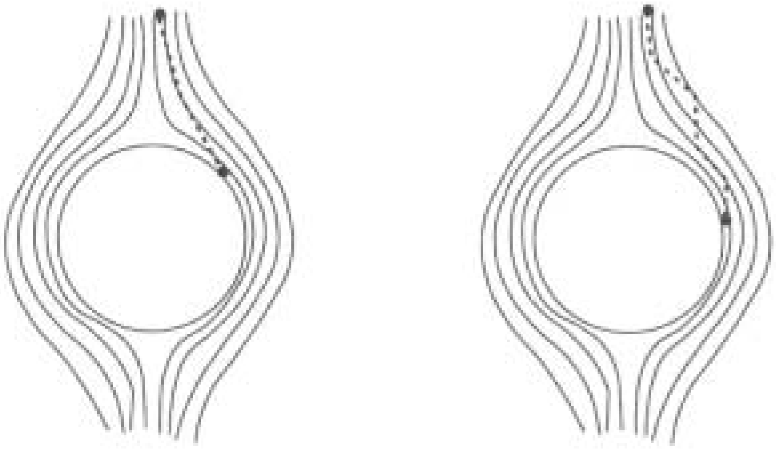
2.1.3.1 Transport

Transportation is the process of bringing the impurities (e.g. particles and micro-organisms present in the filtering water) into contact with the sand grains. Transportation mechanisms will primarily depend on the physical properties of the particles (i.e. size, shape and density). Some transport mechanisms are described below.

- Laminar/Turbulent Flow
- Interception
- Straining
- Sedimentation/Gravity
- Inertial and Centrifugal forces
- Diffusion
- Mass Attraction
- Advection
- Motility and Electrostatic and Electrokinetic forces
- Hydrodynamic forces



Interception Diffusion Inertia



Sedimentation Hydrodynamic

Figure 2.1: Transport Mechanisms in a SSF bed (reprinted from Filtration and Separation, Ives, K.J., *Deep Bed Filtration: Theory and Practice*, pp. 157-166, Copyright (1980), with permission from Elsevier)

Laminar/Turbulent Flow – An understanding of the way in which water flows between media grains is necessary in order to understand how suspended particles are brought into contact with media grains, and why and how they are held there. In the filter pores, ‘laminar flow’ conditions create velocity gradients (shear gradients) with ‘streamlines’ of maximum velocities located in the centre of pore spaces (Figure 2.1 and Figure 2.2), and with parallel streamlines declining in their velocity towards the media grains on either side (Ives, 1975). The flow pattern is smooth and in theory suspended particles proceed along these parallel paths such that each particle exactly precedes the suspended particles in the same streamline in front of it (Webber, 2003). Laminar flow is associated with low flow velocities. SSFs should be operated under laminar flow conditions to ensure minimal disturbance of the biofilm that develops on media grains. In practice this requires a relatively low and constant surface loading rate. Rapid changes to surface loading rates should be avoided.

In turbulent flow the progression of fluid particles is irregular and there is a seemingly haphazard change in particle positions. Motion is eddying and sinuous as a result of fluctuating velocities (Webber, 2003). Turbulent flow conditions in a SSF should be avoided, as they promote detachment of previously removed particles.

Interception – The concept of laminar flow supports the theory that uniformly distributed suspended particles are transported in parallel streamlines (Ives, 1975). Interception is the contact of a suspended particle and a media grain, as a result of a streamline (i.e. the centre of the particle) approaching the media grain to within the particle radius. There is contact without the particle leaving its streamline (Ives, 1982). Therefore rates of interception are increased as the diameter of the suspended particle increases and the pore size between the media grains decreases,

Straining – Straining takes place when a particle in suspension attempts to flow through a pore opening that is smaller than the particle (Ives, 1975).

In cases when straining is a dominant process, consequent accumulation of particles on the filter’s surface lead to formation of a ‘permeable layer’. This is termed ‘cake filtration’ and differs from ‘deep bed filtration’ where removal occurs within the pores (Ives, 1975). For uncovered SSFs, cake formation may occur as a result of algal growth or straining of debris that has fallen into the supernatant. Formation of a surface mat differs from the formation of a ‘schmutzdecke’ (where biological growth in a SSF is responsible for causing surface clogging).

As pore volume decreases during the SSF run (due to clogging by material removed in the media), the probability of the pores being blocked by straining increases. Therefore, dominance of straining and interception in a SSF lead to a rapid headloss development across the upper sand layer (Darby & Lawler, 1990) resulting in short run lengths and an unsustainable treatment process.

Therefore straining should not be a significant transport mechanism in a SSF. Pre-treatment processes should ensure that suspended particles in influent water are smaller than the pore spaces (determined by the correct choice of bed media) and therefore that straining does not dominate removal (Ives, 1980). Although, during the end of a SSF run when headloss is high, straining may become more significant.

Sedimentation - Sedimentation under the influence of gravity will cause removal of suspended particles that are denser than the filtering water. Larger, denser particles will settle first. The surface loading rate will determine the approach velocity of suspended particles and therefore the extent to which sedimentation occurs in SSFs. Higher surface loading rates might be associated with reduced removal due to lower sedimentation rates.

Flocculation (agglomeration of suspended material) will increase sedimentation efficiency, however this may still not settle colloidal matter (colloids are small particles, of diameters of 1µm or less). It is also unlikely that bacteria will settle under gravity, unless it has become unstable and formed flocs (flocculated material). As headloss increases towards the end of a run, flow rates are increased to maintain output, thus limiting settlement to the larger/denser particles. Sedimentation is only likely in mature beds if new attachment sites are provided via detachment, or, if flow rates are reduced.

Inertial - Laminar flow is assumed within a slow sand filter, but convergence of streamlines as water moves between media grains may cause suspended particles with sufficient inertia to swerve off the line of flow that they would otherwise have followed. A particle may come into contact with the sand grain as a result, and attach. This is more likely for dense particles (Ives & Gregory, 1967). In contrast to sedimentation, transport via inertia increases as surface loading rates increase (Ives, 1975).

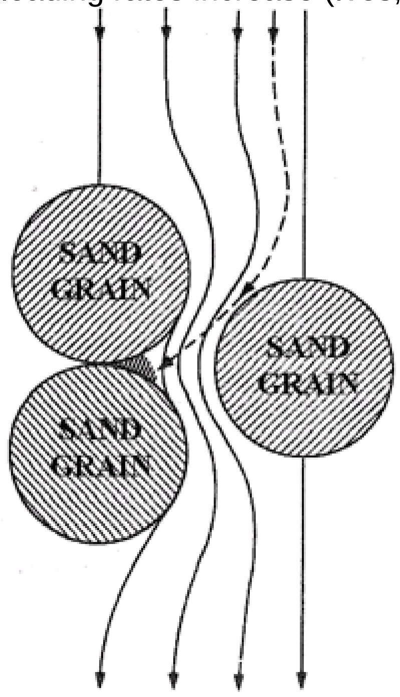


Figure 2.2: Schematic of streamlines within a sand bed and Inertial Transport (reprinted from Huisman & Wood, *Slow Sand Filtration*, Copyright (1974), with permission from the publisher, World Health Organisation, WHO).

Diffusion - Within a biological filter, diffusion is the term used to describe 'mass transport' via Brownian motion (Yao *et al*, 1971). Brownian motion is the movement of suspended particles in a fluid due to their bombardment by molecules in that fluid. Thus there is a transfer of thermodynamic energy to kinetic energy, from the water molecules of the bulk fluid to the particles suspended in it. As a result of its collisions with the water molecules, a suspended particle will take a series of discrete steps (also called a 'random walk', Hendricks *et al*, 1991). These so-called 'Brownian effects' are sometimes also termed 'Stochastic effects' thereby emphasising the randomness of this movement. Diffusion occurs independently of surface loading rate and continues even when the latter is stopped (Huisman & Wood, 1974). However, if the particle is also being transported by convective flow, then diffusion is superimposed onto this, and the particle will move from one streamline to another, until eventually it may collide with a media grain. It follows, that the lower the surface loading rate, the more (diffusion induced) steps a particle can take whilst within the media bed, and the higher the probability that it will collide with a media grain (Hendricks *et al*, 1991).

Diffusion is important for the transport of small non-motile micro-organisms (<1µm) and assists in removing these particles by bringing about the initial contact between the particle and media grain (Ives & Gregory, 1967).

Advection – Advection is the transport of a property (matter or energy) by mass motion (Parker, 1994, Uvarov & Isaacs, 1986). Hence in the context of filtration, suspended matter will be transported through the interstitial spaces due to the flow of the filtering water. Relative to diffusional transport, advective transport is rapid (Boyle, 1993 cited by Evans, 1999).

Motility - Some micro-organisms have surface appendages which enable them to move (e.g. flagella). This enables their movement in search of substrate (food, i.e. impurities requiring removal). Surface appendages may also play an important role in the attachment and aggregation of micro-organisms (Marshall, 1985).

Hydrodynamic Forces- Under laminar flow conditions zero velocity is assumed at the surface of the media grain and parallel velocity streamlines demonstrate increasing magnitude with distance from the media grain (Ives & Gregory, 1967). Thus maximum velocities are assumed to pass through the centre of a pore space. Given the improbability that a particle will be perfectly spherical, and that its centre of mass and hydrodynamic centre will coincide, it is likely that 'out of balance' forces are exerted across it (Ives, 1975). It follows that a suspended particle will experience uneven drag forces on one side compared to another, such that it moves off its original course, across the streamlines, and collides with a media grain.

Summary - It may be summarised that sedimentation, interception and inertia are dominant in removing larger particles (>50µm diameter), and diffusion is largely responsible for the transport of smaller particles (<1µm diameter) to the sand grain's surface. Those particles which do not fit into either of these categories (i.e. with diameters of 1µm to 50µm) are still removed by a SSF, due to hydrodynamic effects (Ives & Gregory 1967).

2.1.3.2 Attachment Mechanisms

Once a particle has come into contact with a sand grain it will need to be held there for particle removal to occur. The mechanisms which hold the particles to the sand grains are termed attachment mechanisms. These operate over short distances (0.1µm; Ives 1980), and will depend largely on the surface characteristics of the media, as well as the chemistry of the filtering water. Some attachment mechanisms are described below.

- Van der Waal's Forces
- Electrical Double Layer Interactions
- Hydration
- Polymers and Extracellular polysaccharides

Electrical Double Layer Interactions – In simple terms, particles in suspension and the surfaces of the media grains may repel or be attracted to one another due to their similar or opposite surface charges respectively.

Van der Waal's Forces - Van der Waal's forces (intermolecular forces) exist between most materials in water and result in mass attraction for distances up to 0.05mm (Ives and Gregory, 1967). Once contact has been made between a sand grain and a suspended particle, mass attraction plays a more significant role in ensuring attachment of one to the other. This is because the distance between the centres of the masses is sufficiently reduced and as a result van der Waal's forces are able to overcome any surface electrical repulsion.

Hydration – Surfaces may be hydrophilic or hydrophobic depending on whether they attract (or are attracted to) or repel (or are repulsed by) water respectively. This can affect the attachment of a suspended particle to a sand grain. For example, some particles (particularly those of biological origin) will have hydrophilic material at their surfaces (e.g. proteins and polysaccharides), which results in 'bound water' on the surface of these particles (Gregory, 1993). This enhances particle stability (i.e. its tendency not to attach to another surface) because in order to bond to this particle, this layer of water must first be penetrated (Ives & Gregory, 1967). This is known as hydration repulsion, because work is required to dehydrate the surface (a prerequisite for contact, Gregory 1993).

Polymers and Extracellular Polymers (EPS) – Micro-organisms in nature are often faced with a 'feast-or-famine' type existence and have evolved systems for the production of polymers as reserve materials (Brock *et al*, 2000). As a result, most bacteria are able to produce so-called ‘extracellular polysaccharides’ (EPS), which may also be described as ‘glycocalyx’ (Costerton *et al*, 1985). Films such as EPS may modify (‘condition’) surfaces in advance of microbiological colonisation (Zobell 1943 cited by Characklis & Marshall, 1990). EPS makes the environment on the sand grain a suitable one for microbiological colonisation and attracts and binds organic and inorganic nutrients in the area immediately surrounding the attached microbe (Costerton *et al*, 1985). EPS therefore aids removal of impurities from the water, rendering the SSF more effective.

2.1.3.3 Detachment Mechanisms

Detachment is the loss of previously attached particles from the media grains (e.g. loss of biomass from the biofilm) and can occur from the onset of attachment (Bryers & Characklis, 1992). Detachment mechanisms are largely influenced by the physical characteristics of the media, particles and biofilm, as well as by the type of micro-organisms and in particular their growth rates (van Loosdrecht *et al* 1995). Detached material may be removed more deeply in the SSF bed, or it may penetrate the SSF completely. Therefore operation of a SSF should try to minimise detachment mechanisms. Detachment may occur within a SSF by one or more of the following mechanisms:

- Shear
- Sloughing
- Avalanche effects
- Shedding of biofilm
- Grazing
- Migration/motility

Shear – Shear is the detachment of previously removed material, brought on by shear stress (i.e. the parallel force exerted on deposited material by filtering water due to its flow). Detachment is provoked by high flow rates or sudden changes in flow, combined with deposit instability (i.e. of the material deposited on the surface of the sand grain). Clearly, detachment during the operation of SSFs is undesirable. In order to minimise detachment by shear, lengthy run lengths should be avoided. This minimises deposit instability. Variability in surface loading rate should also be avoided to minimise shear stress.

Sloughing - Sloughing involves detachment of large aggregates of micro-organisms together with the biofilm and may be caused by number of factors (Wilcock *et al*, 1997). For example the elasticity of the biofilm and therefore its ability to deform under shear forces will influence its vulnerability to sloughing. Detachment via sloughing in SSFs may be minimised operationally by avoiding lengthy run lengths and by maintaining consistency in operational parameters (e.g. influent water quality, surface loading rate, etc).

Avalanche Effects – Large accumulations of attached particles (on the sand grain surfaces) can lead to an increase in this deposit's instability (Ives, 1975). Detachment may be caused by a suspended particle colliding with this deposit, causing it to roll down the slopes of the deposit and sometimes creating a 'micro-avalanche', thereby releasing aggregates into the filtering water (Ives, 1989).

Shedding of Biofilm – Biofilm shedding involves the periodic detachment of micro-organisms from a biofilm and will result in the provision of new 'fresh' habitats for microbiological colonisation (Costerton *et al*, 1995).

Starvation - The prevailing environmental conditions provided within the SSF (in part operationally controlled) will have a marked affect on its suitability for microbiological growth on the sand grains. If a SSF environment becomes unsuitable for a micro-organism it may detach in search of one that is more favourable (Wilcock *et al*, 1997). Detachment as a result of starvation may be minimised in a SSF by maintaining constant environmental conditions through consistency in SSF operational parameters. Excessive run lengths should also be avoided.

Grazing and Predation – Biofilm may be removed via grazing or predation, for example attached macro-fauna may graze the biofilm (so-called 'filter-feeding') and protozoa may predate on smaller organisms (Bryers, 1987). Predation may become more significant during the later stages of a SSF run, once a biomass of bacteria and small animals is established. It can improve performance of the SSF by maintaining the bacteria in an 'active' state (i.e. the bacteria attached to sand grains which remove contaminants). Conversely, predation of attached micro-organisms (and biofilm) may encourage their detachment due to the subsequent excretion of waste products into the filtering water. However, when predation removes suspended micro-organisms then this ensures their removal.

Migration/Motility – Detachment as a result of a micro-organism's motility implies that the motile micro-organism is actively participating in its attachment, and is able to overcome attractive forces in order to migrate away should the environment become unsuitable (Marshall, 1985).

2.2 Factors Affecting SSFs

A slow sand filter is predominantly a biological water treatment process, and therefore its performance is potentially affected by numerous factors. Hendricks and Bellamy (1991) categorised the factors affecting SSF performance (in terms of removal efficiency) according to design, operating and environmental variables (Table 1). The influence of some of these parameters is reviewed in the following sections.

Table 1: Process Variables Affecting Removal Efficiencies in Slow Sand Filtration (adapted and reprinted from Hendricks & Bellamy, *Micro-organism Removals by Slow Sand Filtration*, in Logsdon, G.S., (Ed.), Slow Sand

Filtration, pp. 101-121, Copyright (1991), with permission from the publisher, American Society of Civil Engineers, ASCE).

Category	**Variable**
Design	Hydraulic loading rate
	Sand size (d_{10}), Uniformity coefficient (UC)
	Headloss permitted
	Sand bed depth (max. and min.)
	Treated water storage (i.e. to maintain steady flow)
Operating	Skimming frequency (i.e. run length)
	Drain down time period during skimming
	Bed depth
	Flow rate and its variation (alleviated by water storage)
	Age of schmutzdecke (i.e. time elapsed into filter run)
Ambient	Water temperature
	Raw water quality (particle sizes, turbidity, concentration of organic matter and nutrients etc)
	Microbiological community (species and population)
	Algal growth

2.2.1 SSF Media

The correct choice of media size (or ‘Effective Size’, ES) influences operational and performance parameters. As a SSF accumulates material the media becomes clogged (headloss increases) and eventually it will be too clogged to permit the required flow through the filter and the bed will require skimming. Selection of the appropriate media will influence the frequency with which skimming is required (and thus the filter’s productivity). If the filter media is large then the initial headloss and rate of headloss development tend to be lower (Boller & Kavanaugh, 1995, Cleasby, 1991), but this may be at the expense of removal efficiency (van der Hoek *et al*, 1996, Logsdon *et al*, 2002). As a result, particulates in the water will penetrate more deeply into the filter bed before they are removed (Cleasby, 1991). Conversely, if the media it is too small (e.g. ES<0.15mm) then this might restrict run length due to rapid filter clogging (headloss development). Frequent skimming results in increased operational costs, and decreased productivity (as the filter is frequently out of service). Therefore the choice of media size must balance filtrate quality against filter run efficiency.

The media depth is another consideration. A minimum media depth (together with appropriate surface loading rate) ensures that sufficient contact is made between the filtering water and the surfaces of the media grains to achieve treatment via transport and attachment processes (Section 2.1).

2.2.2 Surface Loading Rate

Surface loading rate is the volume of water that filters through each square metre of the SSF's area, per hour ($m^3/m^2/h$). Filtration rate and flow rate are terms frequently used to describe the surface loading rate of a filter, however these parameters are more accurately defined as the velocity of water filtering through the media (m^2/h). Another commonly used term is throughput, which describes the volume of filtering water per unit time (m^3/h or Ml/d).

The surface loading rate controls the contact time between the media grains and the filtering water. Sufficient contact time is necessary between the filtering water and the sand grains to ensure that biochemical reactions are complete and that biological populations have maximised contaminant removal. The contact time between the filtering water (and its constituents) and the media grains (and/or biofilm) is controlled by the surface loading rate and depth of the media bed.

Controlling the surface loading rate is the key to effective slow sand filter treatment (Visscher, 1988). Although not true on a micro-scale, the density and composition of a SSF's microbiological community (as a whole) is thought to reach a 'steady state' with the SSF environment (Haarhoff & Cleasby, 1991). In order to maintain this balance (thereby ensuring optimal SSF performance) the conditions within the SSF and therefore the surface loading rate, must be kept constant. The optimum surface loading rate will vary with specific raw water quality, bed maturity and SSF design.

Operationally, high flow rates are advantageous because they result in greater productivity (higher volumes of water treated by the same filter area). There is also evidence of filtrate quality improvement, providing rates are not increased in excess. The supply of nutrients, substrate and dissolved oxygen to the SSF's microbiological community will be maximised by an elevated surface loading rates (Bayley, 1985). Higher surface loading rates may also enhance transport mechanisms and 'sticking' opportunities for colloidal and dissolved organic constituents (Collins *et al*, 1992).

High surface loading rates, however, result in penetration of material more deeply within the SSF bed, as well as accelerated headloss development (compared to SSFs operated at lower surface loading rates). Hence, the apparent increase in productivity (via greater throughput rates) may in fact be compromised by the shortening of run lengths (although this will depend on the feed water quality).

Although research and operational experience have demonstrated that under certain conditions higher surface loading rates are sustainable for effective SSF treatment, a fluctuating surface loading rate is not, and will cause effluent quality to deteriorate (Huisman & Wood, 1974). Variation in the surface loading rates will upset the ‘steady state’ reached by a SSF’s microbiological community. From a physical aspect, variability in surface loading rate may also promote detachment of previously removed material.

2.2.3 SSF Influent Water Quality

Use of SSFs as the sole water treatment process may not be appropriate for all situations due to a SSF’s influent water quality requirements. Pre-treatment of water may become necessary if influent water quality is poor and/or variable. Pre-treatment may also be required if operating SSFs at high surface loading rates.

Microbiological populations within the SSF will have adapted to the specific influent water characteristics. Variation in influent water quality may upset the steady-state existence of microbiological communities in a SSF, causing micro-organisms and/or the biofilm they live in to detach, resulting in filtrate quality deterioration. Influent water quality changes that alter the availability of substrate (i.e. food sources for micro-organisms), essential nutrients and DO will affect the conditions within the biofilm.

The effectiveness of a SSF will also be influenced by the surface chemistry of the suspended particles and the media, and this will be largely influenced by the influent water’s chemistry (pH, ionic strength etc) as well as the particular surface properties of the media and particulates (Boller & Kavanaugh, 1995). Hence variations in influent water quality that cause changes to the properties of suspended particles can affect the mechanisms by which these particles are captured, or remain attached on the media grains.

From an operational viewpoint, physical parameters such as influent turbidity levels must remain relatively low and constant in order to avoid rapid filter clogging and the requirement for skimming. This is discussed further in Section 3.3.

2.2.4 Dissolved Oxygen (DO)

Dissolved oxygen (DO) is the amount of oxygen (O_2) dissolved in a given volume of water. Atmospheric oxygen will dissolve in water at the air-water surface until saturation is reached for a given set of environmental conditions. Additional oxygen may be present in the water making it ‘supersaturated’, for example as a result of photosynthesis by algae. Factors also exist which cause DO levels in water to be depleted, for example microbiological respiration.

DO may be expressed as a concentration (mg/l) or in terms of percentage saturation. Values in mg/l are usually more useful, because percentage saturation values will change according to environmental conditions, such as temperature.

Low levels of DO in the water filtering through a SSF may adversely affect the microbiological community upon which the filter relies to effect treatment (Sawyer *et al*, 1994). This can result in the production of unwholesome water, with the filtrate exhibiting high bacteriological counts, discolouration and an unpleasant odour.

Opinions as to what constitutes a minimum DO value for sustenance of an aquatic biological community vary. The World Health Organisation stated that values should be kept as near to saturation as possible (e.g. 9mg/l at 20ºC, WHO, 1996). Chapman (1996) stated values below 5mg/l might adversely affect the survival of biological communities. According to Huisman & Wood (1974), and due to the spatially heterogeneous nature of the media's microbiological community, an adequate SSF filtrate DO level is one above 3mg/l.

In summary, SSF filtrate DO levels must always remain above 3mg/l (24h/d) in order for the filter to perform effectively.

2.2.5 Drain-down Period

SSF operators should attempt to minimise the period of time that a filter bed is drained in between runs (e.g. during skimming). Without the water filtering through it, the sand bed will dry, which in turn will adversely affect the microbiological community still living in the media. In addition, the DO supply to these micro-organisms is stopped whilst flow is stopped. This may result in low DO conditions developing in the SSF, which can lead to the poor water quality during the subsequent start-up. If DO levels drop low for prolonged periods of time (i.e. when it is drained for extended periods) the filter bed may turn black and smell unpleasant. In severe cases the filter bed may need to be excavated and re-instated with clean sand.

Long drain down periods are associated with poorer water quality during the start of a run and longer ripening periods (Section 5.2.7, Steele, 2004).

2.2.6 Algae

Unless a surface water is oligotrophic (nutrient poor) it is likely that it will contain algae. Hence a SSF's raw water source may contain algae and in addition, algae may grow within the treatment processes themselves (e.g. SSF supernatant) if they are uncovered. The type of algae present in a SSF is determined by water source, pH, temperature, chemical composition, turbidity and time elapsed into a SSF run. The algal composition and dominant algal species in raw water may therefore differ from that which exists in the supernatant of a SSF. The algal compositions of both influent and supernatant water are relevant. In areas experiencing marked seasonal variations, algal growth is likely to cause problems for SSF operatives at different times of the year. The dominating algal species will also vary temporally. Algae require light in order to photosynthesise. Consequently their growth in the supernatant will be almost entirely prevented by covering a filter. Algae may still enter the filter via the influent water, however, and therefore pre-treatment processes are required in conjunction with covering to remove all problems associated with algae.

Problems associated with algal growth in SSFs include:

- Diurnal fluctuation in DO levels result from photosynthetic oxygen production (during daylight hours) and respiratory depletion (24h/day). This can cause DO levels to drop markedly at night, which can result in poor filtrate quality.
- pH is affected by algal photosynthesis and respiration. The decreased carbon dioxide content as a result of photosynthesis may cause bicarbonates to dissociate into carbonates and carbon dioxide. The temporary hardness of the water decreases as a result of lowering the bicarbonate content. Subsequent precipitation of insoluble carbonates can cause filter clogging. Variation in pH will also affect down-stream disinfection efficiency (if this process exists).
- Rapid filter clogging, resultant headloss development and thus reduced run length (frequent skimming) are operational problems exacerbated by algal growth.
- En-mass death of algae (e.g. as a result of low temperatures or decline in photoperiod) and the resultant liberation of a large volume of biodegradable organic matter may require a SSF to be taken out of service and skimmed (Bellinger, 1979).
- Operational problems exist regarding removal and disposal of algae when a filter is drained down, for example during skimming. It is important to remove algae as quickly as possible from a drained SSF. If heaped algae is allowed to sit on the drained bed for prolonged periods then the SSF is likely to take longer to achieve acceptable filtrate quality during the start of the subsequent run.
- Presence of algae in treated water is linked to taste and odour problems.
- If SSF filtrate is chlorinated prior to supply then penetration of the SSF by algae will result in an increase in the chlorine demand, which is undesirable financially. There is also the possibility of disinfection by-product formation.
- Algae metabolism ‘leaks’ simple organic compounds such as sugars into the surrounding water. This increases the substrate available for micro-organisms but also increases the organic ‘load’ onto the bed, which may not be advantageous as respiration is increased (which depletes DO levels in the SSF).

In some respects, algae may also be beneficial to SSFs:

- Algae remove organic matter from supernatant water in order to support their own cell growth. Although this is later released when they die off, the organic matter that is liberated upon death is reportedly more easily degraded (Huisman & Wood, 1974).

- Filamentous algae facilitate formation of an active schmutzdecke via production of 'zoogloea'. This is said to improve removal at the schmutzdecke. In addition it encourages the presence of protozoa and other higher organisms, thus enhancing pathogen removal via predation (Huisman & Wood, 1974).
- Supplementation of DO levels through photosynthesis temporarily improves water quality during daylight hours (Kirkpatrick 1917). However the net impact of algae on SSF DO levels is considered to be detrimental.

Lloyd (1974) concluded that algae will only have beneficial effects (for SSFs) when the algae are regularly removed, photosynthesis predominates over respiration, carbon dioxide uptake raises pH rendering process water less corrosive, nutrient uptake lessens the load on to the bed media, and when the increased oxygen content of the filtering water enables increased degradation of organic material by heterotrophic micro-organisms.

Despite the apparent advantages of supernatant algal growth advocated by some, its net impact is usually one that is detrimental to SSF operation. Operational difficulties caused by algae can result in an adverse impact on performance and thus filtrate quality. The affects of algal growth are magnified during the occurrence of algal blooms. The term algal bloom refers to the proliferation of algae typically experienced (in temperate regions) in the spring and summer months when conditions are optimal for algal growth in terms of photoperiod, temperature and nutrient availability. Because algal species will vary in terms of what constitutes optimum growth conditions, different species may bloom during different times of the year. Heavy algal blooms will necessitate frequent filter skimming.

Climate will impact the degree to which algal growth affects slow sand filtration treatment.

2.2.7 Climatic and Seasonal Effects

Climatic conditions influence algal growth in SSFs. For example in temperate regions where photoperiod and temperature vary markedly from one season to the next, there can be an explosion in algal growth (algal blooms) during the spring and summer months, whilst rapid algal die-off can occur during the onset of autumn and winter (Huisman & Wood, 1974). In contrast, in tropical regions where climatic conditions are less variable, algal blooming and algal decay do not occur in such a pronounced manner, and as a result filters may behave more predictably. Thus SSFs in tropical regions may be skimmed at more regular intervals (Huisman & Wood, 1974).

Climate dictates ambient temperatures, sunlight exposure and sunlight intensity, and therefore also the temperature of the SSF. Low temperatures can adversely affect SSF performance. Temperature controls microbiological metabolic rates, as well as the speed of chemical reactions (Huisman & Wood, 1974). An approximate rule is that the rate of a reaction will double for each 10˚C rise in temperature (Sawyer *et al*, 1994). For biological systems this may be true up to a certain optimum temperature, after which the rate decreases at higher temperatures.

Therefore as temperature declines, reaction rates and microbiological metabolic rates will slow. For example, Welte and Montiel (1996) reported that biodegradation processes within a SSF are only significant when temperatures exceed 8˚C. Similarly, Seger and Rothman (1996) reported an improvement in SSF treatment for water temperatures above 8˚C. Huisman and Wood (1974) reported that at a temperature of 6˚C oxidation of ammonia becomes negligible, whilst a consistently low ambient temperature (<2˚C) will either require filters to be covered, or for chlorination to follow filtration to ensure a microbiologically safe water supply.

SSF penetration by micro-organisms is more likely at low temperatures due to the inhibited activity of grazing and predatory organisms (e.g. protozoa). For example, Lloyd (1974, 1996) warned that the re-establishment of protozoan organisms (after the interruption associated with skimming) may be slow for low temperatures and was unlikely to occur at temperatures below 3˚C. Likewise, Toms and Bayley (1988) reported penetration of SSFs by *E.coli* when temperatures fell below 4˚C. Burman (1962, cited in Huisman & Wood, 1974) estimated that the typical 100-1000 fold reduction in *E.coli* associated with a properly functioning SSF might fall to levels as low as a 2-fold reduction, when temperatures dropped to 2˚C or less.

During seasons characterised by high temperatures and long photoperiods, biological growth in the supernatant of an uncovered SSF is high. This may increase the microbiological challenge presented to the filter. The SSF will also be more vulnerable to the development of low DO conditions (Section 2.2.4). Algal growth and its associated problems will also be maximised (Section 2.2.6).

Covering a SSF enables operatives to control climatic variables such as temperature and sunlight exposure, thus restricting algal growth whilst maintaining optimum temperatures for the filter's microbiological community.

2.2.8 Operator Attention and Training

Environmental factors such as sunlight exposure, temperature, influent water quality, and the behaviour of the microbiological community will affect the performance of a SSF. Providing that there is adequate pre-treatment of water and that the SSF structure and its flow control systems are maintained, then these factors can largely be controlled operationally. Therefore a key factor likely to influence the reliability of a SSF is operator attention and training. Improving operative understanding regarding the implication of aspects of SSF control may assist in preventing detrimental operational practices. This is discussed further in Section 5.2.1.

3 Pre-Design Considerations

An understanding of the science behind SSF treatment is useful when designing a SSF since adaptations can be made to design (for example to maximise use of local materials) but these must be done in such a way that treatment is not compromised. Since SSF design often tries to maximise the use of local materials, SSF designs around the world vary, as do the specifications recommended for various SSF design criteria (e.g. sand depth, surface loading rate etc). There are a number of texts outlining SSF design criteria, however these inevitably vary in their recommendations as they consider SSF use at different scales and also under different operating conditions (e.g. rural supply with limited funds vs. large scale filters for European city supply). Therefore the suggested design parameters should be treated as guidelines (Table 6). Furthermore, picking and choosing values for design criteria from various sources is not recommended as each set of values will have been developed by a different group of engineers taking into account all aspects of the filter design (Pyper & Logsdon, 1991). As long as the rationale behind these values is understood and the basic principles of a SSF's operation are upheld, then a SSF can be designed and built with a new set of design values to suit a specific environment and community (Visscher *et al*, 1994). Although, it is recommended that these design values be tested (e.g. via pilot plant studies) before the full scale build begins.

SSFs are often recommended for pathogen removal for drinking water supply in developing countries because slow sand filtration is a proven technology, it is relatively simple to operate and it is of relatively low cost. However, Sharpe *et al* (1994) recommended that an engineer address two questions before proceeding with the actual design and construction of a full scale SSF:

1. Is a SSF appropriate for use in this location and for this community/household?
2. Can it be modified, without compromising its simplicity and low cost, to provide adequate levels of treatment and performance?

For community sized slow sand filtration systems a preliminary survey will provide information as to the feasibility of the project. This requires research into the technical and social feasibility and the possible economic and health benefits (Visscher *et al*, 1987). Some pre-design considerations are reviewed in this Section.

3.1 Suitability of Technology

A range of water treatment processes exist to treat water for drinking purposes. SSFs are one of many that may be suitable. On a **household scale** Brikké & Bredero (2003) review the following for drinking water treatment:

- Straining through fine cloth – raw water is poured through a piece of fine cotton cloth to remove some suspended solids. This may be a pre-treatment for SSFs (Section 4.1.3).
- Aeration – water is aerated by being shaken in a vessel, or by allowing it to trickle through perforated trays containing stones. This may be a pre-treatment for SSFs (Section 4.1.3).
- Storage/pre-settlement – suspended solids and pathogens will settle to the bottom of a container when water is stored in it for 48 hours. The top water can be drawn off. This may be a pre-treatment for SSFs (Section 4.1.3).
- Coagulation/Flocculation and settlement – a liquid coagulant (e.g. aluminium sulfate) is added to water and promotes agglomeration of suspended solids and their subsequent settlement. This is often a pre-treatment for rapid filters. Coagulant dosing will not be an appropriate pre-treatment method for many applications, particularly for low funded, remote installations. For example, Weglin *et al* (who reviewed the rehabilitation of SSFs and a new plant design in rural Cameroon) reported (in 1996) that the addition of chemicals for destabilisation of suspensions is rarely reliable in rural water treatment in developing countries and is "*generally bound to fail*".
- Rapid Sand Filtration – higher flow rates and coarser media than SSFs, rapid filters are a means of removing suspended solids. Although rapid filters can become biologically active (e.g. if used as primary filters without chemical dosing), they are often considered to be a physical/chemical treatment process rather than a biological one. The process is therefore usually less effective at removing pathogenic micro-organisms compared to SSFs. Rapid filters will not achieve the same level of treatment as SSFs unless they are used in combination with other treatment processes, such as coagulation/flocculation (Section 4.1.3).
- Charcoal Filter – granular charcoal or granular activated carbon filters are used to remove taste, odours and colour. These filters will also remove some chemical contaminants. Some biological treatment may also occur.
- Ceramic Filter – only suitable for water that is already relatively clear (i.e. of low turbidity). This involves water filtering through a porous unglazed ceramic cylinder.
- Solar Disinfection – water is exposed to sunlight for a period of time around midday (e.g. for 5 hours). Bottles of water may be left in the sun. The water must already be clear for effective treatment.
- Chemical Disinfection – chemicals such as bleach, chlorine and iodine can be added to water, however the correct dose can be difficult to judge and may change seasonally.
- Boiling – most pathogens will be killed (or 'inactivated') by bringing water to a rolling boil, however this method can be expensive in terms of fuel.
- Desalinisation/Evaporation – distilled water is produced. This can be expensive both because of the capital investment and fuel costs (to heat the water).

(Brikké & Bredero, 2003)

At a **community scale**, potential water treatment processes (in addition to or in place of SSFs) include:

- Storage/Sedimentation – non-colloidal suspended particles settle to the bottom of a storage tank. Solar radiation kills some micro-organisms. Often a pre-treatment for SSFs. This is described further in Section 4.2.2.
- Rapid Filtration (with or without chemical dosing) - higher flow rates and coarser media than SSFs, rapid filters are a means of removing suspended solids. Their media may comprise sand, anthracite or other materials (or a combination of these medias). They are often used after chemical treatment (i.e. coagulation/flocculation) as an alternative treatment process to SSFs (in so-called ‘conventional water treatment’). Alternatively, rapid filters are sometimes used as a pre-treatment to slow sand filtration (as primary filters). Rapid filtration is usually considered to be a physical treatment process rather than a biological one (although rapid filters can become biologically active, depending on their operation and environment). Rapid filtration is widely applicable to a range of water quality conditions, although if used alone it is unlikely to achieve the microbiological removal rates of SSFs. Rapid filtration will only provide an alternative to slow sand filtration treatment if it is used in combination with other treatment processes (e.g. coagulation/flocculation). Chemical usage (coagulants) can be tailored to specific waters based on their quality. Rapid filtration requires more operator attention than slow sand filtration and it is not as simple to operate. The requirement to backwash the filter in between runs results in a more complicated filter with mechanical parts. Higher operator attention and the need to backwash mean that rapid filters incur higher operational costs compared to SSFs. These aspects make it less suitable for small scale water treatment and possibly less appropriate for use in rural areas of the developing world. For example, with regards to coagulant dosing in rural water treatment plants in developing countries, Weglin *et al* (who reviewed the rehabilitation of SSFs and a new plant design in rural Cameroon) reported (in 1996) that it is “*rarely reliable*” and is “*generally bound to fail*”. Furthermore, Galvis (1999) concludes “*the requirements for administration, buying, transporting, storing and properly dosing chemical compounds strongly limits the wider application of this type of technology in rural communities and smaller municipalities*”. Similarly, Shenkut (1996) reported that so-called conventional water treatment (coagulant dosing and rapid filtration) is usually expensive to construct and operate due to their complexity. In addition, the requirement for imported materials and highly trained staff rendered this treatment beyond the capabilities of a community in rural Ethiopia. Conversely, use of package (modular) plants have helped make this technology suitable for small communities (Hendricks *et al*, 1991), although this means that locally sourced materials are not used and that there is a reliance on outside sources for replacement parts. Rapid

filtration also tends to involve higher plumbing costs compared to a SSF (Hendricks *et al*, 1991). If coagulants are used these must be purchased and the sludge that is removed from the process requires disposal.
Rapid filtration will be a more appropriate water treatment technology to use when source water is highly turbid. The suitability of rapid filtration may depend on the population size being served. At a certain population size use of rapid filters reportedly become more economical than SSFs (Hendricks *et al*, 1991). Specifying a maximum population size for sustainable use of SSFs is difficult, and will vary according to the specific set of circumstances. The required system capacity (i.e. design flow based on population size, its projected growth and the design period) as well as the funds available for full time operators are considerations that will help determine whether SSFs or rapid filters are more appropriate.

- Multi-stage Filtration (MSF) – this is described by the IRC as a combination of coarse gravel pre-treatment (i.e. gravel pre-filters, Section 4.2.2) and slow sand filtration, however these processes together in series can treat levels of contamination well above the levels that can be treated by SSFs alone. It is thought to be an appropriate water treatment technology for rural communities in developing countries and has a good track record of sustainable performance in the communities in Colombia where it has been installed. Rubiano (1994) reviewed the success of a multi-stage filtration system for the community of San Felipe in Colombia. Another example is provided by Galvis (1999) who described, in detail, a MSF plant producing "*low sanitary risk water from surface water sources with a wide range of contamination levels in the Andean Cauca Valley*" (Colombia). Weglin *et al* (1996) reported that a MSF system (comprising dynamic and intake gravel prefilters upstream of SSFs) was a successfully used to treat water at a treatment plant in rural Cameroon. Similarly, Li *et al* (1996) reported that a MSF system in China (consisting of a two-stage filtration system) overcame the difficulties of fluctuating raw water quality.
MSF combines effective and relatively simple pre-treatment processes in front of SSFs, thus enabling efficient bacteriological treatment of water by slow sand filtration whilst avoiding the common pitfalls of SSF treatment (e.g. variable raw water quality) via the protection provided by the pre-SSF filtration stages. The numbers of barriers (to passage of pathogenic organisms) provided by a MSF approach means that there is more security in the provision of safe supply water. It is a, so-called, integrated treatment system, which means that one treatment process's strengths compensates for another treatment process's weaknesses (Galvis, 1999). A technical paper has also been produced by the IRC (Galvis *et al*, 1998) and can be ordered from the IRC at www.irc.nl/page/1894
- Disinfection – a chemical disinfection process, for example chlorine, kills pathogens in water and provides a barrier against recontamination. Disinfection is usually a final treatment process (post-SSFs) rather than an alternative to SSFs, however, it may be appropriate to treat water

solely by disinfection when a high quality raw water source is available (Table 2).

The suitability of each technology will depend on the available funds, raw water quality and the population size of the community being served. Choice will also be affected by feasibility of alternative treatment processes, for example the (long term) availability of chemicals, or access to an electricity supply.

SSFs may be built from locally sourced materials and using local labour, hence capital costs are mostly local expenditures (Hendricks *et al*, 1991). SSFs can be designed such that they need no outside supplies and minimal operator intervention. Operation and maintenance is relatively simple and essentially consists of surface loading rate adjustment, headloss and turbidity monitoring and periodic skimming (Hendricks *et al*, 1991). Household scale SSFs can be operated by a single person, and require little daily maintenance. Community scale SSFs are obviously more labour intensive to operate and maintain and will require one or more (possibly full time) operatives with back-up supervision. Low maintenance requirements make SSFs a suitable technology for small rural settlements with low funds. However, raw water quality needs to meet certain requirements in order for SSFs to be operationally sustainable. In addition, problems may be experienced in cold climates and when SSFs are fed using low-nutrient water (Hendricks *et al*, 1991). Galvis (1999) reports that use of slow sand filtration in South America has been relatively unsuccessful because in many cases they were not "*used in harmony with the local conditions*". However, use of pre-treatment processes is a means by which SSFs can be made suitable for water treatment despite local conditions.

Further review of these processes and their effectiveness at treating water as well as other factors to consider when choosing an appropriate means to treat drinking water are discussed by:

- WELL at www.lboro.ac.uk/well/resources/technical-briefs/technical-briefs.htm 'Choosing an Appropriate Technology', Technical Brief 49).
- Brikké & Bredero (2003) at www.who.int/water_sanitation_health/hygiene/om/en/linkingchap6.pdf
- Smet & van Wijk (2002), requires purchase from IRC at www.irc.nl/page/2481

3.2 Source Influent Water

Choice of raw water source will be governed primarily by what is available at adequate capacity, and then secondly (if more than one source exists) which one is 'least potentially dangerous' (Husiman & Wood, 1974). Raw water may be obtained from several sources:

- Ground water – this consists of either finite ‘fossil’ water from deep aquifers, or renewable sources. Ground water can be sourced from springs, wells or boreholes (Visscher *et al*, 1987). Deeper sources tend to be bacteriologically safe, but may have a higher mineral content. This can make the water unpleasant to drink, or even harmful (Visscher *et al*, 1987). For example ground water can contain unacceptable constituents such as arsenic, uranium etc (Bates, 2000). Conversely, if a shallow ground water source is used this may be prone to contamination from surface activities, for example nearby pit latrines, septic ponds or cattle ponds (Visscher *et al*, 1987). Nevertheless as a generalisation, the requirements for ground water treatment (in drinking water supply) are usually minimal compared to other water sources (Bouwer & Crowe, 1988).
- Surface water – derived from streams, rivers, canals, ponds or lakes, surface water sources can vary markedly in terms of their quality. Surface water usually requires more rigorous treatment in order to make it suitable for drinking water purposes (Bouwer & Crowe, 1988). It is likely that surface water will have been exposed to pollution from human activity, surface run-off and possibly biological growth and also eutrophication. Surface water quality is also likely to be more variable both on a daily and seasonal basis (Visscher *et al*, 1987).
- Rain water – In the absence of ground and surface water sources and providing a region’s rainfall is reliable and continuous year round, then rain water may be an appropriate source of water for potable supply. Alternatively, rain water may be used in conjunction with other raw sources, particularly when the other water source is intermittent or its means of supply (e.g. pump) is prone to breaking down (Huisman *et al*, 1981). Storage of collected rain water can balance supply during short periods of no rainfall and may make this a suitable water source for small scale drinking water supply. Rain water can be collected from the roofs of houses, or from surface runoff areas (Visscher *et al*, 1987). Although, collection of water from surface runoff (Plate 3.1) results in the requirement for more rigorous treatment compared to collection directly (e.g. from roof tops).

Plate 3.1: Rain-water run-off at Matimba (Rwanda) in October 2002. This water is subject to contamination.

Raw water intended for treatment by SSFs should be as low as possible in turbidity, bacteria, colour, heavy metals, toxic substances, algae and other detrimental substances such as iron and manganese (Pyper & Logsdon, 1991). Although some of these parameters can be assessed visually, a chemical and microbiological analysis of the raw water is required to ascertain levels of others. Therefore raw water quality testing will help to decide which water source is most suitable. It is also recommended (Pyper & Logsdon, 1991) that the source of the raw water be surveyed (in a sanitary survey) for sources of potential gross contamination, for example are there pit latrines in the vicinity of a borehole, or, does human waste enter the river upstream of the suggested abstraction point? Ideally raw water quality testing should be undertaken for a year-long period in order to determine seasonal changes in source water quality such as peak turbidities during seasons of high rainfall. Such an analysis can be undertaken in conjunction with pilot plant studies (Section 3.9). Instructions on how to undertake a sanitary survey are provided by Lloyd and Helmer (1991). This reference also provides case studies, explains how water surveillance results can be analysed and reviews remedial action.

Quality is not the only issue to consider for SSF influent water, the reliability of this supply is another consideration. SSFs require constant operating conditions. Flow control is needed at the point of raw water abstraction to ensure that the SSF runs continuously and not intermittently as a result of intermittent supply (Lloyd *et al*, 1988).

If river-derived water is unavailable for part of the year, every year, then pre-SSF water storage may be necessary to maintain a constant supply of influent water to the SSF. For example, household scale SSFs can incorporate a header tank that can be filled once every day from whatever supply water is available, although this water source should ideally remain the same throughout the year. Community scale SSFs can also be built with a raw-water storage facility, though this is usually used to balance intermittent abstraction of raw water over a period of hours, rather than days or months. If sufficient funds and space are available a storage reservoir may be built that has sufficient capacity to balance raw water supply and SSF's influent water demands for longer time periods.

Further guidelines for water source selection are provided by WELL at www.lboro.ac.uk/well/resources/technical-briefs/technical-briefs.htm 'Water Source Selection', Technical Brief 55).

3.3 Assessing Influent Quality

Influent water quality will affect SSF operational parameters and hence whether this is an appropriate technology to use in isolation, or whether pre-treatment is required. If extensive pre-treatment is required then this affects the decision to use SSFs based on the simplicity of the process. A SSF is a simple and effective technology, but these benefits can be compromised by the inclination to incorporate advanced technologies in an attempt to make a SSF appropriate to treat a specific raw water quality (Sharpe *et al*, 1994).

The quality of influent water will also determine whether a SSF is an appropriate technology for producing water of adequate quality for drinking water purposes given its treatment capabilities. For example a SSF can be highly effective at microbial removal, however it will be unable to remove heavy metals or non-biodegradable synthetic organic compounds (Cleasby, 1991). Pilot trials could be used to assess whether these contaminants are effectively removed by the SSF (Section 3.9).

When discussing a SSF's influent water quality requirements the reduction of influent turbidity levels (Plate 3.2) has been given priority by many (Huisman & Wood, 1974, Ellis, 1985, Cleasby, 1991, Logsdon *et al*, 2002). This is because influent turbidity values can be used to reflect the general quality of the water, but also because turbidity levels will influence the rate of headloss development (filter clogging), and thus run length and the maintenance costs incurred in cleaning SSFs. A major disadvantage of SSFs is their vulnerability to high suspended solids loads in influent water. High turbidity levels (e.g. for muddy clay-bearing waters) shorten SSF run lengths and may make SSFs inappropriate (at least without pre-treatment) because the filter is out of service for a large proportion of the time (for skimming). As a guideline, Hendricks *et al* (1991) reported that SSFs should be expected to maintain run lengths of over 30 days, whilst run lengths of several months should be considered fortunate.

Huisman and Wood (1974) recommended that influent water should demonstrate turbidity values below 10NTU in order for SSFs to be used sustainably. Visscher *et al*, (1987) stated that SSFs could only deal with raw water with turbidity values below 20-30NTU, and provided a useful table suggesting the levels of treatment required based on raw water quality (Table 2).

Plate 3.2: Turbid source water. River intake for the Nyabwishongwezi Water Treatment Plant, Umatara, Rwanda

Table 2: Guidelines for the Selection of Water Treatment System for Surface Water in Rural Areas (adapted and reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply*), Technical Paper No. 24, Copyright (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

Raw Water Quality	**Treatment Required**
Turbidity: 0-5NTU Faecal Coliform MPN*: 0 Guinea worm or schistosomiasis not endemic	No Treatment
Turbidity: 0-5NTU Faecal Coliform MPN*: 0 Guinea worm or schistosomiasis endemic	Slow Sand Filtration
Turbidity: 0-20NTU Faecal Coliform MPN*: 1-500	Slow Sand Filtration Chlorination, if possible
Turbidity: 20-30NTU (30NTU for a few days) Faecal Coliform MPN*: 1-500	Pre-treatment advantageous Slow Sand Filtration Chlorination if possible
Turbidity: 30-150NTU Faecal Coliform MPN*: 500-5000	Pre-treatment advisable Slow Sand Filtration

	Chlorination if possible
Turbidity: 30-150NTU Faecal Coliform MPN*: >5000	Pre-treatment advisable Slow Sand Filtration Chlorination
Turbidity>150NTU	Detailed investigation including pilot plant study.

*Faecal Coliform (i.e. thermotolerant coliform) counts per 100ml

Ellis (1985) reviewed numerous sources and concluded that influent water turbidity values below 50NTU were sustainable for prolonged periods (and values of 50-120NTU tolerated for 1-2 days). Values over 50NTU for a period of weeks, or over 100NTU for longer than several days will cause filter clogging. According to Cleasby (1991) influent turbidity values should be maintained below 5NTU if run lengths of 1-2 months are desired. Further influent water quality requirements necessary obtain this run length included chlorophyll-a levels below 5mg/m^3, absence of algal blooms, iron concentrations below 0.3mg/l and manganese concentrations below 0.05mg/l (Cleasby, 1991).

Variability in influent water turbidity levels is common in areas that experience uneven but high annual rainfall distribution, for example tropical regions. It is important that the SSF continues to treat water effectively throughout this period as the microbiological quality of raw water is also likely to be poor as a result of inadequately disposed of faecal matter being washed into surface water sources (Ellis, 1985). Pre-treatment processes can be installed to allow SSFs to perform effectively throughout the year. Seasonal variability in raw water quality should be highlighted before design and construction begins by raw water monitoring and pilot plant testing. This point was highlighted in a study by Lloyd *et al* (1988). Sedimentation tanks were used as a pre-treatment to SSFs treating potable supply water for small rural communities in Peru. However these tanks had inadequate capacity to cope with the seasonal peak in suspended solids loads in raw water because when they were built there was a lack of information regarding raw water quality during the rainy periods. The sedimentation tanks were undersized as a result and failed to adequately pre-treat water for the SSFs during these periods.

Another example is reported by Weglin *et al* (1996) for a treatment plant in rural Cameroon. This plant consisted of sedimentation tanks and SSFs, but these were unable to cope with the seasonal deterioration in raw water quality experienced during the rainy season (particularly with raw water quality also deteriorating on a long term basis due to poor watershed management and subsequent soil erosion). By monitoring the raw water quality data was obtained that enabled the design of appropriate rehabilitation work. The sedimentation tanks were converted into gravel pre-filters and new pre-filter types were also incorporated to provide additional protection.

Although information regarding raw water quality is important to design a suitable SSF plant, Hendricks *et al* (1991) cautioned that raw water turbidity measurements can not be used to predict SSF run lengths. Pilot plant studies (Section 3.9) are required to predict run length for a particular raw water undergoing treatment by a particular SSF (and any pre-treatment processes). This is partly because raw water turbidity measurements do not take into account the biological (e.g. algal) growth that will occur within the supernatant and the impact of this on run length (Cleasby, 1991).

The way in which influent water quality affects run length will determine whether SSFs are an appropriate technology to use (with or without pre-treatment) because if run lengths are very short this lead to high operational costs. In addition to influent turbidity, run length will be affected by influent water algal content, and in particular the occurrence of algal blooms in the SSF. Algae cause both operational and quality problems (Section 2.2.6). Covering SSFs is a means of reducing the problems associated with algal growth within the SSF, however, if the algal content of SSF influent water is high then this may shorten run lengths to the point where SSFs are inappropriate without pre-treatment (Visscher *et al*, 1987). Pilot testing throughout different seasons can provide information in this respect. The periods of prolific algal growth may be sufficiently infrequent (on a yearly basis) that they are tolerated (Hendricks *et al*, 1991). In addition to pre-treatment of water prior to slow sand filtration, any water storage should be covered or shaded to minimise algal growth and hence its carry over into the SSFs (as well as to protect against mosquitoes and other parasitic disease vectors from proliferating).

Pre-treatment processes and SSF surface mats are two means of reducing the extent to which a SSF is affected by heavy particulate loads in influent water (Fox *et al*, 1994). Pilot plant studies should be used to ascertain whether a SSF can be used to produce potable water from a given raw water.

Even if a particular raw water is suitable for SSF treatment in terms of its microbiological and physical quality, the chemical composition of raw water may render it unsuitable. SSFs cannot be expected to remove heavy metals and other chemicals from raw water, therefore a chemical analysis of the proposed raw water supply should be undertaken to ensure that its treatment by SSFs (and any pre-treatment processes) will result in a water that is safe for human consumption (Pyper & Logsdon, 1991).

Cleasby (1991) highlighted the impact of iron and manganese concentrations in SSF influent water. Source water obtained from wells or infiltration galleries may contain dissolved iron and/or manganese. Precipitation of iron above the SSF can lead to clogging and shortened run lengths. Pilot plant studies will ascertain as to whether this is an issue for a given raw water.

In summary, a SSF requires influent water that meets certain quality requirements in order to produce treated water that is potable whilst operating in an efficient manner. Raw water quality testing and pilot plant studies are important pre-design steps to ensuring that the final full scale SSF is successful.

3.4 Determining Capacity

Before design can begin the required capacity of the system must be assessed, i.e. what volume of treated water is required per day?

On a **household scale** this is relatively simple:

- How many people live in the household and hence will be served by the SSF(s)?
- What is their daily usage of water?
- Are any new members of the family expected in the short term?

The number of people is multiplied by their per capita daily water requirements to provide the required capacity of the SSF(s).

On a **community scale** SSF design project, similar considerations are made:

- Design population (considering population size and rate of population growth)
- Design period (i.e. anticipated life-time).
- Per capita daily water demand.
- Are there industrial/agricultural users and what are their daily demands?
- Other water demands for example expected leakage (e.g. during distribution of treated water) and emergency store (e.g. for fire fighting).

(Huisman & Wood, 1974, Visscher *et al*, 1987)

Design period affects the cost of the SSF build and its productivity (maximum available throughput). Household SSFs can be built with relative ease and can operate independently of one another, thus design period is a less significant consideration compared to with a community scale design. With community scale systems the capital investment is a significant cost. Furthermore, building additional SSFs at a later date to cope with increased demands is difficult unless careful planning has gone into designing the plant layout and plumbing to cope, respectively, with additional filters and flows. Considerations include:

- Rural communities may not experience the predicted population growth rates due to emigration, with the result that a plant designed for 30 years will be larger than required and a subsequent loss is made in the investment.
- Long design periods increase the capital costs of the build, which may not be a good investment given potentially limited funds and the unpredictability of future water demands.

(Visscher *et al*, 1987)

With these points in mind, for rural community water supply a design period of 10-15 years is recommended (Visscher *et al*, 1994).

Population size and growth rate data may be available from demographic data for a community if it has been collected. This may require checking against estimates of the actual population in the area, and if necessary new data may need to be collected (Visscher *et al*, 1987). Population growth rate estimates should consider socio-economic factors such as:

- Family planning
- Migration
- Medical care
- Economic prosperity.

(Visscher *et al*, 1987).
The design population may be estimated via the use of the following equation:

$P_d = P_p(1 + 0.01a)^Y$
(Visscher *et al*, 1987)
Where
P_d = design population
P_p = present population
a = estimated annual growth rate (%)
Y = design period

The human body requires approximately 3-10 litres per day, depending on the climate and work load (Huisman *et al*, 1981), however water is not needed solely for drinking water purposes. For example, mean water consumption in the UK is 150 litres per head per day (for all domestic purposes), although it is reported that the actual amount of water drank un-boiled may be as low as 30-50ml per head per day (Bates, 2000). In developing countries the volume of water collected from water supply systems varies between 20-150 litres per head per day (Visscher *et al*, 1987), although consumption rates through drinking alone may be under 2 litres per head per day (WHO, 1996). Treated water reduces transmission of water-borne diseases (via water consumption), and also helps prevent incidence of water-washed illness by providing clean water with which to bath and to wash hands (Feachem & Cairncross, 1993). Hence as a minimum, SSF treatment should aim to produce enough water for both the drinking and washing requirements of the community. The WHO stipulates a minimum of 50 litres per head per day be available to prevent water-borne and water-washed illness, though this is a conservative guideline. The daily water usage of individuals is likely to vary according to the water quality, availability (constant supply?), cost, climate (e.g. temperature), cultural practices, convenience and accessibility of the water distribution points and whether water is also used for watering livestock (Visscher *et al*, 1987). It is also highlighted that individual water usage may increase if a community is being provided with the availability of piped water for the first time (Huisman & Wood, 1974).

The demand for treated drinking water is also likely to vary both seasonally and on a 24-hour cycle. When water is distributed directly to homes, water demands usually exhibit peaks in the morning and in the evening. In agricultural areas water is often collected in the mornings (Visscher *et al*, 1987). Lowest demands usually occur at night. Opinions vary on whether to use average or maximum daily demands to calculate a figure for design flow. SSFs should maintain constant surface loading rates regardless of daily demand variation. In order to achieve this a supply reservoir (also called clear water reservoir) is installed downstream of the SSF. This is filled by the SSF 24 hours a day, but water is drawn from it (by customers) mainly during the daytime. Sufficient storage of water and SSF design flow is required to meet the peak morning demands. If long queues and insufficient supply is available during peak periods then users may revert to traditional water sources (Visscher *et al*, 1987).

Sharpe *et al* (1994) highlight that if the system is designed on average daily demand then the filter area will be smaller (reducing costs), but that a large storage tank will be needed to supply sufficient water during maximum and peak hours. Conversely if the system is designed on maximum daily demands, then this will increase costs (as the SSF area is larger).

Demands may also vary for some communities on a weekly cycle. For example in some communities peak demands may occur on Mondays as this is the customary wash-day (Huisman & Wood, 1974).

Water demands will also vary seasonally. There should be consideration for the specific practices of the community and climatic variation. For example, communities which experience winters with below-freezing temperatures may be in the habit of leaving taps running during the winter to prevent freezing, hence unlike temperate countries where water freezing is not an issue, demands increase during the winter (Huisman & Wood, 1974). Demands may also increase for regions experiencing below-freezing temperatures during the winter (where water is piped to distribution points) due to wastage from burst pipes and fittings (Huisman & Wood, 1974). In contrast, temperate regions tend to exert highest annual demands in the summer (4 to 5 times higher than winter demands).

Water demand per capita can be estimated from national guidelines - when these are available. Alternatively, this can be estimated by considering the volumes of water required for daily activities that are typical of individuals living in the specific community (i.e. cooking, cleaning, drinking, washing clothes, flushing, bathing, vegetable garden watering, watering livestock etc, Huisman *et al*, 1981).

To obtain the community scale design capacity flow the design population is multiplied by the per capita water demand. This should then be increased by 20-30% to account for water losses and wastage (Visscher *et al*, 1987). When it is difficult to estimate the population size, the number of families living in the community may be easier to estimate. This number can be multiplied by the average family size to provide the design population (Huisman *et al*, 1981).

The design capacity of the SSF system is used to determine SSF design parameters such as size and number of units.

3.5 Treated Water Quality

Before a SSF is designed and constructed decisions need to be made regarding treated water quality requirements. Will treatment by a SSF meet these requirements? This question is answered by considering the capabilities of the SSF, the quality of raw water and the quality requirements of supply water. What are the regulatory requirements for drinking water in this area? What water source is currently being used and what is its quality? Will SSF treatment improve the quality of water to the extent that health benefits are realised?

Quality requirements for drinking water vary from one country to another. Guidelines are also provided by the World Health Organisation (WHO). When SSFs are used appropriately, the WHO reports they can bring about the greatest improvement in water quality of any single conventional water treatment process. Microbiological removal rates may be 98-99% (WHO, 1996). SSFs can therefore have a significant impact on the reduction of diseases caused by micro-organisms in drinking water. This fact alone may be sufficient evidence to support the construction of a SSF to cater for household or community drinking water supply.

Table 3 demonstrates the performance of SSFs in terms of several water quality parameters. Although very effective at producing microbiologically safe drinking water, a SSF is not a suitable treatment process to use for the purpose of chemical contaminants. Cleasby (1991) reported that true colour (caused by colloidal and soluble substances such as humic substances) is also not removed effectively by slow sand filtration (e.g. 30% removal, Ellis, 1985). A SSF should also not be expected to remove dissolved contaminants such as heavy metals or non-biodegradable synthetic organic compounds (Cleasby, 1991). Therefore an ideal drinking water supply may not be achieved in terms of all chemical, biological and physical water quality parameters, however it might be that SSF treated water is still preferable to the water source currently supplying a community, particularly due to the microbiological treatment achieved. There is the potential to reduce the incidence of water related diseases for those consuming SSF treated water (compared to the same population consuming the untreated raw water). Chemical contaminants may still be present, however it can be argued that "*chemical standards for drinking-water are of secondary consideration in a supply subject to severe bacterial contamination*" (WHO, 1996).

Table 3: Treatment Achieved by SSFs (reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply*, Technical Paper No. 24, Copyright (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

Water Quality Parameter	**Treatment Achieved by SSFs**
Colour	30-100% reduction
Turbidity	Usually reduced to <1NTU

Faecal Coliforms (also known as thermotolerant coliforms)	Usually 95-100% and often 99-100% reduction
Cercariae	Virtual removal of cercariae of schistosoma, cysts and ova
Viruses	Virtually complete removal
Organic Matter	60-75% reduction
Iron and Manganese	Largely removed
Heavy metals	30-95% reduction

If the source water demonstrates high turbidity levels as a result of colloidal clay then SSF filtrate may also demonstrate higher turbidity levels than expected or desired (Cleasby, 1991). Use of locally sourced filter media that contains fines can also result in high turbidity filtrate. This does not mean that this media cannot be used, particularly if the alternative is purchasing an expensive alternative from external sources. Although treated water may not meet the aesthetic quality requirements of the people consuming the supply this does not necessarily mean that microbial penetration/contamination is also an issue. Only pilot plant studies incorporating microbiological testing can confirm this. The community must also be consulted, for example to ascertain whether the level of turbidity in treated water will make this water undesirable and thus avoided.

If it is concluded that a SSF will help to produce drinking water of acceptable quality, then by definition these requirements can be transferred into water quality parameter values. These can then be used to determine how the SSF is operated, for example when is the SSF sufficiently mature to be put back into supply after skimming? Is this decision made according to turbidity, microbiological parameters or some other parameter (Sharpe *et al*, 1994)?

Filtrate quality will not only depend on the performance of a SSF but also the quality of the source water. The achievable filtrate quality for a given raw water can be determined by use of pilot plant studies (Section 3.9) before design and construction at full-scale. The community for which the supply is intended should be consulted as to their potable water quality requirements. What supply is currently being used and what is its quality? Unless the community is satisfied that the treated supply will benefit their well-being and is convenient to access, it is unlikely to replace their current water supply.

It is also highlighted that health benefits are unlikely to be achieved within a community solely by providing sufficient safe water supply. The continuous use of this supply, correct hygiene practices and waste disposal need to be improved in conjunction with water treatment (Visscher *et al*, 1987).

3.6 Community Considerations

Whether a SSF is appropriate for a community's drinking water treatment will be influenced by population (size and growth), community character (customs, traditions, values), politics, regulations, economics (cost of SSFs vs. other technologies) and financing (by whom, how much and for what period, Hendricks *et al*, 1991).

Before a SSF project begins, the local authority is usually contacted to inform them about the project and to request organisation of a meeting to be held in order to obtain the views of the community. Selected groups of the community may be consulted during further meetings to discuss various aspects of the design and construction (Visscher *et al*, 1987). Rubiano (1994) highlighted the benefits to a potable water treatment project obtained by the support of a community leader who has charisma and local respect. Community consultation enables those managing the project to assess the local skills and knowledge (i.e. what resources are available?) and also the community's potable water requirements. In particular, consultation with women is recommended as women are likely to be the principal users (Visscher *et al*, 1987). The aims of this part of the project are to identify the needs of the community before the plant is designed (Huisman *et al*, 1981) and also to obtain support for the project.

If enthusiasm for the project is lacking in the community, then a hygiene education programme may be required to increase awareness about the benefits of a treated drinking water supply. By investing time at this stage of the project to ensure the community is motivated and willing to participate, this safe-guards its sustainability in the long term (Visscher *et al*, 1987). If the installation is not accepted by the community or does not meet their needs, then it will not be used and furthermore will not be looked after (Huisman *et al*, 1981).

Community involvement is also required during any decision-making process regarding possible water charges (imposed on treated water usage). Water tariffs will not be appropriate for many projects, however. This is discussed further in Section 4.2.16.

3.7 Local Resources

Do the environment and community provide the right conditions for SSF treatment to be effective in the long term? Some useful considerations are listed by Visscher *et al*, (1987):

- The quality of supplied water should not deteriorate below the acceptable limits during the design period (life-time) of the SSF.
- Water supply must provide adequate volumes and a constant supply which can be accessed at convenient locations.
- Construction, operation and maintenance (including repair if possible) should be within the ability of local technical staff or users.
- Robust and reliable equipment should be used, and this kept to a minimum.

- Construction and operational costs should be minimised by sourcing materials locally.
- Minimising the use of chemicals, of pumping and of the need for operator attendance will help to reduce the costs associated with operating the SSF in the long term.
- Planning should include community participation to assess the needs and preferences of the users. This will also help those building the SSF to assess the local skills and knowledge. Consultation with women in particular, is recommended as women are likely to be the principal users.
- Appropriate monitoring of the system needs to be set-up.
- There should be measures in place to prevent possible deterioration of the raw water quality and the breakdown of the treatment system.

(Visscher *et al*, 1987)
Household SSFs are easily fabricated from locally obtainable materials and require few skills to construct. Community scale SSFs may also be built from locally sourced materials and using local labour, although supervision (during design and construction) will be required by a professional engineer. The operation and maintenance requirements of a SSF will depend on its size and the number of units. On a household scale one family member may spend on average one hour per day maintaining the SSF. On a community scale SSF the attention required may also only be once daily for several hours (i.e. part time work for one operative), though more operatives will be periodically required when skimming is undertaken. In addition to these personnel, a supervisor will be needed for community scale systems, but one supervisor may supervise many small scale installations in an area. Hence the requirements for the SSF build, operation and maintenance are within the local resource capabilities of many small rural communities.

3.8 Climatic Factors

Climate can influence the performance of a SSF (Section 2.2.7) and therefore in order to achieve effective slow sand filtration treatment the design of a SSF may need to incorporate measures to optimise the environment in which it operates. Climate considerations include:

- Temperature
- Photoperiod (number of daylight hours) and light intensity
- Rainfall (quantity, intensity and seasonality).

For example, high raw water turbidity levels often follow rainstorms, or may occur in the spring as a result of run-off from snow melt (Hendricks *et al*, 1991). Consider the seasonality of climate and the impact this has on the raw water supply (volume) and on its quality. Turbidity levels below 5NTU may prevail during one part of the year, but during other seasons rise to 40NTU, hence the assumption that pre-treatment is not required may be ill-judged if inadequate pre-design monitoring was undertaken (Logsdon, 1994). Ideally the quality of the influent water supply should be tested by pilot plant studies over the period of a year to establish raw water quality changes with season and also the impact season has on performance. This enables the design of the SSF system to be tailored to the conditions encountered throughout the year.

Temperate regions may need to consider the impact of algal blooms on SSF operation during the summer months. Long photoperiod, high light intensities and high temperatures encourage algal growth which can result in operational problems such as short run lengths. Shading or covering the SSFs can help prevent this problem. Oligotrophic (nutrient poor) water in temperate climates does not usually support algal blooms.

Low temperatures can cause operational and performance issues. Freezing of water after the SSF has been drained for cleaning will hamper the skimming process and delay its return to service. Low temperatures may also result in poor filtrate quality since the filter's microbiological community (which treats the water) may be adversely affected by the cold (Section 2.2.7). Covering and insulating the SSF (e.g. by mud walls) can help prevent these problems.

Climatic factors will also affect the per capita demand for water supply. The human body requires 3-10 litres of water per day for normal functioning, depending on climate and work load (Huisman *et al*, 1981).

3.9 The Role of Pilot Plants

3.9.1 Purpose

In the context of this text, 'pilot plant study' is a term used to refer to experimentation using small-scale SSFs, with the aim of providing information that can then be taken into account during the subsequent design of a full scale (larger e.g. community scale) SSF. Pilot plant studies are an essential (initial) stage of community scale SSF projects. For household scale projects it would probably be equally advisable to complete a small scale study (e.g. using cheaper materials) before proceeding to the full scale installation of a permanent SSF system into a household (the latter which can then be built using more hard-wearing materials to a design with which there is confidence in its treatment ability).

Hence pilot plant studies identify the appropriate design parameters and any pitfalls, thus saving time and money in the long run. Engineers should resist the temptation to reduce project costs by omitting pilot plant testing (Logsdon *et al*, 2002). Based on information obtained from pilot plant studies the application of SSF technology can be optimised for the given set of environmental conditions, materials available and community requirements. This may enable lower capital costs to be realised if a lower cost design alternative is shown to be capable of meeting the required treated water quality (Leland & Logsdon, 1991) whilst being operationally sustainable.

Therefore, when designing and constructing a SSF it is strongly recommended that pilot plant studies be undertaken before the design and construction of the full-scale SSF begins (Logsdon, 1994). This is the best way to determine whether SSFs will work for a specific raw water, operating under a specific set of environmental conditions and with the intended SSF system (Sharpe *et al*, 1994). Even where SSFs are being built for small communities using limited funds it is advisable to conduct pilot plant studies before building a full scale SSF (Hendricks *et al*, 1991). The operator has few options for correcting malfunctions or dealing with raw water that is difficult to treat once the SSF has been built (Leland & Logsdon, 1991). Pilot plants can be used to assess:

- Treatability of the raw water and any pre-treatment requirements.
- Suitability of the media for SSF treatment (ES, UC, porosity, fines content etc).
- Suitability of the media depth range (maximum and minimum depths).
- Preparation and washing procedures required for locally obtained media.
- Sustainable surface loading rates. This determines the productivity of the SSF and hence the number of units required to meet design flows.
- Typical ripening periods.
- Typical run lengths given the chosen surface loading rate and media.
- Flow control systems (inlet versus outlet controlled systems).
- Intake design requirements.
- Algal control needs.
- The impact of climate and season.
- Other design considerations such as covers, surface mats, supernatant depth etc.
- Intake design requirements.

(Leland & Logsdon, 1991).
If pilot plant studies are not undertaken and problems are experienced with the full-scale SSF, then this can cause consternation in the community. A SSF is more likely to be successful in the long term if problems are not experienced from the onset of its operation (Logsdon, 1994).

Pilot plant studies can also be opportunities to train future operating staff as this experience is directly transferable to full scale SSF operation (Leland & Logsdon, 1991).

3.9.2 Method

1. Preliminary assessment of raw water

Is slow sand filtration suitable? Is it possible for the final treated water to meet the quality requirements given the treatment options available, or is raw water unsuitable? This is discussed in Section 3.3.

2. Plan the study

During the planning stage a list should be drawn up of the design variables that require testing. The design of each investigation needs to consider what data will be collected, at what frequency, what analytical methods will be used and what steps taken for quality assurance (Leland & Logsdon, 1991). Work plans for each pilot plant study can assist in maximising productivity from each study, by considering the following (before the study is undertaken):

- Purpose – why is the study useful?
- Goals – what will be achieved using the results obtained?
- Objectives – how will the goals be achieved?
- Scope – what are the limits of the study?
- Significance – who benefits from the study?
- Method – what equipment, sampling, analyses etc will be undertaken and how?
- Work plan – identify tasks and assign these to specific people.
- Results expected? – what relationships are expected between different parameters? If results are different to those expected then further investigation may be needed.
- Budget – what are the expected costs and are these within the budget?
- Personnel – who is working on the study and what are their roles? What are their training requirements?
- External Review – obtain feedback on the plans from a third party.

(Hendricks *et al*, 1991)

If several variables will be assessed then multiple pilot plant filters are advised as the length of each study can be significant (Leland & Logsdon, 1991). For example, in order to assess the impact of seasonality, pilot plant studies need to extend at least a year. This requires planning pilot plants well in advance of the intended full scale construction dates (Leland & Logsdon, 1991). Building more than one pilot plant SSF reduces the time period over which testing needs to take place as several aspects can be tested simultaneously. The more pilot plant filters built, however, the higher the cost of the pilot plant construction. A higher number of filters will also be more time consuming to monitor and hence more labour intensive. Conversely, if funds are limited then fewer pilot scale SSFs can be built but the study period is likely to be longer as a result. A list should be drawn up of what factors are being tested and these should be listed in order of priority. Hence, those parameters of greater importance can be tested first (whilst funds are still available).

For temperate regions Leland and Logsdon (1991) recommended beginning pilot plant studies for SSFs in the late spring or early summer. This allows the pilot scale filters to establish a microbiological community relatively quickly (as temperatures are high), and by the time the winter temperatures are encountered the filters will support a fully developed microbiological community.

3. Equipment

As with small scale (household) SSFs, pilot plant SSFs can be built from locally available materials and require limited plumbing skills. Some basic plumbing materials would be required to make sure the SSF is water tight, and also to enable flow control. Pilot plant costs vary considerably and may be minimised by using local materials and labour.

During pilot plant trials the pilot filters are usually operated for extended time periods, for example a complete pilot plant filter run (i.e. from skim to terminal headloss) may be several weeks to months. In order to minimise the labour required to man such long trials the equipment should be designed to be as low maintenance as possible (Leland & Logsdon, 1991).

Pilot plant SSFs should be designed with the same depth dimension as the intended full-scale SSF (Ives, 1980, 1982, AWWA, 2002, Davies, 1983). As with a full scale SSF design, the following components need to be built:

- SSF container/box/tank.
- Filter bed (media).
- Under-drainage.
- Influent and filtrate piping.
- Headloss measurement.
- Flow control systems.

The pilot plant SSF box is often built using cylinders bolted together to provide the required height. In the absence of plastic column sections, drums or similar containers could be adapted for SSF use. These must be made of materials that are durable and which do not change the quality of the water in any way (Leland & Logsdon, 1991). Note that tanks must be water-tight and clean, and metal tanks may require protection from oxidation (e.g. by painting with suitable i.e. non-toxic paint/sealant).

The transparency of the materials used to construct a SSF is a consideration for SSFs manufactured from plastic column sections, drums or other similar materials. The section of the column where the media is laid must be blocked from sunlight exposure. The supernatant water should be left exposed to sunlight if these are the intended conditions for the full-scale SSF. To minimise operational problems and if the intended full scale SSFs are to be covered, then the pilot plant SSFs should also be completely blocked from sunlight exposure. Hence the SSF tank walls must not be transparent, and the tanks will require lids.

The container used for the SSF box must be the same height as the intended full scale SSF structure (i.e. SSF ‘box’, Section 4.2.9). A sufficient supernatant depth in the SSF tank (e.g. 1-1.5m) ensures that a sufficient head of water exists above the filter bed to drive the flow of water through the media throughout its run length. In addition, adequate depth needs to be provided for the free-board, maximum media depth, gravel layers and under-drainage. The intended methods for skimming and re-instatement should be considered before the pilot scale filter is built. It may be necessary for the SSF to be constructed in segments so that they can be easily dismantled to allow periodic cleaning.

The diameter of the SSF tank is a factor often discussed in SSF pilot plant designs, because if an insufficient filter area is provided, then this can result in significant ‘edge effects’. This term refers to the affect of the pore spaces between the sand grains and the inside wall of the SSF tank, upon SSF flow. These pore spaces are not typical of the pore spaces in the filter bed and result in atypical flow patterns and thus unrepresentative filter performance. Edge effects in both pilot scale and full scale SSFs can be reduced by appropriately designing the filter walls (Section 4.2.9). However, edge effects are only significant when the pilot plant SSFs are very small in area. Edge effects are usually avoided by comparing the diameter of the pilot filter (D) to that of the media particle diameters (d). Experimentation has shown that atypical pore spaces represent less than 2% if the D/d ratio is greater than 50 (Ives, 1980). Therefore, for media grains of 1mm diameter, a filter column of diameter 50mm will experience only 2% of its flow through the atypical pore spaces. Hence, pilot plant SSFs can have relatively small cross-sectional areas (e.g. 0.2-0.5m) and still avoid significant edge effects. An additional consideration, however, is the ease of skimming and re-instating the SSF. Narrow pilot plant filters are difficult to skim. If the SSF box cannot be dismantled then it is imperative that the diameter of the box enables access to the filter bed to allow operational procedures to take place (e.g. diameter>1m).

A possible pilot plant design is presented in Figure 3.3. By locating the filter downhill of the water source the system could be gravity fed. Alternatively the SSF may be pump fed, though this requires a (reliable) power source, pump and the appropriate location and adequate protection of the pump at the source water. The pilot plant design may require the incorporation of a header tank. This is placed at a height above the SSF tank, with a hose feeding the SSF supernatant, from the bottom of the header tank. Providing that there is a sufficient water storage volume in the header tank, this may only require filling once per day.

If more than one pilot scale SSF is built, it is recommended that design allows for the individual control of surface loading rates. Water is fed into the top of the SSF and prevented from disturbing the media via use of a splash plate. The rate at which water enters the supernatant should slightly exceed the rate at which water filters through the bed so that a constant head of water remains above the bed. The excess water is allowed to drain away via an overflow facility. The overflow facility compensates for any imbalance between the influent and filtrate flows, making the filter easier to operate. With this arrangement, surface loading rate is controlled at the outlet valve.

A pilot scale SSF should incorporate a means to monitor headloss, for example using a water manometer (Figure 3.2). This requires lengths of clear tubing that are longer than the depth of the filter and supernatant combined. One end of the tubing should be covered by gauze or fine mesh to prevent entry of sand. This end is placed inside the SSF bed at the base of the filter and exits the filter structure from the side. It is then curved upwards and affixed to the outside wall of the SSF. A second piece of clear tubing is placed inside the SSF supernatant, just above the bed's surface. The water level in the two tubes can be compared and the difference recorded as headloss measurements. As the SSF ripens and matures the difference in the water level between the two tubes will increase. Alternatively, an electronic means to monitor pressure differential may be available. Manometer tubes should be protected from biological growth by preventing their exposure to sunlight (e.g. by covering in black-out cloth or similar).

At the base of the filter, perforated pipe can be used to manufacture the under-drainage. If the pilot scale SSF is relatively small (e.g. <0.3m diameter) a single section of perforated pipe may suffice. If the pilot scale SSF is relatively large (e.g. >0.3m diameter) then several sections of pipe may be required. A possible under-drainage design is described below and illustrated in Figure 3.1:

Obtain four sections of pipe just shorter in length than the radius of the SSF tank. Drill holes into each pipe section right the way round the pipe's circumference. Connect the four pieces of pipe together to form an x-shape. Three of these pipe sections should have their outer ends capped. The x-shaped pipe is laid flat on the base of the SSF tank. A hole should be drilled in the side of the SSF tank at its base, and a tank connector fitted which connects to the uncapped pipe section. Pipe (or hose) is then fitted to the tank connector at the external side of the SSF tank wall. This section of pipe should be extended upwards such that the SSF filtrate will be forced to flow up to the level of the SSF filter bed (the pipe forms a 'swan neck' curve). At this height it is then curved downwards slightly to provide an 'hydraulic break'. This arrangement ensures that negative pressure does not develop within the filter bed leading to problems with air binding. The section of pipe (or hose) that exits the SSF at its base will require a flow control valve to be fitted to enable surface loading rates through the filter to be regulated. Once this set-up is installed, the pipe sections (under-drainage) inside the SSF tank should be covered by the layer(s) of gravel. This completes the under-drainage and flow control system.

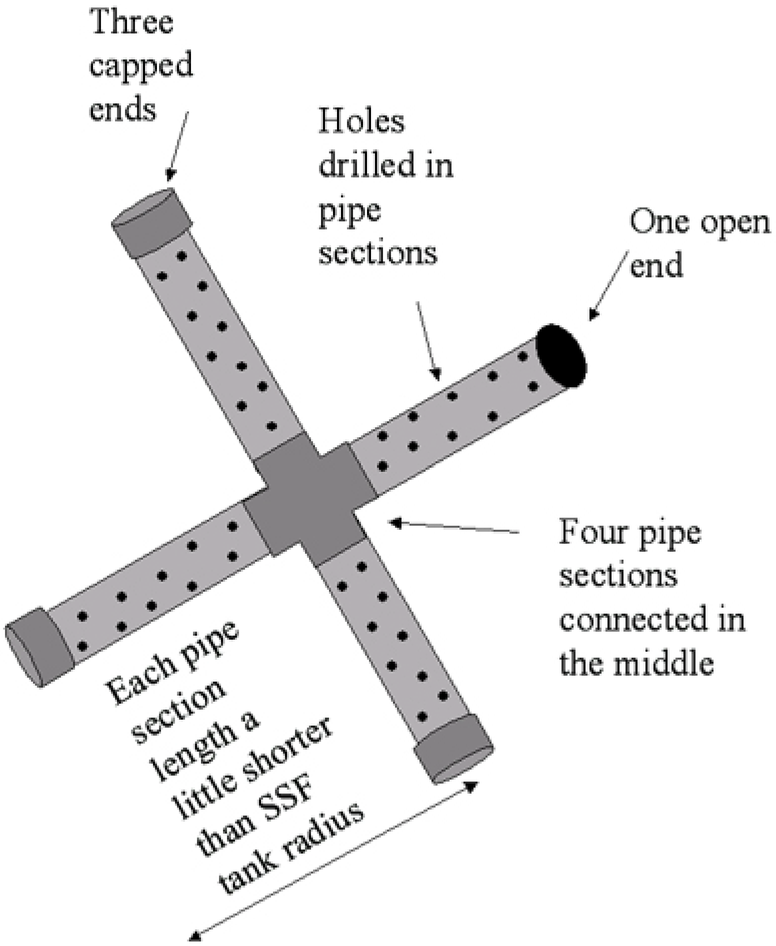


Figure 3.1: Sketch of an Under-drain for a tank (pilot scale or household) SSF

Thus water filtering down to the base of the filter enters the perforated pipe and drains out of the filter container through this pipe. Surface loading rate is controlled via the outlet valve and measured using a container (of known volume, e.g. measuring cylinder) and stop watch (a standard watch may be used as long as one minute can be accurately timed).

The pilot plant SSF shown in Figure 3.3 has been fitted with control valves both on the influent and outlet pipes, and either could be used to regulate surface loading rate through the SSF.

In the absence of valves, a section of hose can be fitted onto the tank connector exiting the filter, and the surface loading rate can be controlled by restricting the diameter of this flexible hose (e.g. using a hose clamp or similar). An alternate means of outlet flow control is shown in Figure 4.2.

Water should be allowed to flow continuously from the outlet pipe at the required flow rate.

All pipe and hose should be made of materials that do not encourage biological growth (Leland & Logsdon, 1991). For example clear plastic hosing may promote biological growth and should be avoided (with the exception of that used for the water manometers).

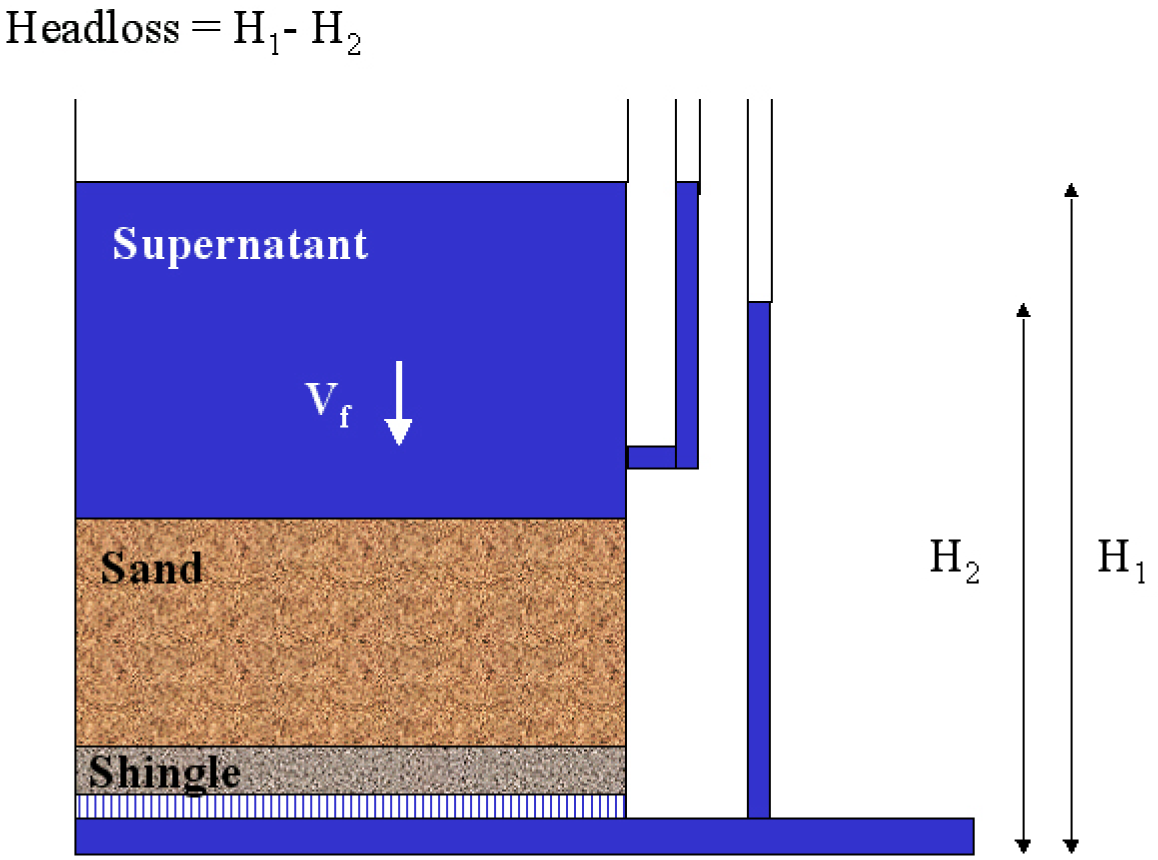


Figure 3.2: Headloss measurement using a Water Manometer

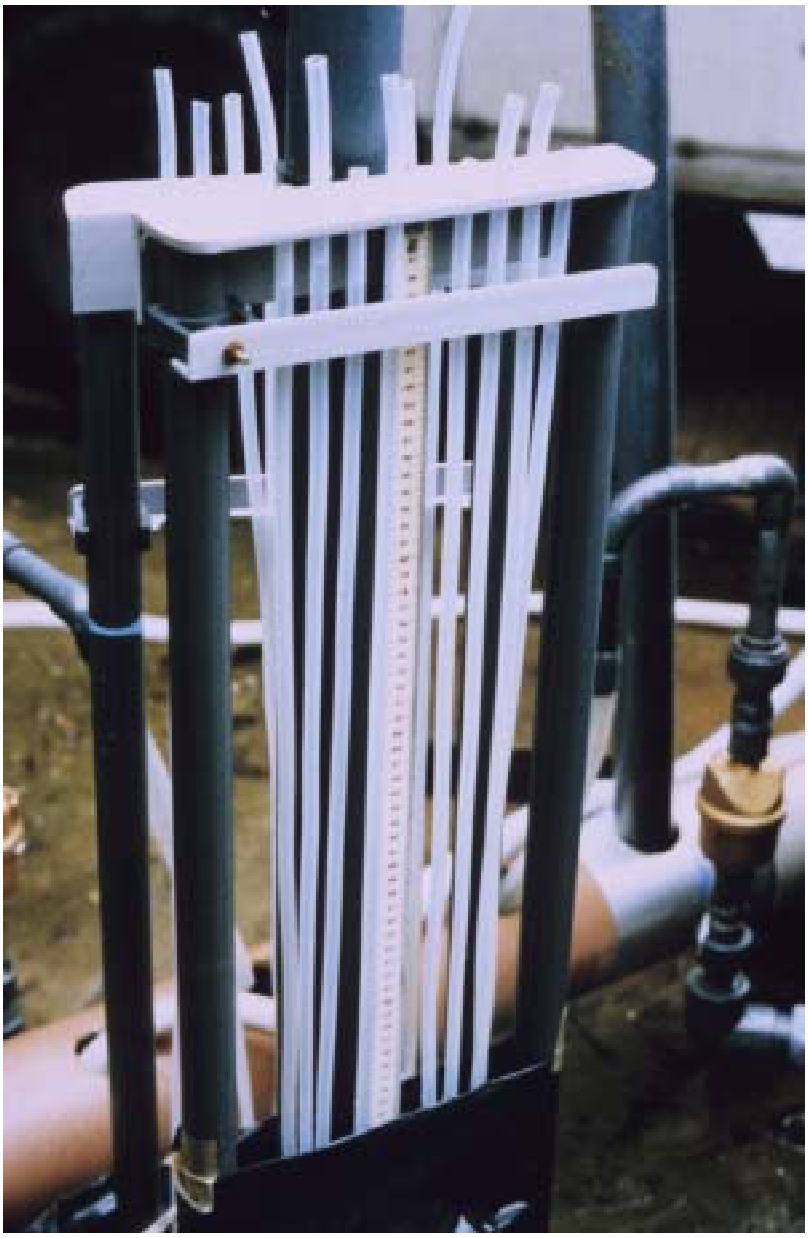


Plate 3.3: Manometer tubes and the scale used to measure headloss between tappings, for a pilot scale filter at Surbiton (London, UK)

Plate 3.4: Manometer tubes exiting a filter at Surbiton (London, UK). Note their arrangement to enable headloss measurement and also their protection against sunlight exposure.

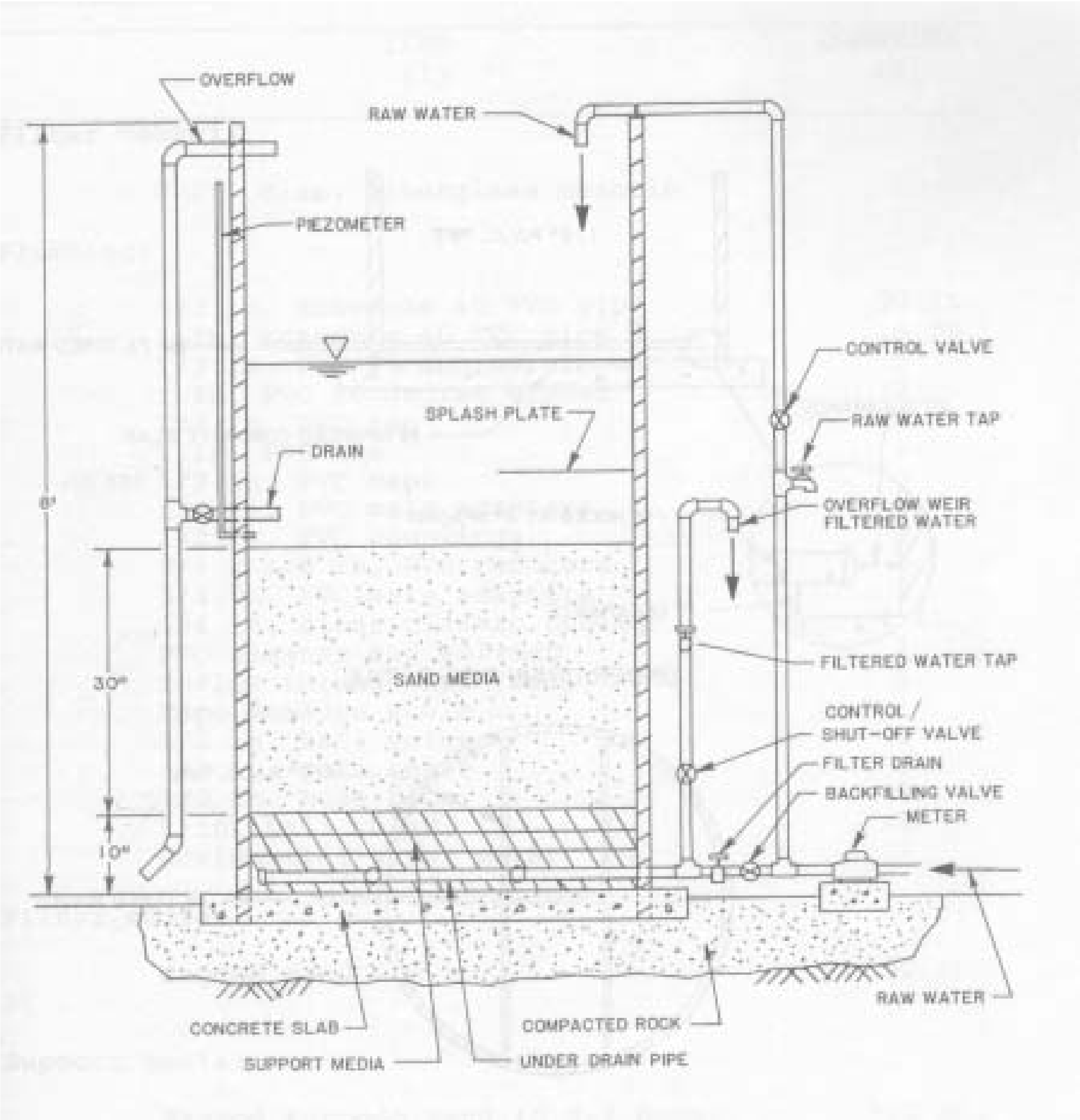


Figure 3.3: Schematic of a pilot SSF (adapted and reprinted from Leland & Logsdon, *Pilot Plants for Slow Sand Filters*, Copyright (1991), with permission from the publisher, American Society of Civil Engineers, ASCE)

3.9.3 Experimental Techniques

The pilot plant should be operated in the same location as the intended works, using the same raw water source. During the pilot plant study the same environmental conditions should prevail as those expected during the full scale SSF's operation. Therefore the filters should be outdoors, and only covered if the intention is to cover the final full scale SSFs.

Pilot plant SSFs should be allowed to operate continuously and for long periods of time (Leland & Logsdon, 1991). During pilot plant investigation, SSF runs should be repeated for different design and operational scenarios. Parameters to test include:

- Media type.
- Filter depth.
- Surface loading rate.
- Run length.
- Headloss development and terminal headloss.
- Filtrate quality achieved (e.g. length of ripening period, length of period of elevated filtrate turbidity when locally sourced media is used etc).

In order to test the influence of one design parameter on its own, all other parameters should be kept constant whilst the one parameter under investigation is altered and the impact of this on performance monitored. Thus only one parameter should be varied per filter run. For example where there is a choice of media types, the pilot SSF should be operated for repeated runs, each using identical operational procedures but with each run using a different filter media. Alternatively, multiple pilot SSFs could be operated for a single run, with each operating identically, but using a different filter media.

When surface loading rate is investigated using a pilot plant this may involve undertaking a series of identical SSF runs. For each run the filter is operated at a slightly higher surface loading rate but all other parameters are kept constant (i.e. using the same media type, filter bed depth, etc). Alternatively multiple pilot plant SSFs may be set-up and operated identically, with the exception of varied surface loading rates for each.

Where there is a choice of more than one media material, the pilot plant SSF can be operated for a series of runs to ascertain which media performs best in terms of treatment achieved, and regarding operational parameters (e.g. headloss development, run length). When only one media material is locally available, a pilot plant run will demonstrate whether this material is suitable as a SSF media (again in terms of treatment achieved and operational parameters such as headloss development). Pilot plant studies can also determine the maximum and minimum media depths required for operationally sustainable and effective treatment. A series of identical runs can be undertaken with decreasing media depths.

During each pilot plant study, quality and operational parameters are monitored and logged. A comparison of each data set allows selection of the most sustainable surface loading rate under the circumstances. This in turn enables calculation of the productivity of the SSF (i.e. achievable treated water volume per square metre per hour) and thus determination of the required number and size of SSF units to produce water given the community's requirements (Section 4.2.5).

3.9.4 Pilot plant Monitoring

Pilot plant studies are only useful if the performance of the SSFs is monitored and this data logged. Data collection during pilot plant studies should include:

- Water quality monitoring (e.g. turbidity, faecal indicator organisms such as thermotolerant coliforms).
- Operational data (e.g. run length, media type, filter bed depth, surface loading rate, headloss).

In the absence of laboratory or field instrumentation some basic water monitoring may still be possible (headloss, surface loading rate, turbidity, Section 5.2.9).

Surface loading rate can be measured using a measuring cylinder (or container of known volume) and stop watch (standard watch is adequate if a one minute period can be accurately timed).

The use of manometers (Section 3.9.3) enables collection of headloss measurement data (i.e. the difference between the water levels in the clear manometer tubing).

Pilot plant studies require frequent monitoring (3-7 days/week) but not round-the-clock attention (one visit per day will usually suffice) and therefore some staff recruitment and training will be required. This provides the opportunity for staff training as the experience obtained is transferable to a full scale SSF (Leland & Logsdon, 1991). Once per week the pilot plant system should be checked over completely and any repairs and maintenance undertaken in advance of problems arising.

All the results of monitoring and any modifications made to the operation of the SSFs should be documented and filed in an organised system.

3.9.5 Application of Pilot Plant Results

Pilot plant studies should provide data that provide information regarding SSF performance. This includes not only performance in terms of the filtrate quality achieved, but also in terms of operational parameters (e.g. run length). By analysing these data the SSF design parameters can be chosen that demonstrate optimum SSF performance (quality and operation). Bacterial levels, turbidity and headloss data can be plotted on graphs to shown trends. Hence the most appropriate media type, filter bed depth, surface loading rate, raw water source, supernatant depth, use of covers etc. can be chosen for the full scale SSF.

The chosen design parameters should ideally enable the full scale SSF to achieve:

- 90-99% coliform bacteria removal (or more)
- filtrate water turbidity less than or equal to 1NTU in 95% of measurements

- filter runs of 1-2 months
- ripening periods of several days-2 weeks
- no progressive deep clogging of the filter media
- required removal of other pathogens/parasites locally present
- any other local requirements.

4 Full Scale Design

SSFs are more likely to be accepted as a long-term solution to water treatment if they are successful from the onset (Logsdon, 1994). Thus careful selection of the correct design parameters and the use of pilot plant studies to confirm these figures may be a relatively lengthy process, but one which will ultimately save time compared to insufficient consideration at the pre-design stage resulting in changes being required after construction.

With regard to a community scale SSF installation, the information provided in this section is intended for guideline purposes only and will need to be supplemented with the results of pilot scale studies as well as research into the local requirements of the system.

If the intention is to build and operate a household scale SSF, then an investigation into the treatability of raw water, experimentation with SSF construction materials and assessment of the ripening period and filtrate quality achieved is still advised prior to filtrate consumption (i.e. drinking the water or its use in preparing food etc). This assessment can be done using the actual household filter. Therefore this text should also only be treated as a set of guidelines. Several design options are provided and possible construction materials suggested, however, the most appropriate household SSF design will depend on what materials and skills are available. As long as the basic principles of slow sand filtration are understood then successful household SSFs may take a variety of forms.

4.1 Household Scale

4.1.1 Materials

Household SSFs are intended for small scale water treatment. For example potential water production is 380 litres/day for a tank of 0.45m diameter. The sorts of household SSFs described in these sections could be manufactured by a local artisan (Brikké & Bredero, 2003). The cost of building a SSF of this scale will vary with the price of tanks and parts.

A small scale SSF system can be made from a variety of materials. For example tanks, barrels or other containers made of steel, plastic or ferrocement. For example, Shenkut (1996) reported that in Ethiopia tanks (in this case sedimentation tanks used in pre-treatment) were constructed from masonry stone. The thickness of the walls was not more than 40cm and was made water tight by plastering the inside surface with chicken wire (ferrocementing).

Other materials required to build a small scale SSF system include pipe, hose, a bowl, washed sand and gravel, lids for the tanks and some limited plumbing parts.

If steel containers are used then these should be treated (e.g. using non-toxic protective paint or cement mortar) to prevent oxidation. Small scale SSFs may be more vulnerable to short-circuiting of flow. This is when supernatant water flows directly down the sides of the walls to the under-drainage without being filtered. This can be minimised by roughening the walls of the container used to construct the SSF (Visscher *et al*, 1987).

The SSFs do not need to be round, any shaped container can be used providing it is of adequate height and of a material which is relatively inert and allows holes to be drilled into it. Round SSFs are sometimes favoured for small scale systems since this minimises use of construction materials (e.g. cement when ferrocement structures are built).

Choosing an appropriate media for the SSF is an additional consideration. This is discussed in Section 4.2.10 with regards to community scale SSFs, however the principles are the same for household SSFs.

Guidelines (and in some cases instructions) for constructing household SSFs are provided on the Internet by several bodies and organisations. Some links to these websites are provided below:

- WELL www.lboro.ac.uk/well/resources/technical-briefs/technical-briefs.htm ('Water Treatment 2',Technical Brief 42).
- Brikké & Bredero (2003) at www.who.int/water_sanitation_health/hygiene/om/en/linkingchap6.pdf
- Medair www.medair.org/sandfilter/default.htm
- Centre for Affordable Water and Sanitation Technology CAWST www.cawst.org/technology/waterteatment/filtration-biosand.php

When viewing these methods it is important to remember that so long as the basic principles of slow sand filter operation are maintained, a SSF can be constructed out of the materials available. If the stipulated materials are not available, then there may be an alternative material that is locally available that works just as well.

4.1.2 Design Options and Guidelines for Construction

Two types of household SSF are described in this Section:

1. Three-tank SSF – consists of a header tank, SSF tank and clear water reservoir. Flow control is at the inlet. A continuous water supply is required. This design option is based on one described by Brikké & Bredero (2003) at www.who.int/water_sanitation_health/hygiene/om/en/linkingchap6.pdf

It is also reviewed in a text by the IRC (IRC, 1988), which can be ordered from:
www.irc.nl/page/1905

1. 2. Two-tank SSF – consists of a SSF tank and clear water reservoir. Flow control is at the outlet. The supernatant of the SSF tank can be filled daily, although a continuous flow of influent water is recommended (Section 4.2.4). This design option is based on that described by Skinner and Shaw from WELL (Skinner & Shaw, 2004, www.lboro.ac.uk/well/resources/technical-briefs/technical-briefs.htm 'Water Treatment 2',Technical Brief 59).

Option 1 – 3 Tank SSF System

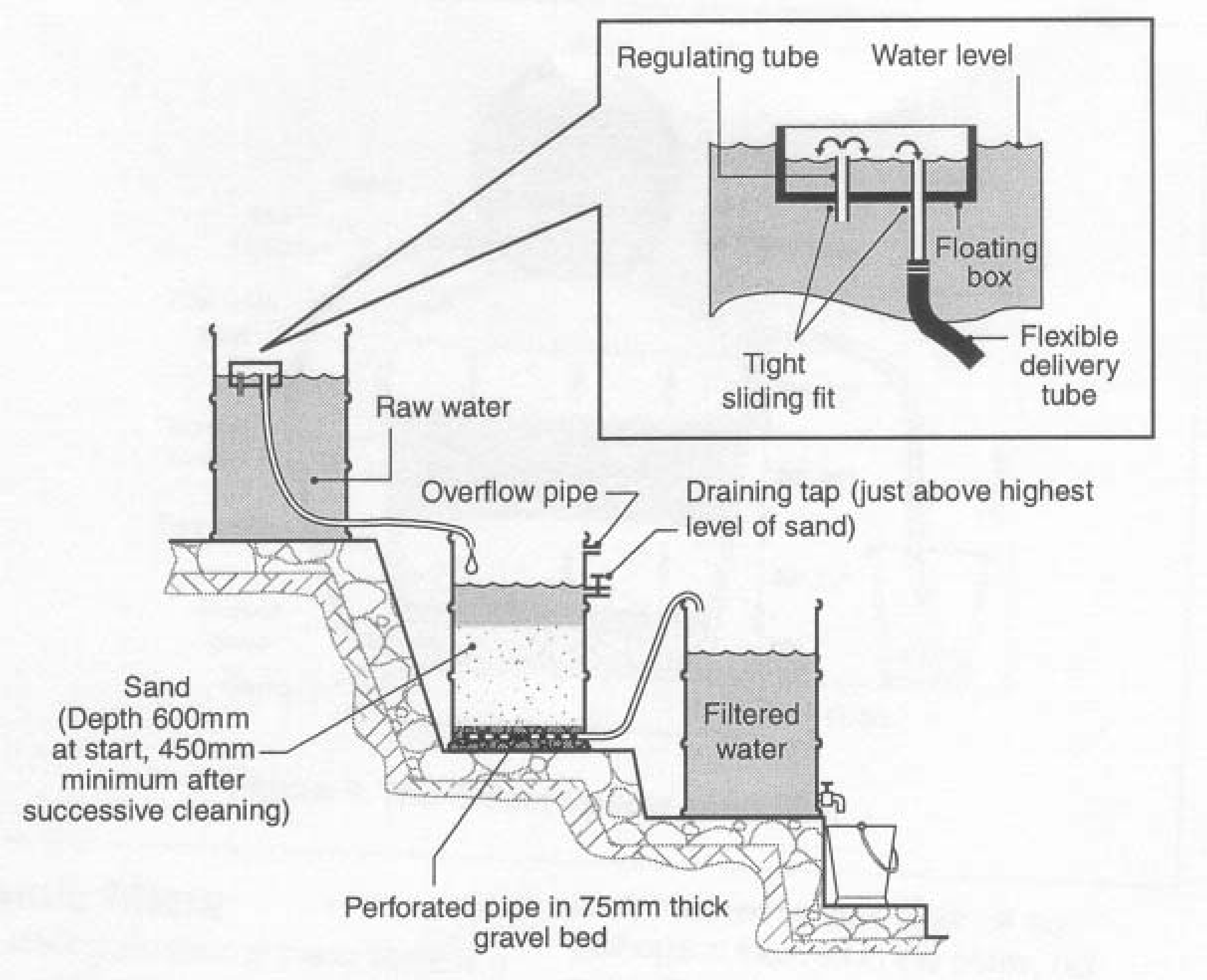


Figure 4.1: Schematic of a 3 Tank SSF system (reprinted from *Community Self-Improvements in Water Supply Sanitation*, Training Series No. 5,

Copyright (1988), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

Plate 4.1: Header tank and filter tanks in series (an MSF system), operating under gravity flow at a pilot plant at Surbiton (London, UK).

Plate 4.2: Filter tanks operating in series under gravity flow, at a pilot plant at Surbiton (London, UK).

The system consists of three containers in series, placed at heights that allow water to gravitate between them. The first container is called a header tank and sits on a level higher than the other two tanks (an example is shown in Plate 4.1). The second tank is the SSF and this sits at a height in between the other two tanks. The third tank is the clear water well (treated water storage) and sits at the lowest level with respect to the other two tanks (Figure 4.1). Hence three terraces should be dug into sloping ground, or alternatively bricks (or similar) may be used to raise two of the three tanks to the required heights off the ground (such as with the MSF system shown in Plate 4.2).

The first tank (header tank) contains the raw water supply for the SSF. Depending on the raw water source, funds and materials available, influent water to the SSF system can be gravity fed or pumped into the header tank. The raw water feed hose (or pipe) should be long enough to reach the base of the header tank, and should be fixed so that it feeds water into the bottom of the tank. This ensures that water does not short circuit in the header tank.

Water is fed to the SSF tank from the surface of the header tank. The device (a ‘floating weir’) used to do this is also used to control the surface loading rate through the SSF. A floating weir can be made from a bowl, two small tubes and a hose (Brikké & Bredero, 2003). The height of the water in the bowl determines the flow of water into the SSF tank and therefore the supernatant height, and in turn the surface loading rate onto the sand. The height of the tube through which water enters the bowl regulates the height of water in the bowl (and therefore the SSF's surface loading rate). Hence the left tube is moved downwards to increase the surface loading rate applied to the SSF.

An alternative means of flow control, this time at the outlet, is shown in Figure 4.2.

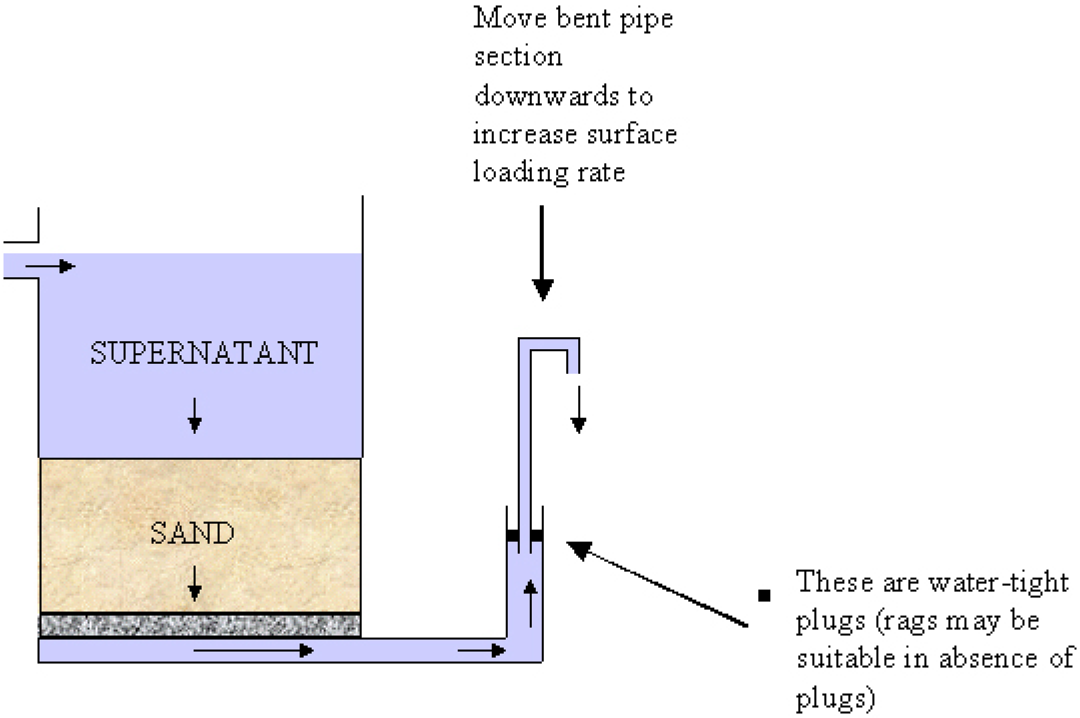


Figure 4.2: Possible Outlet Flow Control Device for Household scale SSFs

At the base of the header tank the hose (connected to the weir) exits the header tank. The hose needs to be long enough to enable water to flow from the top water level in the header tank to the base of this tank and into the top of the SSF tank. This hose should not be transparent. If only transparent hose is available then this should be blackened, or covered to prevent its exposure to sunlight.

The second tank is the SSF. Therefore it must have:

- Adequate supernatant depth.
- A filter bed of sand or similar media.
- A 5-10cm layer of support gravel.
- An under-drainage system.

Water enters the second tank at the top (Figure 4.1) and is prevented from disturbing the media via use of a 'splash plate'. For example a stone can be used as a splash plate if it is laid on the surface of the sand directly below the influent water hose (Skinner & Shaw, 2004). An overflow facility compensates for any imbalance between the influent and filtrate flows, making the filter easier to operate.

At the base of the filter, perforated pipe can be used to manufacture the under-drainage. An example of how this may be done is provided below and illustrated in Figure 3.1.

Obtain four sections of pipe just shorter in length than the radius of the SSF tank. Drill holes into each pipe section right the way round the pipe's circumference. Connect the four pieces of pipe together to form an x-shape. Three of these pipe sections should have their outer ends capped. The x-shaped pipe is laid flat on the base of the SSF tank. A hole should be drilled in the side of the SSF tank at its base, and a tank connector fitted which connects to the uncapped pipe section. Pipe (or hose) is then fitted to the tank connector on the outside wall of the SSF tank. This section of pipe (or hose) should be curved upwards such that the SSF filtrate will be forced to flow up to the level of the SSF filter bed inside the tank (the pipe forms a 'swan neck' curve). At this height it is then curved downwards slightly to provide an 'hydraulic break'. Once this set-up is installed the pipe sections (under-drainage) inside the SSF tank should be covered by the layer(s) of gravel. This completes the under-drainage.

Thus water filtering down to the base of the filter enters the perforated pipe and drains out of the filter container through these pipes. Water should be allowed to flow continuously from the outlet pipe at the calibrated surface loading rate. In order not to waste this water, but still maintain the constant surface loading rate for the SSF, a third tank is used to store treated water. Hose is attached to the SSF's outlet pipe and carries filtrate into the top of this third tank (clear water reservoir). At this height it is curved downwards such that it makes a swan-neck shape (to provide a hydraulic break). The outlet hose should be raised to a height above that of the surface of the SSF media. Furthermore this hose should not be curved back down into a U-shape that extends below the level of the SSF media (otherwise water will be siphoned from the SSF tank). The third tank should be placed on a surface below the SSF tank to allow the filtrate to gravity flow into the third tank. A tap at the base of the third tank allows treated water to be collected on demand.

The transparency of the materials used to construct a SSF is a consideration for SSFs manufactured from plastic column sections, drums or other similar materials. If only clear containers are available then these can be painted to prevent sunlight exposure to the water and media. All three tanks should also be covered (e.g. using lids) to prevent exposure to sunlight and to prevent contamination of the water by debris and birds.

Option 2 – 2 Tank SSF System

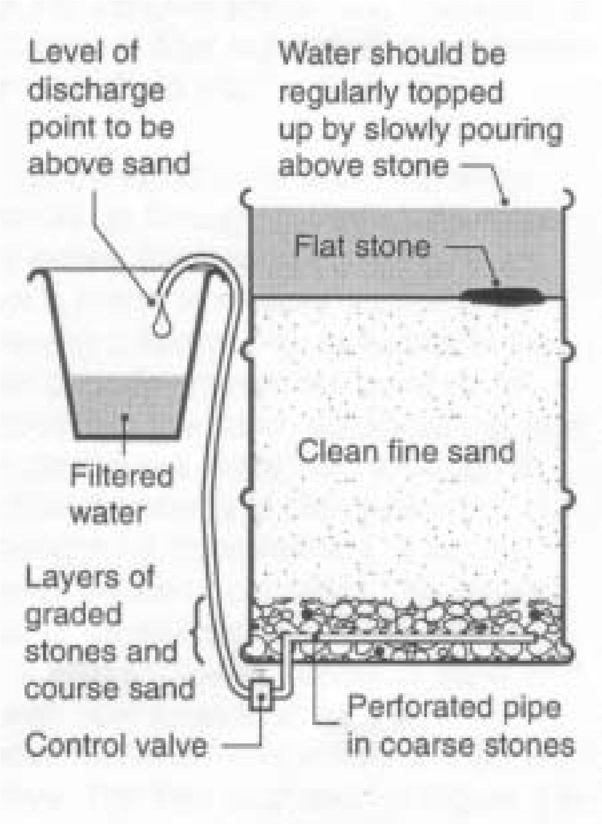


Figure 4.3: Schematic of a 2 Tank SSF system (reprinted from Skinner & Shaw, *Household Water Treatment 2*, Technical Brief 59, Copyright (2004), with permission from the publisher, Water and Environmental Health at London and Loughborough, WELL).

Two containers are used in this system. The first is a SSF tank. The second is a 'clear-water reservoir' (stored treated water). As with design Option 1, any container of suitable size can be used. The SSF tank needs to provide an adequate volume of water above the media. This ensures that there is the necessary head to drive water through the media bed, and it also ensures that the supernatant only requires topping up with raw water at practical time intervals. It is highlighted, however, that if possible a continuous supply of water should be fed to the SSF tank and an overflow facility incorporated to help balance influent and filtrate flow rates. This is because a system where the supernatant is allowed to drain daily will be operated under declining surface loading rates and will be subjected to variability in flow rate. This can detrimentally affect performance (Section 4.2.4).

If a continuous supply of water is not available, the SSF tank may be filled with raw water by hand (using a bucket or similar container). This water is carefully poured into the supernatant above the stone (splash plate), to prevent disturbance of the media. Provided an adequate volume is provided by the supernatant (SSF tank) this may only need filling with raw water once daily, however it is worth considering at this point that one person will need to have enough time at the same time every day to carry the required volume of raw water from its source to the header tank. If this is unrealistic then the SSF system must be located near the raw water source and arrangements made to gravity feed or pump water to the SSF tank.

At the base of the filter, perforated pipe can be used to manufacture the under-drainage. An example of how this may be done is provided below and illustrated in Figure 3.1.

Obtain four sections of pipe just shorter in length than the radius of the SSF tank. Drill holes into each pipe section right the way round the pipe's circumference. Connect the four pieces of pipe together to form an x-shape. Three of these pipe sections should have their outer ends capped. The x-shaped pipe is laid flat on the base of the SSF tank. A hole should be drilled in the side of the SSF tank at its base, and a tank connector fitted which connects to the uncapped pipe section. Pipe (or hose) is then fitted to the tank connector at the outside wall of the SSF tank. This section of pipe (or hose) should be extended upwards such that the SSF filtrate will be forced to flow up to the height which is level with the SSF filter bed (the pipe forms a 'swan neck' curve). At this height it is then curved downwards slightly to provide an 'hydraulic break'. This arrangement ensures that negative pressure does not develop within the filter bed leading to problems with air binding. Once this set-up is installed the pipe sections (under-drainage) inside the SSF tank should be covered by the layer(s) of gravel.

Thus water filtering down to the base of the filter enters the perforated pipe and drains out of the filter container through these pipes. The section of pipe that protrudes from the base of the SSF should be fitted with a flow control device (e.g. valve) to enable surface loading rates through the filter to be regulated. In the absence of valves, a section of hose can be fitted to the pipe exiting the SSF (and secured using jubilee clip), and the surface loading rate can be controlled by restricting the diameter of this flexible hose (e.g. using a hose clamp or similar).

An alternative means of outlet flow control is shown in Figure 4.2.

After flowing through the flow control device, filtrate water is carried (by hose or pipe) to the top of the second tank (clear water reservoir). This hose needs to discharge water at a height above the filter bed surface. At this height it is curved downwards such that it makes a swan-neck shape (to provide a hydraulic break). The outlet hose should be raised to a height above that of the surface of the SSF media, however, this hose should not be curved back down into a U-shape that extends below the level of the SSF media (otherwise water will be siphoned from the SSF tank).

Water is continuously discharged into the second tank (at constant flow rate) regardless of demand. A tap at the base of the second tank allows treated water to be collected on demand.

4.1.3 Pre-treatment Options

Pre-treatment processes increase the efficiency of the SSF, producing feed water that meets the quality requirements of SSFs. Whether or not to include pre-treatment is decided by assessing the raw water quality (Section 3.3). Some SSF pre-treatment options for household scale water treatment are:

- Straining through fine cloth – raw water is poured through a piece of fine cotton cloth to remove some suspended solids.
- Aeration – water is aerated by being shaken in a vessel or by allowing it to trickle through perforated trays containing stones.
- Storage/pre-settlement – suspended solids and some pathogens will settle to the bottom of a container when water is stored in it for 48 hours. The top water can be drawn off for SSF treatment.
- Coagulation/Flocculation and settlement – a liquid coagulant (e.g. aluminium sulfate) is added to water and promotes agglomeration of suspended solids and their subsequent settlement. This is often a pre-treatment for rapid filters.
- Rapid Sand Filtration – higher flow rates and coarser media than SSFs, rapid filters are a means of removing suspended solids. Often a treatment used after coagulation/flocculation.

Further information can be found at:

- Brikké & Bredero (2003) at www.who.int/water_sanitation_health/hygiene/om/en/linkingchap6.pdf
- WELL www.lboro.ac.uk/well/index.htm
- Smet, J., & van Wijk, C., (2002), requires purchase from www.irc.nl/page/2481

4.1.4 Optional Components

4.1.4.1 Headloss Measurement

A SSF may incorporate a manometer to enable headloss measurement. Headloss measurement is useful for being able to predict when the SSF will require skimming.

Constructing a water manometer for a small scale SSF requires lengths of clear tubing that are longer than the depth of the filter bed and supernatant combined. One end of the tubing should be covered by gauze or fine mesh to prevent entry of sand into the tube. This end is placed inside the SSF bed at the base of the filter and exits the filter structure from a hole drilled into the side. This connection needs to be made watertight (e.g. using tank connector and jubilee clip). The tubing is then curved upwards and its end vertically fixed to the outside wall of the SSF tank. This arrangement is repeated for a second piece of clear tubing except that this time the bottom end is placed inside the SSF supernatant, just above the filter bed’s surface. Once again the tubing exits the filter via a hole made in the SSF tank wall and this connection is made watertight. The other end of this second piece of tubing is fixed at the top of the SSF tank. Both lengths of tubing should be located on the same side of the SSF tank. The water level in the two tubes can be compared (i.e. H_1 and H_2, Figure 4.4). The difference in water level between the two tubes is the headloss measurement. Initially this number will be low. As the SSF ripens and matures the difference in the water level between the two tubes will increase. This indicates that the filter media is becoming increasingly clogged and can be used to predict when the filter will require cleaning (skimming).

It is advisable to protect manometer tubes from sunlight exposure as this can promote biological growth in (and hence blocking of) the tubes.

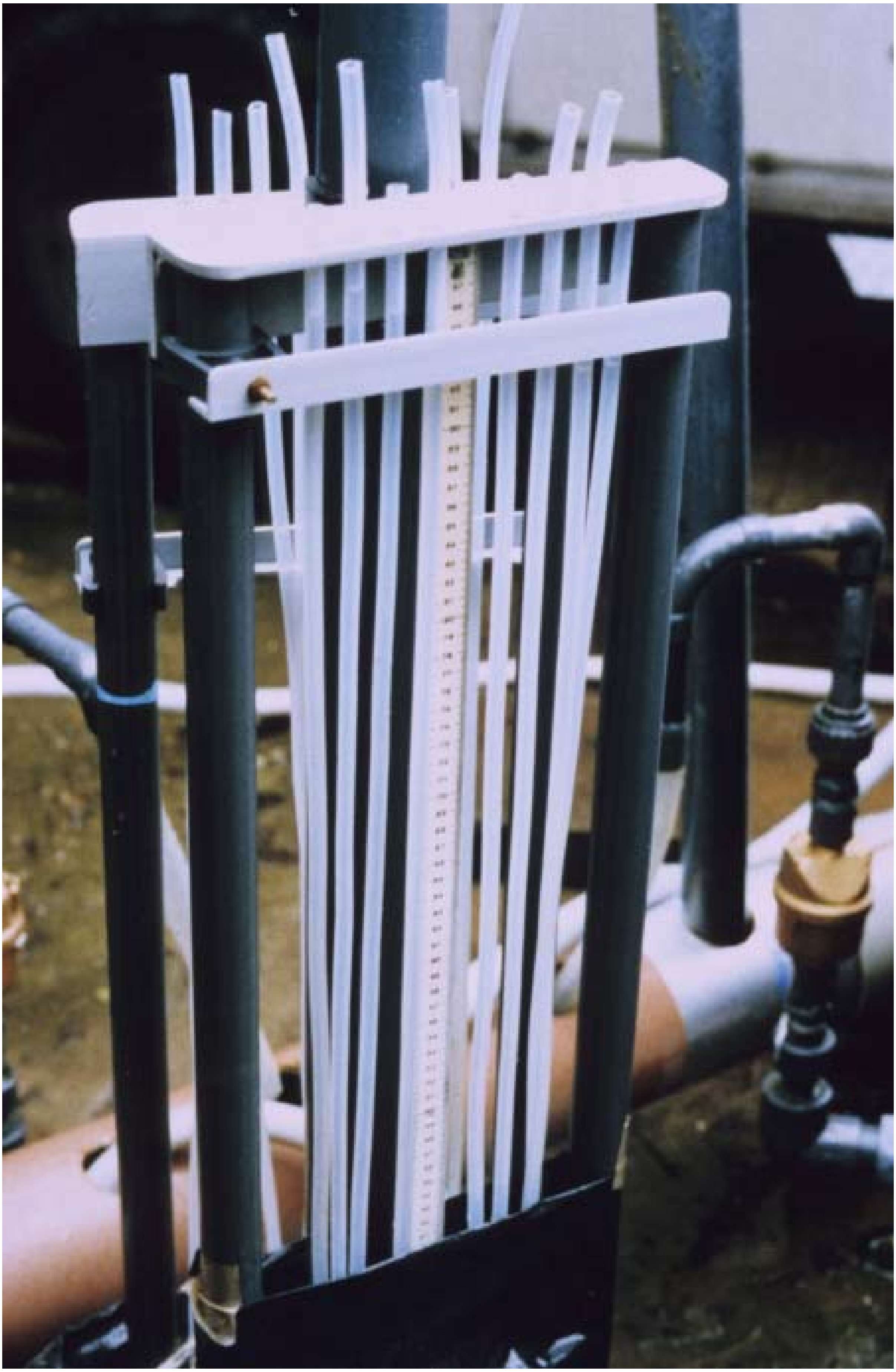


Plate 4.3: Manometer tubes and the scale used to measure headloss between tappings, for a pilot scale filter at Surbiton (London, UK)

Plate 4.4: Manometer tubes exiting a filter at Surbiton (London, UK). Note their arrangement to enable headloss measurement and also their protection against sunlight exposure.

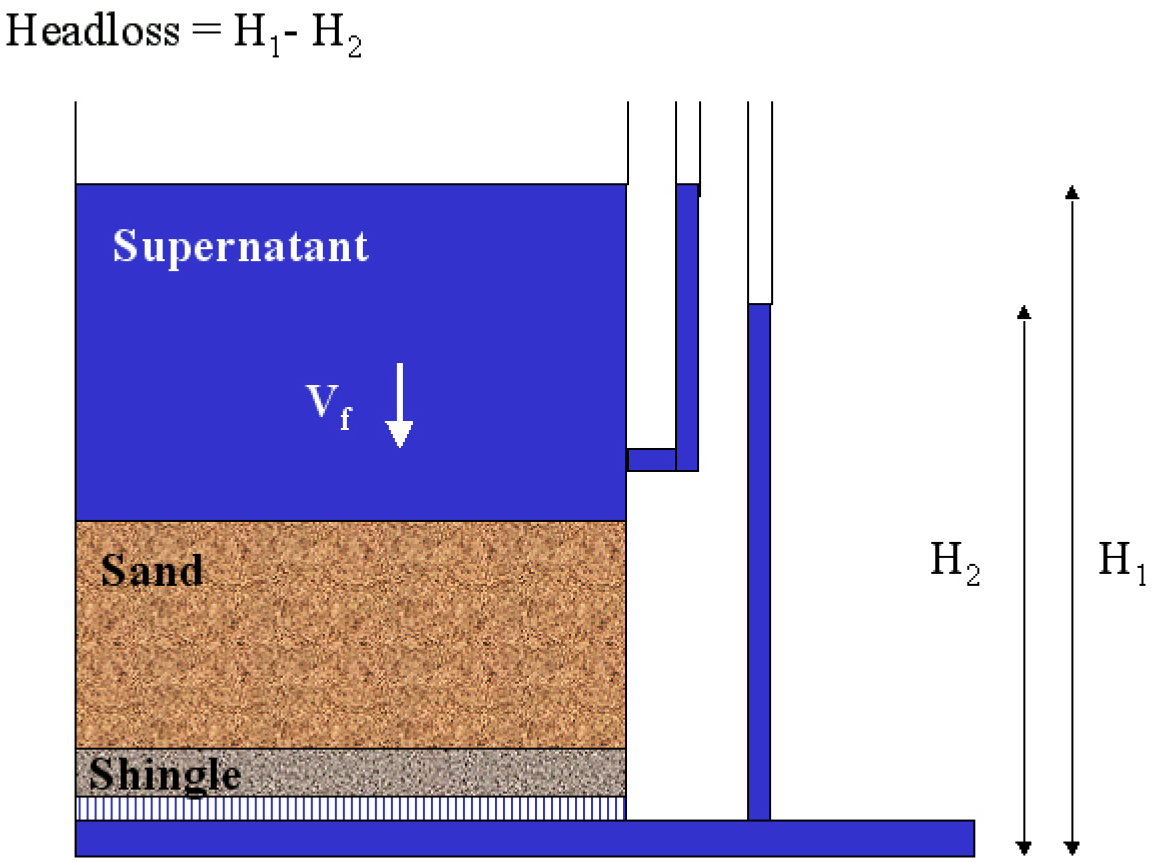


Figure 4.4: Headloss measurement using a Water Manometer

4.1.4.2 Covers

Use of covers (lids for tanks) is advised for household scale SSFs. Covering prevents biological (e.g. algal) growth in the SSF supernatant and header storage tanks. Covering also prevents contamination of treated water. By covering the SSF tank this slows filter clogging and enables longer running times in between skims. It therefore minimises time spent on maintaining the SSF and makes the filter more productive.

Covering water treatment processes such as SSFs and sedimentation ponds is also necessary to prevent disease transmission via the insect vectors as open water can form a suitable habitat for (insect) proliferation (Feachem & Cairncross, 1993).

4.1.4.3 Surface Mats

Surface mats (a layer of fabric of equal size to the SSF surface area) may be placed on top of the sand's surface of an uncovered SSF in order to improve performance. A suitable fabric may be locally available. Advantages include:

- Protection of the filter media from sunlight thus preventing rapid headloss development and short run times.

- Equivalent or possibly enhanced filtrate quality (compared to a conventional SSF). The aim of the surface mat is to concentrate the purification processes in the fabric layer itself, which in turn may improve removal rates.
- Avoidance of aquatic plants rooting in the filter.
- Protection of filter bed from coarse debris (e.g. leaves, bird-droppings).
- Extended run lengths (e.g. 3-4 times longer, though this will depend on the fabric and specific operating conditions).
- The SSF is less vulnerable to variable raw water quality. For example, an increase in influent water turbidity levels may result in rapid filter clogging, however, remedial action may only entail the removal and washing of the fabric, as opposed to skimming (which would be the course of action for a SSF without a surface mat).
- Simplified filter cleaning. Only the fabric is removed, and this can be washed by hose and re-used. This may reduce cleaning costs (for relatively small SSFs).
- The SSF demonstrates almost complete recovery in terms of headloss, after the replacement of the fabric.
- It is a relatively cheap amendment to a SSF.

(Mbwette & Graham, 1987, Klein & Berger, 1994, Mbwette *et al*, 1990).

In order to achieve the above it is recommended that the fabric demonstrates:

- Open structure with high porosity (0.7-0.95).
- Pore size of approximately 0.1mm.
- Small light transmission (below 20%).
- UV light stability.
- Low specific weight per unit area.
- 1-3mm thickness.
- High resistance to breaking.
- Easy disposal after use, if not re-used (e.g. via incineration)
- Low price.

(Klein & Berger, 1994).

Suitable fabrics are often described as 'non-woven synthetic fabric' (geotextile, Klein & Berger, 1994). The term synthetic fabric refers to man-made textiles. This means that the components that form the textile (i.e. fibres, webs or yarns) are artificially produced (i.e. not naturally produced such as cotton, Mbwette & Graham, 1987). The term woven refers to synthetic fabrics made from yarns or tapes, for example those produced by weaving or knitting. These are not considered suitable as they are usually very thin (usually less than 1mm, Mbwette & Graham, 1987).

Disadvantages of surface mats include:

- Not practicable for large SSFs due to difficulties in removing and disposing of the used cover.
- The advantages are only achieved if suitable fabrics are used.

- Care must be taken when removing the fabric not to disturb the surface sand layer below.
- If the SSF is uncovered then practical problems may arise in resisting the upthrust caused by trapped gas bubbles produced by algae and microbes on the fabric. This problem may be resolved by laying small stones on top of the fabric (sparingly used and evenly spaced).

(Mbwette & Graham, 1987, Clarke *et al*, 2004, Luff, 2000)

Plate 4.5: Surface Mat Installed onto a pilot scale SSF Bed at Shalford (Surrey, UK)

Plate 4.6: Surface Mat Ready for Installation onto a pilot scale SSF at Shalford, Surrey, UK (Plate 4.5)

Plate 4.7: Surface Mat Installed onto a SSF Bed at Surbiton (London, UK)

4.2 Community Scale

The details of a community scale SSF design and construction will vary according to the local resources and environment and as such are beyond the scope of this document. This level of information can only be provided by professional engineers, builders and plumbers who are familiar with the environment and local availability of labour and materials. The information in the following sections aims to provide guidance for the conceptual design of a community scale SSF. For a detailed set of design and construction guidelines refer to Visscher *et al* (1987) and Hendricks *et al* (1991). Galvis *et* *al* (1998) provides equivalent information for a multi-stage filtration system (which includes SSFs as a final treatment stage).

Plate Error! Style not defined.**.**Error! Bookmark not defined.**:** Covered community scale SSFs at Nyabwishongwezi Water Treatment Plant, Umatara, Rwanda

4.2.1 Raw-water Intake and Pumps

Raw water may be pumped, or gravity fed. Gravity fed systems run continuously, whilst pumped systems may only abstract water intermittently. The intake is designed according to the requirements of the treatment systems (Visscher *et al*, 1987). For example, for systems that continuously abstract raw water, flow control is needed at the point abstraction to ensure that a continuous and constant supply is fed to the SSFs (Lloyd *et al*, 1988). When choosing the location for a river intake, considerations include:

- Flow velocity - Intakes on rivers should be located in an area where flow velocities are relatively slow (as this maximises settlement of suspended particles), for example on the inside bend of a river.
- Sufficient water depth is required at all times (in order to maintain a continuous water supply).
- Water quality should be as consistent as possible.
- Bank stability is required.
- Locate the intake upstream of any nearby settlement to avoid contamination by human wastes entering the river.

- Elevation – if possible water should be taken from a higher elevation and gravity fed to the filters.

(Visscher *et al*, 1987)

4.2.2 Pre-treatment Options

Slow sand filtration is a process that requires consistency with regards to its operation and in terms of influent water quality. SSFs also have specific influent water quality requirements (Section 3.3). One of the fundamental problems suffered by SSF plants in many countries is their inability to cope with high turbidities (Lloyd *et al*, 1988). Therefore a combination of treatment processes often exist up-stream, which treat water to a quality that enables optimum SSF performance and sufficiently long running times to make the process operationally viable.

The changes made by pre-treatment to the chemical, physical and biological properties of the water being treated are relevant to the operation of a slow sand filter. It is also important to understand how changes to the operation of pre-treatment processes affect the performance of the SSF. Pre-treatment processes are necessary to improve SSF performance in terms of quality, to render slow sand filtration operationally sustainable, and to reduce operational costs. Installing and operating pre-treatment processes will incur a cost, however, these costs are partly offset by the prolonged operation of the SSFs. For example, it is thought that if pre-treatment will enable a SSF operating at surface loading rates of $0.1m^3/m^2/h$ to be operated at rates 20% higher, or, if a SSF operating at $0.2m^3/m^2/h$ can be operated at rates 60% higher, then this may be financially attractive (Huisman & Wood, 1974). If extensive pre-treatment is required, however, then this largely negates the use of SSFs as a simple technology. Conversely, if simple pre-treatment can be provided this renders SSFs a more widely applicable technology (Hendricks *et al*, 1991).

The aim of pre-treatment is to ensure:

- An integrated treatment system – The strengths and weaknesses of each treatment stage must be understood in order to select the correct composition of treatment processes (Galvis, 1999). There must be consideration for what is required to ensure the continuous production of safe water as well as to ensure that these treatment processes are operationally sustainable (e.g. gravel pre-filters protect SSFs in an MSF system, enabling longer SSF runs).
- Safe water supply due to a multiple barrier approach – Each treatment process is a barrier preventing the passage of pathogenic organisms or other contaminants. Hence, pre-treatment increases the number of barriers in place guarding against the transmission of diseases in drinking water (Visscher *et al*, 1987). The more treatment processes in place, the less likely it is that pathogens will penetrate these processes and will be present in supply water.

A number of pre-treatment options exist:

- Plain Sedimentation – this refers to the removal of suspended solids by their settlement under gravity. Particles smaller than 20µm will not be removed by this process (Wegelin, 1994). Short term plain sedimentation (<12 hours) is useful for pre-treatment of river water carrying high sediment loads (e.g. during flood flows, Cleasby 1991). For example Hendricks *et al* (1991) reported a case where settling ponds reduced raw water turbidity from 10-50NTU after storms and during periods of spring run-off to turbidity levels between 1 and 2NTU. Longer-term sedimentation, however, can encourage algal growth in the body of water (assuming it is not oligotrophic) and hence possible water quality deterioration in this respect. Therefore long-term plain sedimentation is unlikely to be successful as the sole pre-treatment process for water being treated in preparation for SSFs (Cleasby, 1991).

Sedimentation is a useful pre-treatment process where the suspended solids in the influent water are of sufficient size to settle readily within a few hours (Ellis, 1985). Lloyd *et al* (1988) cautioned that settlers would only be effective if they have been designed with sufficient capacity and baffling, and are routinely cleaned.

Plate Error! Style not defined.**.**Error! Bookmark not defined.**:** Sedimentation Tank (50m^3) at the Nyabwishongwezi Water Treatment Plant, Umatara, Rwanda

- Gravel pre-filters (also called 'Roughing Filters') – these filters use coarse (rough) gravel as a filter material (e.g. graded grain sizes between 5-40mm), with differently-sized filter material which successively decreases in the direction of water flow. Alternatively gravel pre-filtration may consist of a series of gravel beds of decreasing grain size (i.e. gravel pre-filters in series). Gravel pre-filters operate at relatively low filtration rates (compared to rapid filtration processes) and do not use chemicals. Advantages of this pre-treatment process include its simplicity, lack of mechanical equipment and the stability of the treatment process (Wegelin, 1994). Gravel pre-filters may be upflow, downflow or horizontal flow. Downflow gravel pre-filters may be less appropriate for low technology small scale applications as they require upflow backwashing (Cleasby, 1991). In contrast, upflow gravel pre-filters are cleaned by high rate gravity drainage downward. Upflow gravel pre-filters are also advantaged as the greatest solids accumulation occurs at the base of the filter, which facilitates cleaning by gravity drainage (Cleasby, 1991). Galvis (1999) describes a 'dynamic gravel pre-filter' (DyRF) where water is filtered downwards through 3 gravel layers (of increasing grain size). However for a DyRF only 10% of the water that enters the filter actually percolates through the gravel beds. The remaining 90% flows laterally across the filter and overflows to waste at the opposite end to where it entered. The filter is cleaned by periodically raking the media surface.

Weglin *et al* (1996) reported that dynamic and intake gravel prefilters were used successfully at a treatment plant in rural Cameroon as a pre-treatment to SSFs. Gravel pre-filters have also been successfully incorporated into small rural SSF plants in Peru (Lloyd *et al*, 1988), Rwanda (Clarke *et al*, 2004) and Ethiopia (Shenkut, 1996). A series of gravel pre-filters may provide protection to slow sand filters in what is termed multi-stage filtration (Section 3.1). Galvis (1999) provides a methodology for selecting between treatment options to include in a MSF system, based on pollution levels in the raw water source. A technical paper has also been produced by the IRC (Galvis *et al*, 1998) and can be ordered from the IRC at www.irc.nl/page/1894

- Riverbank Filtration (also termed Bankside Infiltration) – shallow wells are drilled into permeable soil (alluvial deposits of sand and gravel) alongside a river. The mixture of ground water and filtered river water is abstracted for further treatment (e.g. SSFs, Cleasby, 1991). Shenkut (1996) reported that infiltration galleries were an effective initial pre-treatment stage for SSF plants in Ethiopia.
- Coarse Filtration at the Point of Abstraction – a filter can be made from a basket of pebbles which is placed in the river and through which water must be sucked. For a shallow stream, a perforated abstraction pipe can be laid on the river bed (at right angles to the direction of flow) on the up-stream side of a low weir. The pipe is covered in gravel, and the river deposits a layer of silt. Hence water abstracted through the pipe is filtered through these two layers (Ellis, 1985).
- Coagulation/Flocculation and settlement – a liquid coagulant (e.g. aluminium sulfate) is added to water and promotes agglomeration of suspended solids and their subsequent settlement. Often a pre-treatment for rapid filters (in so-called conventional treatment). Use of chemical dosing to promote settlement of particles in water treatment plants in rural locations in developing countries is discouraged by Weglin *et al* (1996) as this is rarely successful (Section 3.1).
- Rapid Filtration - higher flow rates and coarser media than SSFs, rapid filters are a means of removing suspended solids. They may be used after coagulation/flocculation (and before SSFs), however they may also be used as an alternative treatment process to SSFs when used in combination with other processes (e.g. coagulant dosing, Section 3.1). Rapid filtration is usually considered to be a physical treatment process rather than a biological one. Rapid filtration is widely applicable to a range of water quality conditions, although it is unlikely to achieve the microbiological removal rates of SSFs (unless combined with other treatment processes such as coagulation/flocculation). Furthermore, this combination of treatment processes is discouraged by Weglin *et al* (1996) when the application is water treatment for rural locations in developing countries (Section 3.1).

Further information can be found at:

- Smet, J., & van Wijk, C., (2002), requires purchase from www.irc.nl/page/2481
- Brikké & Bredero (2003) at www.who.int/water_sanitation_health/hygiene/om/en/linkingchap6.pdf
- WELL www.lboro.ac.uk/well/index.htm

4.2.3 Raw-water balancing tank

A raw water balancing tank assists in supplying a continuous supply of influent water to the SSF when continuous pumping is not possible (or for example when using rainfall water as a raw water source). When raw water is pumped, a raw water balancing tank safe-guards against disturbance to SSF flow as a result of power cuts. A raw-water balancing tank can also help reduce the capital costs of the SSF. This is because when elevated, it enables continuous operation of a smaller sized SSF when otherwise the operating mode would be declining filtration rate (Section 4.2.4), which requires a larger sized SSF in order to achieve comparable throughput (Visscher *et al*, 1987). A SSF operating with a declining filtration rate is not recommended.

When possible, advantage should be taken of natural slopes, by locating the raw water tank above the SSF tank (Oxfam, 1994). When natural slopes do not exist it may be worthwhile constructing an elevated earth platform to enable gravity flow. However in order to take the weight of the tank a gravel or concrete foundation ring may be necessary (Oxfam, 2004). When the raw water tank is placed on the same level as the SSF tank the water level in the raw water tank must be elevated above that of the SSF tank.

The size of the raw-water storage tank will depend on what volume of water is required to service the SSF and the number of hours that the pumps can operate daily, and at what capacity.

4.2.4 SSF Mode of Operation

Three modes of SSF operation can be identified:

1. Continuous
2. Declining filtration rate (not advised)
3. Intermittent (not advised).

(Visscher *et al*, 1994)

Continuous Operation

During continuous operation, a SSF is supplied by influent water 24 hours a day either by gravity flow, or by continuous pumping. When continuous pumping is not possible a storage facility upstream of the SSF (header tank or balancing tank) may used. This is fed during certain daily time intervals and contains sufficient storage of water to allow this to gravity feed the SSF 24 hours a day (Visscher *et al*, 1994).

Declining Filtration Rate Operation – NOT ADVISED

The declining filtration rate mode for outlet controlled SSFs involves feeding influent water into the SSF supernatant only during certain hours of the day (e.g. due to restricted pumping capabilities). This mode of operation is not recommended, although some report that this may be a suitable solution for areas with intermittent power supply (and without an up-stream balancing tank). Water is pumped into the supernatant whilst power is available, however, the outlet valve remains open 24 hours a day (Visscher *et al*, 1987). When pumping is stopped the supernatant levels drops, which in turn decreases the driving head, and the filter's surface loading rate declines. Before the supernatant water is depleted, the pump is switched on again to fill the SSF supernatant. This mode may be more costly than the continuous mode since a larger SSF area is required to provide the same throughput of water as continuously operated SSFs (Visscher *et al*, 1994).

Declining rate filtration is not possible for inlet controlled SSFs (Section 4.2.14.1). This is because the supernatant water level is low and therefore this top water would drain relatively quickly (Visscher *et al*, 1987).

Declining rate filtration SSFs may experience problems with performance due to flow variation (e.g. low DO as surface loading rate declines). Hence, continuous SSF operation should be favoured as a design option. It is recommended for areas of interrupted raw water supply (e.g. due to intermittent power supply to pumps) that a balancing tank be built up-stream of the SSF(s) such that a constant filtration rate SSF can be used.

Intermittent Operation – NOT ADVISED

Intermittent SSF operation refers to the filtration of water only when water is required. **Intermittent operation should not be used with SSFs**. Consistency in SSF operation is fundamental for effective water treatment by this process. Intermittent operation of a SSF is likely to result in poor filtrate quality, potentially causing illness in those drinking the treated water.

4.2.5 Number and Size of SSF Units

Both the community population size (taking into account population growth rate i.e. design population) and the chosen design period are parameters required to calculate the required design flow capacity of the plant. The required system capacity is a pre-design consideration and was discussed in Section (3.4). Given this design flow, and assuming the SSFs will operate at guideline surface loading rates (Section 4.2.14.2), the total required filter bed area can be calculated. This area can then be divided up into individual SSF unit areas. Although it might be thought that a community’s drinking water needs can be met by building a single SSF, there are advantages of providing several smaller units instead. When a single filter unit is built this can present some problems:

- When problems with the SSF mean that it is removed from service, there is no alternative supply of treated water.
- During skimming or maintenance procedures the available treated supply is limited to the storage capacity of the clear water reservoir (tank).
- There is pressure on the operatives to skim and return a SSF to service as quickly as possible. Although minimising the drain-down period during SSF skimming can assist in improving filtrate quality during the start of the subsequent run (Section 2.2.5), beware of subjecting operatives to levels of pressure which lead to the temptation to not do the job properly.

(Logsdon, 1994).

Building several smaller SSF units in place of one large one increases the flexibility of the system. Already constructed SSFs can be divided into multiple units. With rectangular SSFs this relatively easy. With round SSFs the filter may be subdivided into ‘pie’ segments (Logsdon, 1994).

As the number of filter units increase, the excess plant capacity that must be built to meet demands (when SSFs are out of service) decreases (Pyper & Logsdon, 1991). For example, when only two units are built then each SSF must be large enough to cope with 100% of the design flow. In contrast if four SSFs are built then each SSF would need to be able to cope with 33% of the design flow, so the total plant is only 33% larger than needed (Pyper & Logsdon, 1991). This makes smaller units more economical. Conversely, the more filters that are built, the more expenditure there will be on valves and pipes etc. These factors all influence costs and should be evaluated when deciding on the most appropriate number of SSF units.

Huisman & Wood (1974) warned that the necessary precautions against thermal expansion, shrinkage of concrete, uplift of floors and unequal settlement become more difficult as the size of the SSF increases. Therefore in order to ensure that the SSF is water-tight, a larger number of smaller SSFs is recommended in place of fewer, but larger SSFs.

The area of each filter unit will depend on the intended skimming method (Section 5.2.3) and the number of operatives available to undertake the skim. An individual SSF unit should be small enough (in area) to enable it to be skimmed within one day. If manual skimming is used then a unit’s area will depend on the time taken to manually skim the SSF unit and the number of operatives available to undertake the skim. A method for calculating the area of individual units based on this information, is provided by Hendricks *et al* (1991):

Area of 1 unit, a = (skim rate in m^2/person/hour) x (no. of operatives) x (hours allotted to skimming)

Based on data from a SSF studied by Hendricks *et al* (1991) this was estimated at:

Area of 1 unit, a = ($19m^2$/person/hr) x (3 operatives) x (8 hours allowed for skimming)

$= 456m^2$

NB SSF was out of service for 16 hours:
4 hours to drain the supernatant, 8 hours to skim and 4 hours to re-charge the filter.

If fewer operatives are available, obviously the filter unit areas will be smaller. Visscher *et al* (1994) recommended that a minimum of two filter units should be built, and that for rural communities where manual skimming is practiced, the appropriate area of an individual SSF unit varies between 5 to $200m^2$ per filter (depending on demand). Although, care must be taken to ensure that a sufficient surface area is provided to permit access for cleaning. Huisman & Wood (1974) and Sharpe *et al* (1994) suggested a minimum SSF area for one unit of $100m^2$. This equates to dimensions of 9.1 by 9.1m for a square filter, or a circle of diameter 10.7m for a circular SSF. A minimum size is recommended due to:

- Cost – larger units have an initial lower cost per square metre than smaller units.
- Quality – smaller units may be more vulnerable to water short-circuiting the filter at the wall. This can be minimised by roughening the inside wall surfaces.

Despite the possible advantages of SSFs larger than $100m^2$ (in surface area) it is still recommended that two or more smaller filters be built in preference to just one filter, even if the individual SSF units (used to make up the total SSF surface area required to serve the community) have surface areas below the minimum SSF unit area recommendations.

Once a suitable area for each SSF unit has been calculated, this information can be used together with the design flow of the system (Section 3.4) and the selected maximum surface loading rate of an individual SSF (Section 5.1.2), to determine the number of SSF units required. The required total surface area of all SSF units can be calculated as follows:

$$A = \frac{Q + Q_1}{V}$$

Where
Q = design flow capacity of the plant i.e. site throughput (m^3/h, see Section 3.4)
A = total filter area (m^2)
V = surface loading rate (maximum permitted, $m^3/m^2/h$, Section 5.2.2)
Q_1 = throughput for one SSF (m^3/h) = (V x individual SSF unit surface area)

This calculation assumes that the site can still treat the design flow (site throughput) when one SSF has been taken out of service (e.g. for cleaning or repair). In order to provide the facility for outage of more than one SSF, Q_1 should be multiplied by the required number of SSF units (that may be out of service whilst still meeting supply demands).

Once the total filter area (A) has been calculated, this can be divided by the area of individual filter units (see above), to give the number of filter units that need to be built to meet the community's needs.

When a SSF is removed from service its influent water should be diverted onto the SSFs remaining in service in such a way that their surface loading rates are gradually increased (ensuring that the same volume of water is treated by the SSFs remaining in service). However, if all the SSF units are needed to meet demands during normal operations then the flow through those units remaining in service (whilst one is removed from service) will be significantly higher. This is not an issue when the calculation above is used (as it incorporates an additional filter to compensate for outage during maintenance). Furthermore, evidence suggests that surface loading rates up to $0.3m^3/m^2/h$ for these filters for this short time period will not adversely affect their performance (Visscher *et al*, 1994). Pilot plant studies (Section 3.9) can be used to determine the maximum surface loading rates at which a specific SSF performs effectively (given the conditions under which it operates). As a guideline, Hendricks *et al* (1991) reported that SSFs should be expected to maintain run lengths of over 30 days, whilst run lengths of several months should be considered fortunate. Huisman *et al* (1981) reported that if filter runs much longer than 2 months prove possible (as demonstrated by pilot plant testing), then the nominal surface loading rate may be increased and hence the number of SSF units decreased.

If mechanical skimming is intended then it is recommended that SSFs be built of equal sizes in a rectangular shape. The minimum SSF unit area will depend on the mechanical skimming method practiced (Section 5.2.3).

In summary:

- Define the per capita water demand.
- Multiply this by the number of people the SSFs are intended to be able to supply, to provide design flow, Q.
- Decide the intended nominal and maximum permissible surface loading rates (pilot plant studies can determine these values).
- Calculate total filter surface area, A.
- Determine how many operatives will be available to skim the filter and how long this is likely to take given the equipment available.
- Calculate maximum individual SSF unit area, a.
- Divide 'A' by 'a' to calculate the number of SSF units required.
- Check that maximum surface loading rates will not be exceeded for filters remaining in service when one filter unit is out of service (e.g. for skimming).

4.2.6 Inlet Structure

The inlet structures purpose is to enable operative control of the flow of water into the filter without disturbing the filter media. This structure is usually a box, with water entering from a pipe (fitted with regulating valve) on one side. The water level in the inlet box is allowed to rise up to a level at which it flows over into the SSF box (Figure 4.5). Another valve located on a pipe exiting the bottom of the inlet box allows rapid drainage of the supernatant (Ellis, 1985). This set up also allows the supernatant water level to be controlled (Visscher *et al*, 1994). For inlet controlled SSFs the inlet structure must incorporate a device to enable flow measurement.

The facility to drain a SSF through the bottom of the inlet structure saves time when draining the supernatant, however, water will only drain by this route if the wall of the inlet structure (up against the media bed) is reduced in height in line with the declining depth of the filter bed (as is skimmed). This wall should therefore have an adjustable sill along at least part of its length (Huisman & Wood, 1974). These facilities quicken the rate at which the SSF can be drained and hence the time that the SSF is out of service for maintenance (which in turn reduces operational costs).

Inlet structures should also be fitted with a splash plate to prevent influent water flow from disturbing the media. This is particularly important for inlet controlled SSFs where the supernatant level drops low and is then top-filled. Filters that are top-filled rather than back-filled during recharge are also more vulnerable to media disturbance at the inlet and should be fitted with a splash plate (Pyper & Logsdon, 1991).

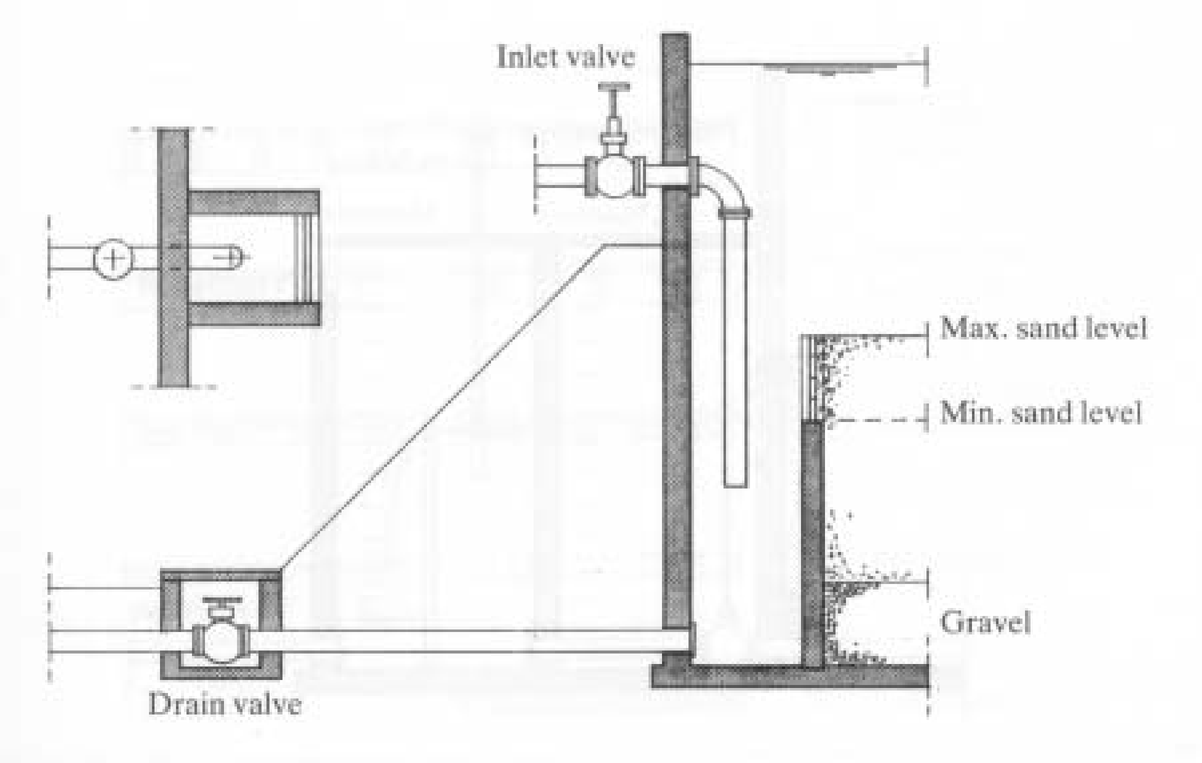


Figure 4.5: Typical Inlet Structure (reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply* Technical Paper No. 24, Copyright (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

4.2.7 Supernatant

The size and design of the upper section of the filter (i.e. where the supernatant resides during operation) will depend on the mode of operation of the SSF (Section 4.2.4) and the flow control system set up (Section 4.2.14.1). A sufficient head of water is required to drive flow through the SSF media. A deeper supernatant enables a longer filter run, and thus less frequent skimming, for any given water quality condition (Pyper & Logsdon, 1991). The height of the supernatant will also influence costs and the degree of water storage. Supernatant water is usually 1-1.5m in depth. Above the supernatant water the walls of the SSF box are extended upwards a further 20-30cm (termed the ‘freeboard’, Huisman & Wood, 1974).

4.2.8 Scum Outlet

Scum outlets are troughs on the sides of the SSF which allow the removal of surface scum (dirt, debris, oil etc). On large SSFs several of these are provided so that scum can be removed under varied wind directions. To remove surface scum via the scum outlet, the influent water flow is increased slightly and this causes the supernatant to rise to the scum outlet and overflow over the lip of the trough. The water entering the trough runs to waste. A scum outlet also protects against overflow during careless operation (Huisman & Wood, 1974).

4.2.9 Filter Box

The filter box refers to the structure (or container) in which the filter bed sits. It must be high enough to accommodate the:

- Supernatant (e.g. 1.25m)
- Maximum filter bed depth (e.g. 1.25m)
- Gravel layer (e.g. 0.35m)
- Under-drainage (e.g. 0.16m)
- 'Freeboard' (0.2-0.3m wall above the supernatant)

(Huisman & Wood, 1974, Hendricks *et al*, 1991)

In the example above this leads to a total SSF box height of 3.21m. As a general rule, the SSF box will be between 2.5m and 4m in height (Huisman & Wood, 1974).

Another consideration (for permanently covered SSFs) is that there needs to be sufficient height for a person (6ft, 183cm) to stand upright on the media when the SSF is at its maximum bed depth so as to enable cleaning and other maintenance (Logsdon, 1994, Hendricks *et al*, 1991).

Guidelines for calculating the appropriate area of the SSF box is discussed in Section 4.2.5.

The walls of the SSF box can be artificially roughened to ensure that supernatant water does not flow directly down the sides of the walls to the under-drainage without being filtered (short-circuiting the bed). Another method to prevent short-circuiting is by making a groove in the inner box wall (at a height within the SSF bed) that runs around the complete circumference of the SSF box. Another effective precaution is to give the walls a slight outward batter (Huisman & Wood, 1974). This means that the inner wall of the SSF slopes inwards slightly towards its base. SSFs with relatively small areas (e.g. <5m^2) will be more vulnerable to short-circuiting of water down the walls of the SSF.

SSF boxes may be made from reinforced concrete, mass concrete, masonry (natural stone, quarry stones or bricks), ferrocement, or an excavated structure within protected sloping walls ('earthen berm construction' Pyper & Logsdon, 1991, Visscher *et al*, 1987). Locally sourced materials and locally used building methods should be encouraged if these are suitable. For example, Shenkut (1996) reported that in Ethiopia, tanks (in this case sedimentation tanks used in pre-treatment) were constructed from masonry stone. The thickness of the walls was not more than 40cm and was made water tight by plastering the inside surface with chicken wire (ferrocementing). Instructions for constructing tanks made of ferrocement are provided by WELL at www.lboro.ac.uk/well/resources/technical-briefs/technical-briefs.htm ('Ferrocement Water Tanks', Technical Brief 36).

Sloping walls reduce the structural stresses by making fuller use of the bearing capacity of the ground, thus enabling the structure to be built more cheaply. Sloping walls will also help prevent the short-circuiting of water (as described above). However sloping walls require a larger SSF area, and may present problems with aquatic growth at the edges (Visscher *et al*, 1987). This box design is also associated with more problems regarding water-tightness (Huisman & Wood, 1974). Making sure the SSF box is water-tight is important not only to minimise water wastage, but also to prevent ingress of groundwater that could potentially contaminate the filtrate (Huisman & Wood, 1974). The upward thrust from ground water is another consideration for sunken SSFs. For this reason, it is advised that where possible the floor of the SSF box is situated above the water table.

A SSF box that is sunk into the ground has the advantage that access is made easy and also that the SSF is insulated. This approach may therefore be favoured in cold climates (although it should not be practiced in areas that experience permafrost). For sunken SSFs the freeboard section of the box wall should protrude above the ground in order to minimise the entry of dust and debris (Huisman & Wood, 1974).

If the SSF tanks stand above ground level, advantage should be taken of natural slopes by locating the tanks above the clear water reservoir (but below the raw water tank, Oxfam, 1994). When natural slopes do not exist it may be worthwhile constructing an elevated earth platform for the whole or part of the plant, to enable gravity flow. However, in order to take the weight of the tanks a gravel or concrete foundation ring may be necessary (Oxfam, 2004).

The most appropriate material for building a SSF box will depend on local resources and the design of the SSF. Reinforced concrete may be a disadvantage as it requires a complicated framework. Circular filters may be an advantaged as they are inherently strong, and have a minimum perimeter (wall length) for a given surface area (realising costs savings, Pyper & Logsdon, 1991). For multiple SSFs, hexagonal shaped SSF units (with shared walls) keeps the ‘foot print’ of the plant to a minimum, however, this arrangement may lead to issues regarding access (e.g. during cleaning). Further considerations are reviewed by Visscher *et al* (1987).

When more than one SSF is built (strongly advised) circular SSFs are disadvantaged compared to rectangular or square SSFs as they cannot share walls (a means of reducing cost). Rectangular and square boxes may also be more convenient where mechanical skimming is practiced as access ramps may be easier to install (Pyper & Logsdon, 1991).

The structural design of the SSF box and the materials used will depend on the pressures exerted on to the box. For example, if the SSF has its walls below ground level then the structure must not only be able to withstand the hydraulic pressure exerted on the inside of the box, but also the soil pressure exerted on the outside of the box (Hendricks *et al*, 1991). If a SSF is to be covered then the walls must be built to support the roof (Pyper & Logsdon, 1991). Whenever SSFs are built with common walls then each wall should be built to withstand a scenario where there is the full water load on one side and no water on the other (Pyper & Logsdon, 1991). Such analyses are beyond the scope of these guidelines and will require the services of a professional engineer trained in structural design and geotechnical engineering. Visscher *et al* (1987) provide some information in this respect for relatively small sized community scale SSFs. Some of this information is summarised in Table 4.

Once the SSF box has been built, markings may be made on the inside walls to indicate the maximum and minimum filter media depths. This assists during the SSF’s operation in determining when the SSF requires re-instatement (Section 5.2.4).

Table 4: Applicability of various types of constructions for slow sand filters (reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply* Technical Paper No. 24, Copyright (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

Type of Construction	Size Range per Unit (m^2)	Thickness of Lining or Wall (m)	Comment
Protected sloping well	Rectangular 40-4000	0.04-0.10	Low cost Minimum skilled labour required for construction.
Mass concrete or masonry	Circular or square 2-300	0.20-0.30	Particularly suitable for small filters in low

			groundwater-table situations.
Ferrocement	Circular 2-120	0.05-0.08	Possible deformation of filter walls. Construction and curing of ferrocement require due attention.
Reinforced Concrete	Rectangular 4-400 Circular 4-400	0.20-0.25 0.15-0.20	Skilled labour required for formwork and reinforcement.

4.2.10 Filter Media Bed

There are several factors to consider in the design of the filter bed:

- Media type (e.g. sand).
- Media specification (e.g. ES, UC, see below for explanation).
- Media depth (maximum and minimum)
- Media preparation (e.g. washing).

Media Type

Although sand is usually chosen, any inert granular material can be used to make up the media bed in SSFs. Sand is usually the media of choice since it is effective, cheap, durable, inert and widely available (Visscher *et al*, 1994). Pilot plant studies can ascertain whether a particular media type meets these requirements (Section 3.9).

Media Specification

Guidelines vary on the recommended specifications of sand media for SSFs (Table 6). The grading and classification of sand uses the following terminology:

- Effective Size or Effective Diameter (ES or d_{10}): the size of the sieve opening through which 10% of the media will pass (Hazen, 1908). The ES is usually used in reference to the size of individual SSF media grains.
- Uniformity Coefficient (UC or d_{60}/d_{10}): the ratio of the sieve size through which 60% of the media (e.g. sand) will pass, to the size through which 10% will pass (Hazen, 1908). This quantifies the degree to which particles are mainly of the same size or whether there is a large range in their diameters.
- Porosity (relative void volume): If a SSF bed is saturated with water (assuming water completely fills the interstices) then the porosity may be defined as the percentage of the total volume of the sand bed that is occupied by water.

The correct choice of media size (ES) influences operational and performance parameters. As a SSF accumulates material the media becomes clogged (headloss increases) and eventually it will be too clogged to permit the required flow through the filter and the bed will require skimming. Selection of the appropriate media will influence the frequency with which skimming is required (and thus the filter's productivity). If the filter media is large (in diameter) then the initial headloss and rate of headloss development tend to be lower (Boller & Kavanaugh, 1995, Cleasby, 1991), but this may be at the expense of removal efficiency (van der Hoek *et al*, 1996, Logsdon *et al*, 2002). As a result, particulates in the water will penetrate more deeply into the filter bed before they are removed (Cleasby, 1991). Conversely, if the media it is too small (e.g. ES<0.15mm) then this might restrict run length due to rapid filter clogging (headloss development). Frequent skimming results in increased operational costs and decreased productivity (as the filter is frequently out of service). Therefore the choice of media size must balance filtrate quality against filter run duration.

The appropriate choice of media and its depth will be influenced by the chosen surface loading rate (Section 4.2.14.2). Although research (Rachwal *et al*, 1988) has demonstrated that high surface loading rates (up to $0.5m^3/m^2/h$) do not adversely affect SSF performance (providing adequate pre-treatment exists) another study (Poynter and Slade, 1977) suggested that SSF penetration by some micro-organisms (viruses and bacteria) might be more likely when the sand depth is shallow and surface loading rate high. Therefore a higher minimum bed depth value might be prudent if surface loading rates are high. Note also, that high surface loading rates will increase the rate of headloss development and shorten run lengths, however, by choosing a larger (diameter) media size this will reduce headloss, thus increasing run length (Ryan, 1988) and may render high surface loading rates sustainable. Care must be taken that the correct balance is struck between rendering the SSF as operationally efficient as possible whilst not compromising filtrate quality.

A finer media (smaller ES) usually results in higher removal rates by the SSF, but will shorten a SSF's run length. Pilot plant studies should aim to identify the largest sand size that can be used without compromising treated water quality. Media should be no finer than is necessary so as to maximise SSF run lengths (Fox *et al*, 1994). For example, Weglin *et al* (1996) reported that a sand media with a relatively large ES was successfully used for SSFs at a water treatment plant in rural Cameroon. This increased run lengths and was not found to significantly reduce coliform removals. If there are concerns with the performance of a SSF using a relatively coarse media, then increasing the sand depth to safeguard against SSF penetration is a possible solution. In fact, Ellis (1985) reported that increasing the sand depth to safeguard against SSF penetration is preferable to decreasing the sand size of the media. A SSF should be designed to operate for run lengths of at least 2 weeks when subjected to the worst raw water quality it is likely to receive throughout the year (Huisman & Wood, 1974).

Although guidelines for suitable SSF media exist, it is stressed that media which does not conform to these specifications might also be suitable. Sometimes it may be necessary to select a media that is locally available (even if it does not meet the specifications in Table 6) in preference to a media which meets these specifications but which is not locally available and hence much more expensive. Studies have demonstrated that use of 'builders or construction grade sand' in SSFs can produce equivalent filtrate quality to SSFs laid with specially prepared filter sand (Letterman, 1991).

UC and ES values can be calculated for a particular media by sieving it through a set of sieves of decreasing mesh sizes (of known size). These sieves are usually stacked one above the other with the largest mesh size at the top. A known weight of dried sand is placed onto the top sieve and the stack is shaken. The weight of sand retained in each sieve is weighed and these values are converted to percentages (of the sample's total dry weight). This data is used to plot percent finer (percentage values) against grain diameter (sieve mesh size) on probability paper (Hendricks *et al*, 1991). A best-fit line is drawn between the data points and the d_{10} and d_{60} are equal to the grain diameters when percent finer is 10% and 60% respectively. By dividing d_{60} by d_{10}, this provides the UC.

This data can also be plotted on lin-lin (i.e. both axes as linear scales) and linear-log paper (one axis logarithmic and one axis linear), however, a curved line is obtained (e.g. Figure 4.6). Probability paper simplifies the analysis by linearlizing the trend.

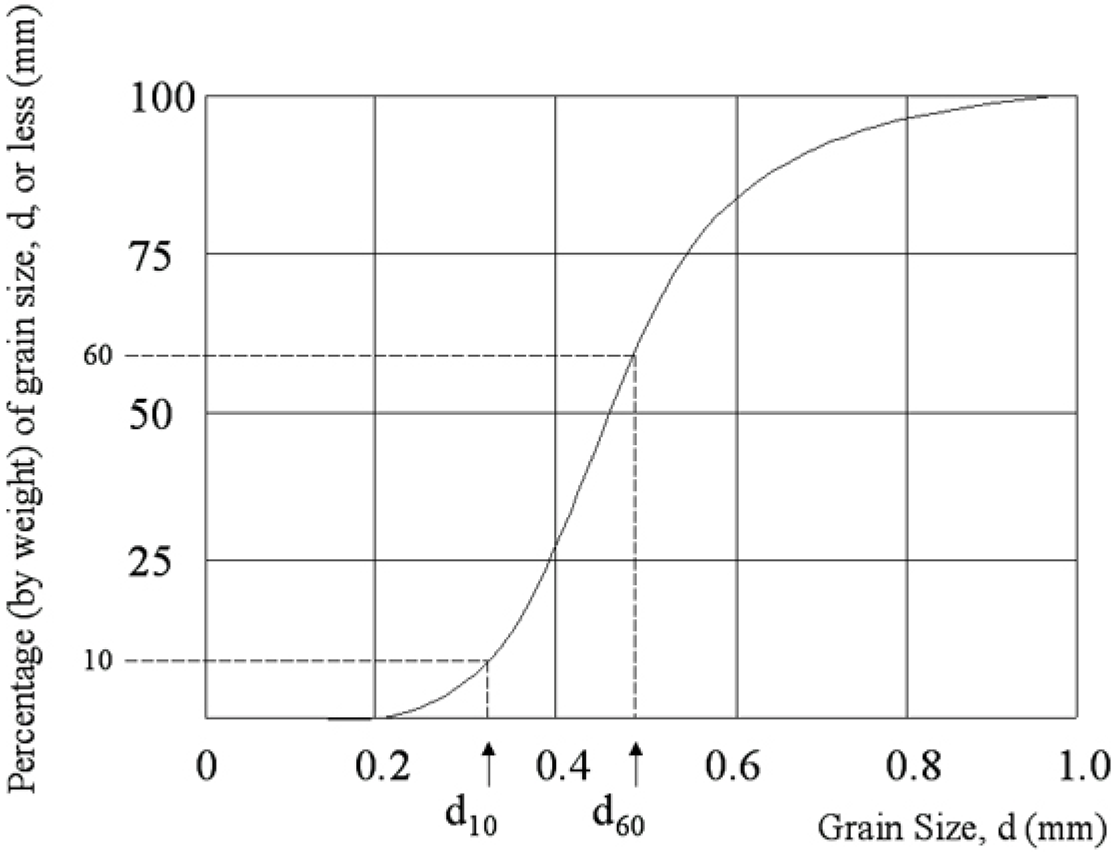


Figure 4.6: Example of sieve analysis data for potential filter media. Results are plotted on lin-lin paper and a curved line is obtained.

If laboratory analysis is not possible when selecting the media, then Visscher *et al* (1987) advise that two ASTM sieves are used: No. 18 (1.0mm) and No. 70 (0.21mm). If most of the sand particles pass through No. 18 and are retained on No. 70 (i.e. <10% pass through) then the sand is suitable for use in a SSF. If this is not the case then alternative sand should be sourced if possible. Alternatively, if most of the sand is retained in sieve No. 18 then this could be used for a SSF bed but will require sieving first. Mixing of sands from several locations may also be an option (Visscher *et al*, 1987). Mixing must be thorough, however, which may be achieved using a concrete mixer (Huisman & Wood, 1974). Mixing sand does not give a linear result, however, therefore mixed sand should be re-graded (if possible) using sieves.

In the absence of sieves, Delmas and Courvallet (1994) suggest that a uniformly sized sand media may be obtained by sieving it through mosquito netting.

Media must be free from dirt, soil, silt, clay and organic material before it is laid in the bed (Pyper & Logsdon, 1991). Silt content can be assessed by placing a 100ml sample of the sand into a measuring cylinder (or glass container of known volume) and adding water to the 200ml mark. This is shaken vigorously and then allowed to settle (for approximately 20 minutes). Three layers will be formed:

1. turbid top water
2. silt (settles in the middle of the container)
3. sand media (settled at bottom of container)

The silt content is calculated by measuring the height of the band of settled silt (Figure 4.7). This can be converted into a percentage of the total media sample height. Visscher *et al* (1987) advised washing sand with more than a 1% silt content.

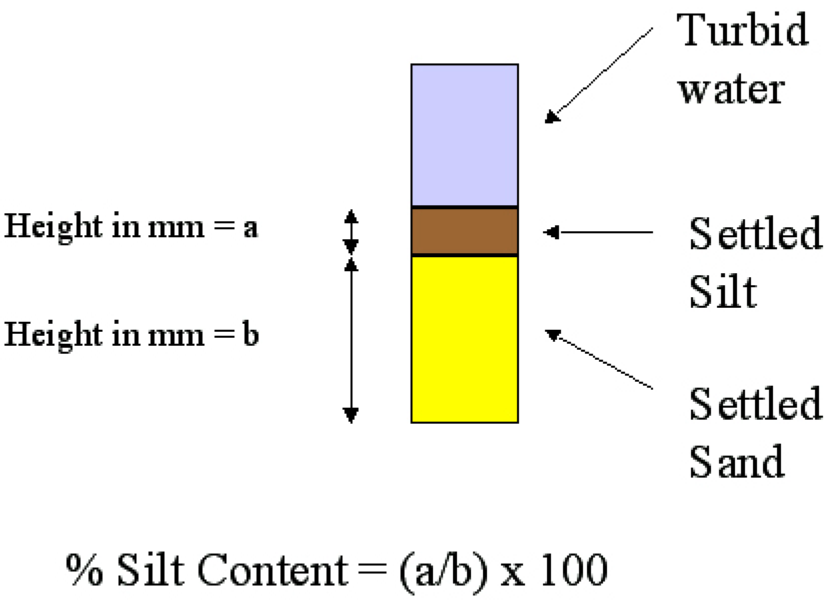


Figure 4.7: Calculating Silt Content of Media Samples (not to scale)

Additional parameters to consider when selecting a media are listed in Table 5. Presence of metals in media can cause problems with filtrate colour, however depending on the available resources this may be tolerated. Carbonates present in the filter media may cause problems with filter blocking when algae are present in the supernatant. These factors can be investigated at pilot scale (using various media types) before the full-scale SSF build begins.

Table 5: Specification for Silica Sand Media

Parameter	**Value**
Grain Density	2.65g/cm^3
Bulk Density	1560kg/m^3
Cleanliness	Free from clay, dust, organic matter. Sand shall not originate from, and be stored at, places where there are no visible signs or history of contamination by sewage or other pollution sources.
Dry Weight Solids Content	Maximum 1.0kg/m^3
Particulate Organic Carbon	Maximum 0.1kg/m^3
Metals	<0.1% w/w of iron, manganese or aluminium
Carbonates	<2% w/w of carbonates
Faecal Contaminants (e.g. thermotolerant coliforms)	<10cfu/100cm^3 based on 100g media in 500cm^3 of sterile water. No detectable spores or oocyst producing organisms shall be present

In order to ensure that the media is free of dirt and fines it must be washed prior to its installation (Section 5.2.8). Sand for a SSF may be able to be sourced locally. This has the advantage of reducing costs. Pilot testing (Section 3.9) is important to assess the suitability of locally supplied sand (Pyper & Logsdon, 1991). Logsdon (1994) cautioned that locally quarried media for SSFs may result in problems with filtrate turbidity. This is because of its high fines content resulting in turbidity ‘bleeding out’ of the media for possibly extended periods (even if it was pre-washed). Examples were given by Logdson (1994) where filtrate turbidity levels exceeded influent water turbidity levels and these levels remained elevated (1NTU) for over a year. However other quality criteria such as microbial counts were met. Hence high filtrate turbidity levels do not necessarily indicate passage of micro-organisms and may be tolerated, although it is advisable to first consult the community of their aesthetic requirements for treated supply water (Section 3.6). This sort of problem can be identified before SSF construction begins by pilot plant tests (Logsdon, 1994) and community consultation. Therefore the optimal media can be selected from the materials available in the area. Any problems identified by pilot plant studies (regarding media fines content) will also alert engineers to the requirement for rigorous sand washing procedures (Logsdon, 1994).

Media Depth

A minimum media depth (together with appropriate surface loading rate) ensures that there is sufficient contact time (between the filtering water and the surfaces of the media grains) to achieve treatment (Section 2). If SSFs are the only form of water treatment then a minimum depth of 0.6m is recommended by Visscher *et al* (1994).

The maximum sand depth will depend on the number of skims required between re-instating the SSF bed (Section 5.2.4). Deeper SSF beds will operate for longer periods of time before re-instatement is necessary, however run lengths are likely to be shorter because starting headloss will be higher (Hendricks *et al*, 1991). A deep media bed will also require a taller SSF structure, which may increase construction costs. SSFs should be designed and operated in such a way that under the worst conditions of raw water quality, run lengths still do not drop below 2 weeks (Huisman & Wood, 1974). The following equation can be used to choose the maximum sand bed depth:

$$Y = \frac{D_i - D_f}{R \times S}$$

(Hendricks *et al*, 1991)

Where

Y = years of operation before filter bed needs re-instatement.

Di = initial sand depth (cm)

Df = final sand depth before re-instatement (cm)

R = sand depth removed with each skim

S = number of skims per year (dependant on run length, estimated by pilot plant studies).

Table 6: Guideline Design Criteria for SSFs in Rural Water Supply

Design Criteria	**Recommendation**			
Design Period	Not specified	10-15 years	7-10 years	Not specified
Period of Operation	24h/d	24h/d	24h/d	24h/d preferred
Surface Loading Rate	0.08-0.2 $m^3/m^2/h$	0.1-0.2$m^3/m^2/h$	0.1-0.2 $m^3/m^2/h$ (possibly up to 0.5$m^3/m^2/h$ when pre-treatment rigorous)	0.06-0.29 $m^3/m^2/h$
Filter Unit Area	Not specified	5-200m^2	100-200m^2 (up to 5000m^2 for non-rural locations)	Not specified
Starting Media Depth	1.2-1.4m	0.8-0.9m	1.25m	1.2m
Minimum Media Depth	0.6m 0.3m for moderate filtrate	0.5-0.6m	0.7m	0.3-0.6m

	quality			
Sand ES or d10	0.2-0.3mm	0.15-0.3mm	0.15-0.35mm	0.2-0.35
Sand UC	>2 and <3	<5, preferably <3	1.5-2 and <3	<2
Supernatant Height	1-1.5m	1m	1-1.5m	0.9-1.3m
Gravel and Under-drainage Height	0.5m	0.3-0.5m	0.4-0.5m	Not specified
Source	Ellis, 1985	Visscher *et al*, 1987	Huisman & Wood 1974	Hazen, 1908

4.2.11 Gravel

A gravel layer is usually placed between the filter media (i.e. sand) and under-drainage of a SSF. This gravel layer is needed if the openings of the under-drainage are larger than the diameter of the media grains (Pyper & Logsdon, 1991). This prevents the loss of filter media through the cracks/holes in the under-drainage.

Several layers of different sized gravel are recommended by Huisman & Wood (1974) such that a layer of relatively fine gravel overlies a layer of relatively coarse gravel. The specifications of each gravel layer are reviewed by Huisman & Wood (1974). These are quite specific. Alternative guidelines are provided by Visscher *et al* (1987), who recommend three layers as follows:

- Coarse sand of diameter 1.0-1.4mm, 100mm thickness
- Gravel of diameter 4.0-5.6mm, 100mm thickness
- Gravel of diameter 16.0-23.0mm, 150mm thickness

Alternatively use of just one layer of gravel (0.1m thickness) may be suitable in conjunction with corrugated pipes (as under-drainage) placed one metre apart (Visscher *et al*, 1987).

As with the sand media, the gravel should be free from sand, clay, loam and organic impurities and if necessary should be washed before installation to ensure it is clean (Huisman & Wood, 1974).

4.2.12 Under-drainage

The aims of the under-drainage system are:

- To support the media bed (and any machinery and people entering the SSF during maintenance operations such as skimming).
- To ensure uniform flow of water through the filter bed by allowing unobstructed exit of treated water uniformly across the filter bed.

(Visscher *et al*, 1994, Huisman & Wood, 1974).

Under-drainage systems vary:

- Perforated pipes.
- A layer of ceramic bricks laid on another layer of bricks (without mortar).
- Precast concrete slabs on concrete ribs.
- Concrete tiles on concrete ribs.

- Corrugated pipes (e.g. PVC, 6cm in diameter placed 1m apart and covered with 0.1m of gravel).
- Other locally available materials that will not degrade by constant immersion in water.

(Visscher *et al*, 1987, Visscher *et al*, 1994)

Free and even flow of water through the under-drainage is achieved by providing a sufficient number of collection orifices (holes, slots, spaces) and by ensuring that headloss within the under-drain's conduit (drain pipe) is negligible relative to the orifices (Hendricks *et al*, 1991). This is ensured by designing the correct ratio of orifice area to conduit area. Huisman & Wood (1974) recommended that the total headloss in the under-drainage system should not exceed 10% of the headloss through the clean bed of sand when it is at its minimum depth (i.e. just before re-instatement). Drawing up a hypothetical hydraulic grade line (HGL) is a useful exercise. A HGL calculates the hydraulic profile within the system from supernatant though to final discharge (Visscher *et al*, 1987). Further information and an example of an HGL analysis is provided in detail by Hendricks *et al* (1991).

Use of concrete slabs, bricks or tiles enables free flow of water over a relatively large area. This means that under-drainage can be constructed using these materials without calculation of the hydraulic characteristics (Visscher *et al*, 1987).

When using perforated and corrugated pipes more care is required in the design of the under-drainage (Visscher *et al*, 1987). The size of these orifices and the spacing and diameter of under-drain pipes will influence the performance and capacity of the under-drainage system. For example, when perforated pipes are spaced evenly across the filter floor, the distance between these pipes will influence the streamlines of flow through the filter media. The closer these are, the more even is the distribution of flow (which is favourable).

With regards to under-drainage capacity, a prudent approach is to err on the side of over-design. Although this increases costs, it protects the capital investment of the overall plant (Hendricks *et al*, 1991).

Further considerations include the materials used in manufacturing the under-drainage - these should be non corrosive and robust. Once installed, an under-drainage system cannot be inspected without complete filter re-instatement. Therefore it must be designed and constructed such that

- It does not become choked by granular material.
- It collects water evenly across the filter at all times.
- It is not damaged or disturbed by operational procedures such as skimming and re-instatement. During skimming the under-drainage of a manually skimmed SSF must be able to support the weight of the filter bed plus a wheel barrow full of wet sand. When mechanical skimming is practiced using vehicles the under-drainage will be subjected to the weight of a dumper truck loaded with sand (as well as that of the filter bed). Further to this weight there will be an additional downward force as a result of the vehicles movement. The advice of an engineer is required.

(Huisman & Wood, 1974, Pyper & Logsdon, 1991).

Plate 4.10: Laying under-drainage for a pre-filter at the Dennery Water Treatment Plant in St Lucia (also suitable for SSF under-drainage)

4.2.13 Outlet Chamber

When a SSF is controlled at the outlet (Section 4.2.14.1) the outlet chamber typically comprises two sections separated by a wall. The filtrate pipe runs along the bottom of the first section and is fitted with an outlet valve to enable flow regulation. A flow measuring device is also required here. The pipe transmits water into the second section of the outlet chamber. This section is divided by a wall, on top of which a weir is placed such that the overflow of water is at a height above the level of the sand bed's surface (Figure 4.8). This avoids the development of negative pressure in the filter bed. The free-fall of water over the weir elevates the DO level in treated water (which is beneficial). This process requires the outlet chamber to be well ventilated. The weir also allows the filter to be operated independently of the water-level fluctuations in the clear water reservoir (Huisman & Wood, 1974).

Facility should also be made (in the outlet chamber) to enable back-filling of the SSF via the under-drainage (Visscher *et al*, 1994). The outlet chamber should also include a pipe and valve through which SSF filtrate can be directed in order to be run to waste (Pyper & Logsdon, 1991).

If the SSF is inlet controlled (Section 4.2.14.1) then the outlet chamber may consist of only one section. This section is the same as the second section of an outlet controlled SSF outlet chamber (as described above). This is more clearly illustrated in Figure 4.10.

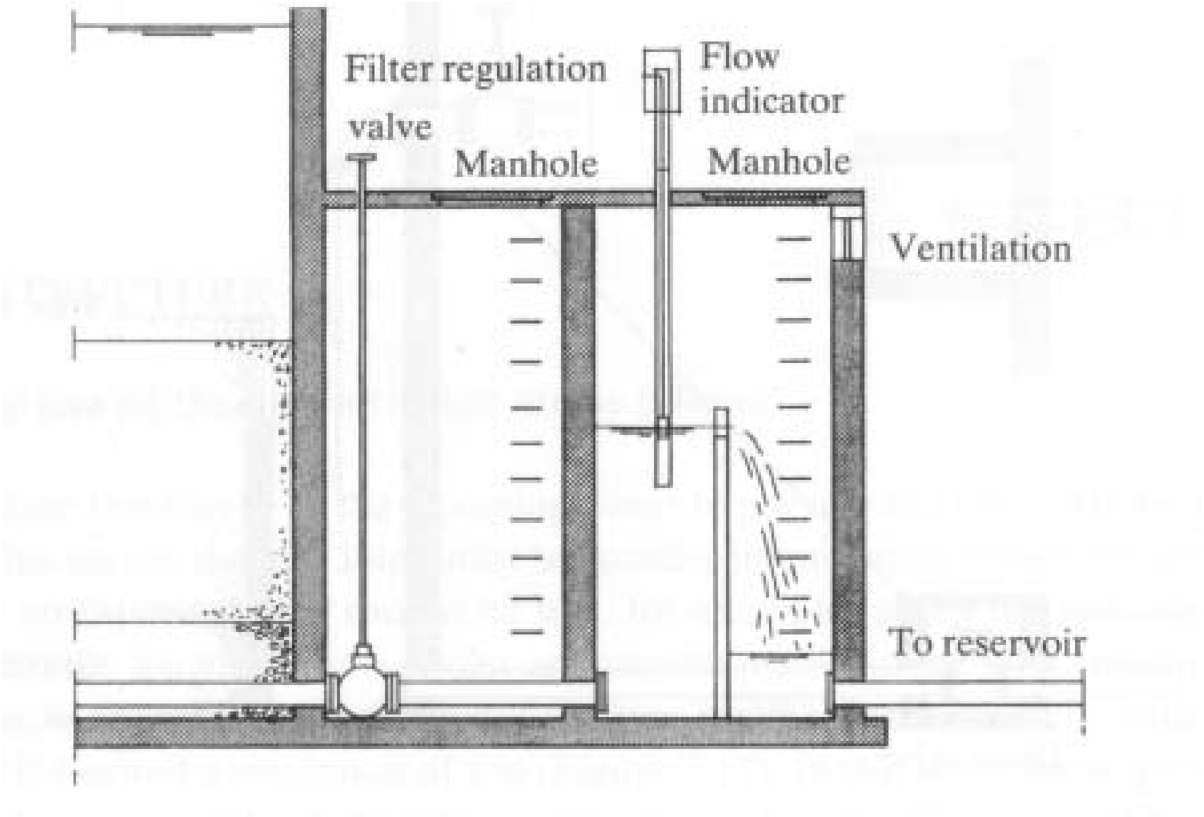


Figure 4.8: Typical Outlet Chamber Design (reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply* Technical Paper No. 24, Copyright (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

4.2.14 Filter Hydraulics

The major functions of filter hydraulics are:

- To allow entry of influent water into the SSF supernatant without eroding the filter bed.
- To collect filtrate uniformly across the filter bed area.
- To enable the supernatant to be drained in preparation for filter skimming.
- To provide an overflow facility for the filter box.
- To measure the surface loading rate.
- To control surface loading rate.
- To measure headloss development.
- To provide for the plumbing needs (e.g. run to waste facility, drains, directing flow, back-filling etc).
- To avoid negative pressure developing in the bed.

(Hendricks *et al*, 1991)

Whenever possible the movement of water through the treatment system should be by gravity flow. By avoiding the use of pumps this makes the system simpler to run, more reliable and more cost-effective (Visscher *et al*, 1987). Pumps incur costs not only through purchase but also as a result of energy consumption and maintenance. Hence, use of longer pipelines is preferable (to pumps) if this is necessary to ensure gravity flow (Visscher *et al*, 1987).

4.2.14.1 Flow Control Systems

SSFs usually operate under gravity. For a handbook detailing the steps to take during the design and construction of gravity-flow water systems for small communities refer to Jordan (1980). The following sections provide a review of design considerations only. Flow control systems ensure operator regulation of the surface loading rate. Two types of flow control system can be identified:

1. Outlet controlled.
2. Inlet controlled.

(Visscher *et al*, 1994)

Outlet Controlled SSF

With the first option, a valve at the outlet pipe controls the surface loading rate through the SSF. Initially this valve is partially closed, however, it needs to be gradually opened (periodically) to maintain a constant surface loading rate as the filter clogs (i.e. as headloss develops, Huisman & Wood, 1974). At the beginning of a filter run little adjustment will be necessary to the outlet valve. The need for filter skimming is indicated by an increasing need to open the outlet valve (i.e. headloss development, Huisman & Wood, 1974).

Although this set-up involves flow control at the outlet, an inlet valve may also be installed to control the flow of water into the supernatant. With this design both valves need continual checking to ensure that the supernatant water level remains constant and that the outlet valve is opened enough to permit the required surface loading rate without water being ‘sucked’ through the filter bed. Balancing an inlet and outlet valve system is made easier by fitting a float valve sensor at the inlet to control the rate of flow into the filter (Pyper & Logsdon, 1991). A weir down stream of some SSFs assists in maintaining a constant head of water above the filter bed (Section 4.2.13).

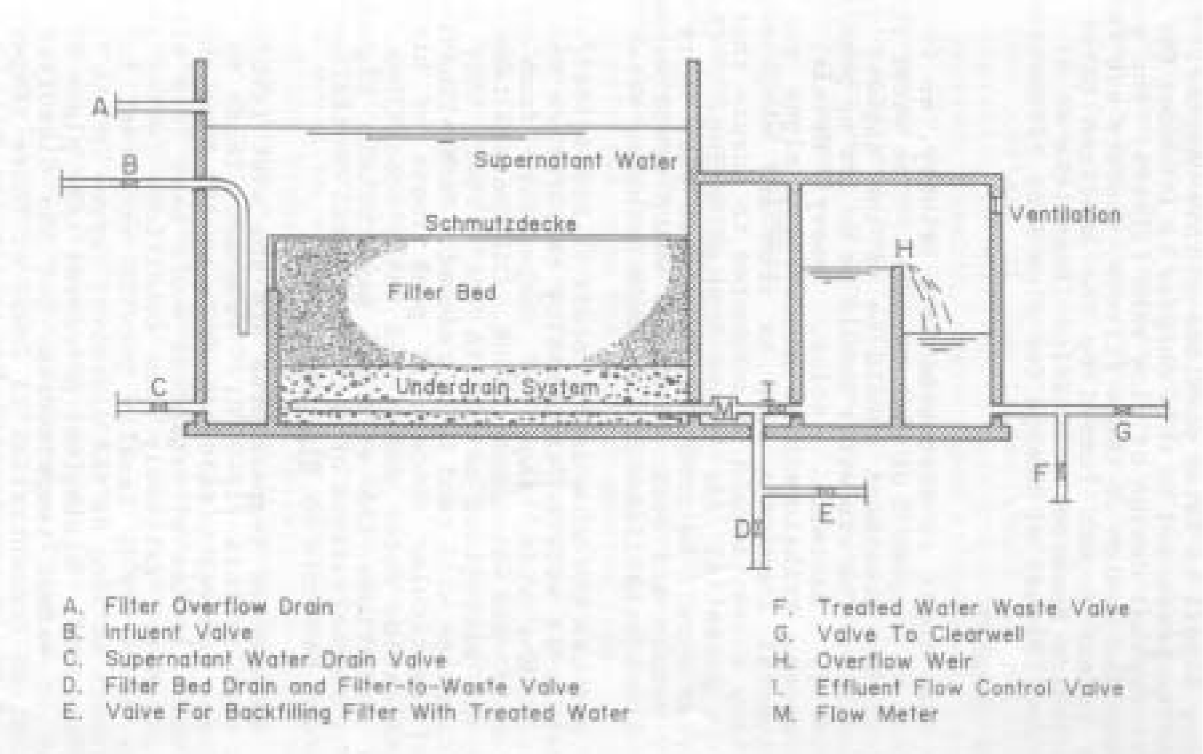


Figure 4.9: Basic Components of an outlet controlled SSF (reprinted from Pyper & Logsdon, *Slow Sand Filter Design*, in Logsdon, G.S. (Ed.), Slow Sand Filtration, pp 122-148, Copyright (1991), with permission from the publisher, American Society of Civil Engineers, ASCE)

Inlet Controlled SSF

With the second option a valve at the inlet regulates the flow of water into the supernatant. A weir (Section 4.2.13) downstream of the filter ensures a constant head of water above the filter bed (Logsdon, 1994). Once set, the inlet valve requires no further adjustment. Initially the supernatant is relatively low, however as the filter clogs and the flow of water is restricted through the media the supernatant level slowly climbs until it reaches an overflow facility. The increased head of water above the sand enables the surface loading rate to remain relatively constant until the final stages of the filter run. Once the overflow is reached the SSF requires skimming (Visscher *et al*, 1994).

The advantage of the inlet controlled system is that less operator attention is needed with regards to surface loading rate control. Disadvantages include more difficult removal of scum and algae from the supernatant and possibly adverse effects resulting from the lower supernatant retention times during the ripening period. Furthermore, it is reportedly not a suitable flow control method for SSFs operating in areas where aquatic weeds can enter the SSF and grow at the sand's surface, unless the SSF is covered to prevent the latter (Visscher *et al*, 1987).

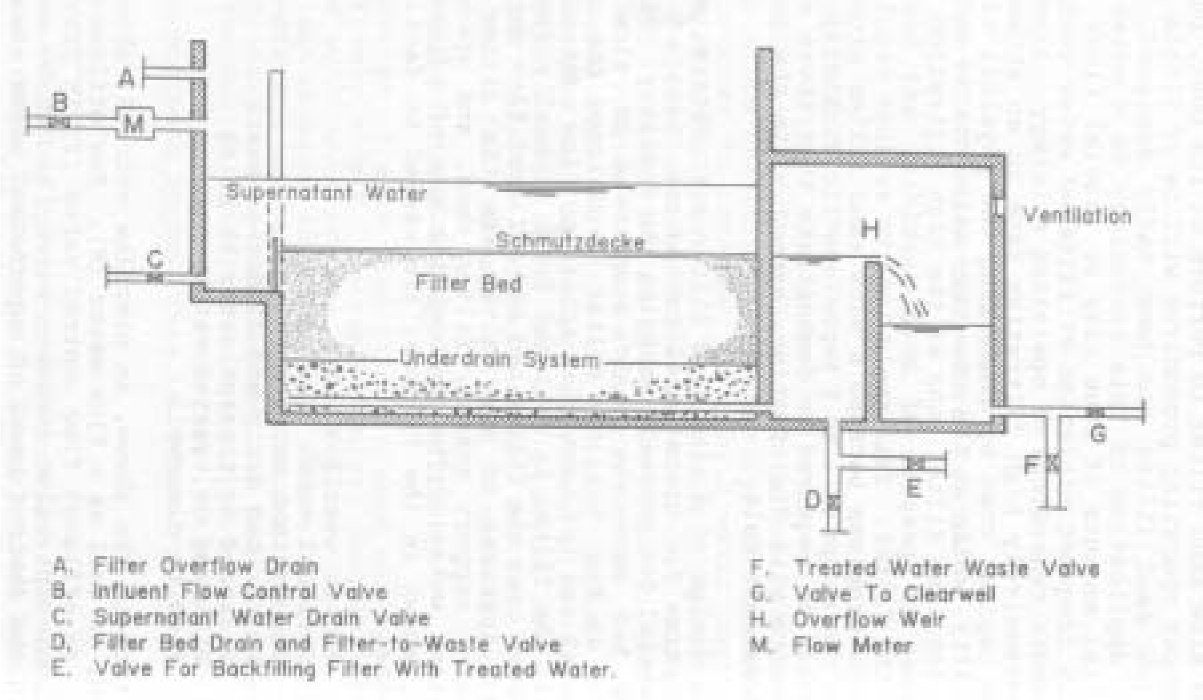


Figure 4.10: Basic Components of an inlet controlled SSF (reprinted from Pyper & Logsdon, *Slow Sand Filter Design*, in Logsdon, G.S. (Ed.), Slow Sand Filtration, pp 122-148, Copyright (1991), with permission from the publisher, American Society of Civil Engineers, ASCE)

Variability in surface loading rate must be avoided if SSFs are to perform effectively (Logsdon *et al*, 2002). If more than one SSF is being operated, then the flow control systems should be designed such that the diversion of flow from one filter when it is taken out of service (e.g. for skimming) does not induce unacceptable surface loading rates onto those filters still in service. Such variability in surface loading rate can be avoided by building a sufficient number of SSF units (Section 4.2.5).

Variability in flow can also arise from variation in customer demands for water. Valves should not be continuously opened and closed during a one-day period to match demands. For example reducing the surface loading rates for SSFs overnight (e.g. as demands drop) should be avoided as this increases the risk of low DO conditions developing (which may result in unacceptable filtrate quality). Constant surface loading rates through the SSFs can be balanced with variable customer demands by incorporating sufficient treated water storage capacity (Section 4.2.19).

4.2.14.2 Measurement of Surface Loading Rate

Surface loading rate is the rate at which water is allowed to flow into the filter bed. Measurement of surface loading rate is crucial to SSF operation. Surface loading rate may be measured by installation of a venturi flume. Venturi flumes contract the diameter of the pipeline for a short distance and the pressure difference is measured between the two diameters through which water is flowing (pipe and venturi flume). This pressure differential is used to calculate the flow rate, since the flow is proportional to the square root of the pressure differential (Hendricks *et al*, 1991).

An alternative method (suitable for small installations) is a gauge showing the height of water flowing over the weir (Huisman & Wood, 1974). This will obviously be less accurate and harder to read, although more economical than a venturi meter (Huisman & Wood, 1974). V-notch weirs may be used in preference to rectangular weirs as the elevation difference over the v-notch weir is greater, although the rectangular weir is advantaged in that it provides better water surface elevation control (Hendricks *et al*, 1991).

Plate 4.11: A 60° v-notch weir at the Nyabwishongwezi Water Treatment Plant, Umatara, Rwanda

Another alternative to a venturi flume and one which is also less expensive, is use of orifice plates (Hendricks *et al* (1991). This method uses two plates each with different sized circular holes in their centres. They are placed between two flanges inside the pipeline and a manometer is used to measure the pressure on either side of the plates. From these measurements, and with the known diameters of the circular holes and pipe, the flow rate can be calculated. This is explained further by Hendricks *et al* (1991).

Propeller meters are also used to measure flow rate. A propeller is placed inside the pipe and rotates in proportion to the flow velocity (the number of revolutions can be converted to the volume of flow, Hendricks *et al*, 1991).

Flow measurement should be undertaken immediately upstream of the regulating valve and a meter dial placed adjacent to the flow control gear, such that readings can be taken whilst adjusting the flow.

In addition to measuring the flow of water exiting the individual SSFs, where more than one SSF exists flow measurements should be possible on a collective filtrate pipe (Pyper & Logsdon, 1991).

A simple means to measure the surface loading rate for a SSF is by undertaking a 'drop test'. The inlet is shut off and the drop in water level (i.e. supernatant level) is measured for a set time interval.

4.2.14.3 Headloss Measurement

Headloss measurement is advised, particularly when more than one SSF exists as this assists in determining when each SSF is likely to need skimming. Without headloss measurements the only indication that an outlet controlled SSF will shortly require skimming is the extent to which the outlet valve has been opened. For inlet controlled SSFs the level of supernatant water serves as an indicator.

Headloss measurements are made possible by the installation of a water manometer (Figure 4.4). This consists of a number of clear tubes (2-4cm diameter) which are fixed side by side onto the wall of the filter along side a metric scale. The bottom ends of these tubes feed into the SSF at different depths. As a minimum, two tubes should feed into the SSF. The bottom ends of these tubes fit onto taps that each feed into the SSF box. The first tap enters the bed just above the bed's surface (bottom of the supernatant) whilst the second tap enters the retaining wall of the tail water. Headloss is quantified by measuring the difference between the water levels in the tubes. This difference increases as the filter bed becomes increasingly clogged.

Where the taps enter the SSF bed they should protrude into the media by approximately 15-20cm and must be protected from media entry, for example by covering with a mesh that is finer than the diameter of the sand grains (Hendricks *et al*, 1991). All parts should be resistant to corrosion. Furthermore the clear manometer hose should be protected from sunlight exposure to inhibit biological growth in these tubes.

Plate 4.12: Manometer tubes and the scale used to measure headloss between tappings, for a pilot scale filter at Surbiton (London, UK)

Plate Error! Style not defined.**.**Error! Bookmark not defined.**:** Manometer tubes exiting a filter at Surbiton (London, UK). Note their arrangement to enable headloss measurement and also their protection against sunlight exposure.

4.2.14.4 Pipe Gallery

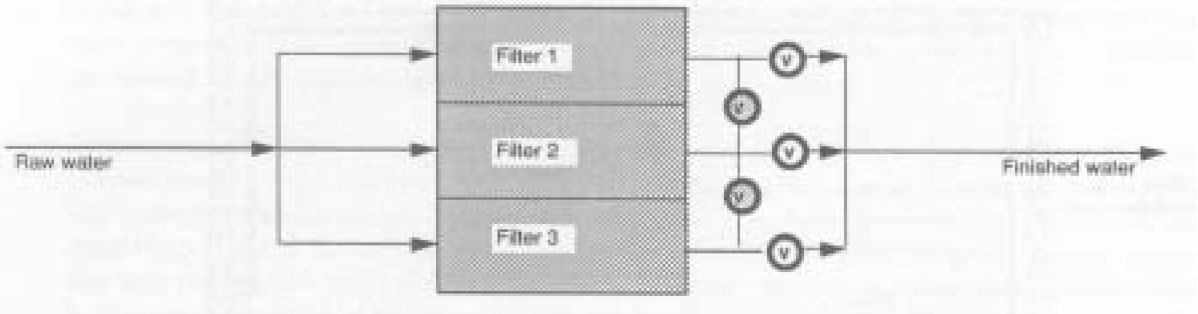
The size of the pipe gallery will vary with the size of the filter. This is the area where pipes that carry the flow of water into and out of the SSF converge, however, influent raw water pipes and drain pipes should be located at a distance from treated water pipes so as to avoid cross contamination (Visscher *et al*, 1987). For large scale SSFs the pipe gallery may be the entire height of the SSF and might be where water sampling and headloss measurements are taken (a filtrate sample tap can be fitted to the wall of the outlet chamber). Particularly if water sampling and monitoring procedures are undertaken in the pipe gallery, it is important to ensure that sufficient space is provided for access, that the area is well ventilated, well drained and that the layout of pipes is un-cluttered (Hendricks *et al*, 1991). When the pipe gallery is located below the ground level it is advised that access is provided by stairs rather than a ladder as operatives are likely to have their hands filled with sample bottles and a note book when entering (Logsdon *et al*, 2002).

Sample taps in the pipe gallery are required for individual SSF filtrates. Sampling of the filtrate when it is being run to waste (RTW) should also be possible. Therefore individual SSF filtrate sample taps should be located upstream of the point where flow is diverted down the RTW pipe (Pyper & Logsdon, 1991).

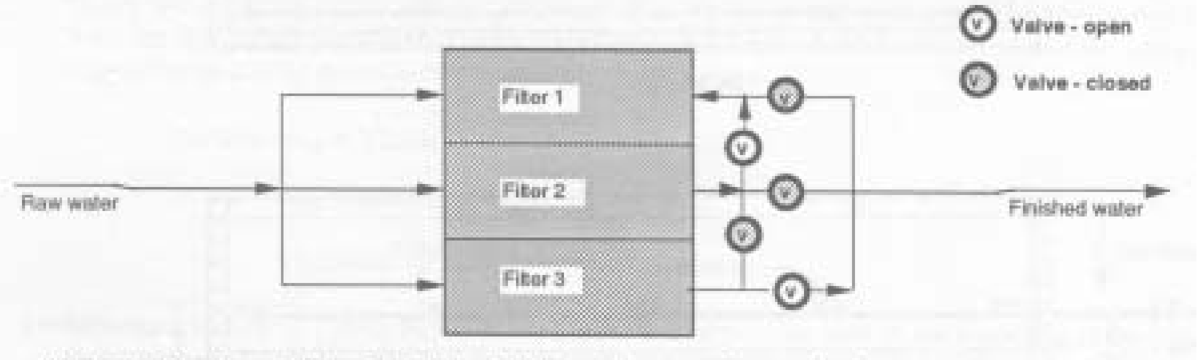
4.2.14.5 Plumbing and Valves

Plumbing needs to be provided for the routine operation of the SSF as well as other functions such as back-filling a SSF with treated water, running a SSF filtrate to waste, draining of the supernatant etc (Hendricks *et al*, 1991). Flow is regulated through a SSF system by positioning valves in key locations. A flow sheet can be used to decide where valves should be placed (Visscher *et al*, 1987). The location of valves for SSF flow control is illustrated in Figure 4.9 and Figure 4.10.

Individual valves and drain pipes should be provided for each effluent line (i.e. at the outlet to each SSF) so that individual filtrate streams can be recharged or run to waste if necessary whilst other units remain operational (Logsdon, 1994). Figure 4.11 provides a suggested valve configuration.



(a) Normal operation (three filters in operation)

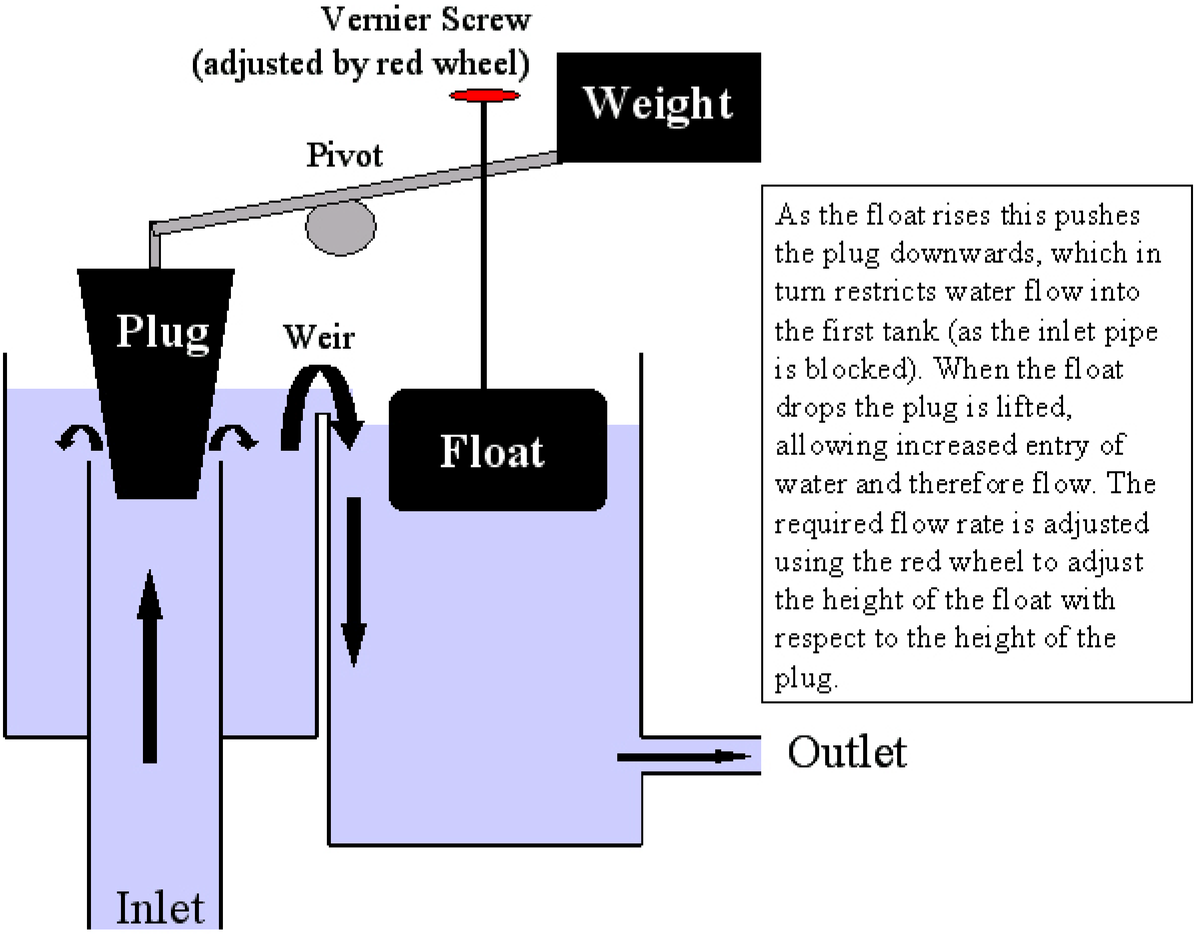


(b) Backfilling from Filter 2 to Filter 1 (Filter 3 in normal operation)

Figure 4.11: Possible Valve Configuration for Individual SSF Control (reprinted from Hendricks *et al*, *Manual of Design for Slow Sand Filtration*, by permission. Copyright© 1991, American Water Works Association and Awwa Research Foundation)

The type of valves installed will depend on the project's funds and local availability - not only for the initial purchase of valves but also for their future repair and replacement. For rural areas in developing countries Visscher *et al* (1987) recommended use of gate valves for pipelines. This is the simplest control device, but not as accurate (in controlling flow) as other valve types, for example butterfly valves. Alternatively globe valves may be suitable, these are cheaper than butterfly valves, but have very good flow control. A disadvantage of the globe valve is its higher headloss compared to gate or butterfly valves (Visscher *et al*, 1987).

Another possibility is the use of 'ball and float valves' (Figure 4.12). These were used to regulate influent flows into some filters at London's water treatment works until relatively recently (1995).



As the float rises this pushes the plug downwards, which in turn restricts water flow into the first tank (as the inlet pipe is blocked). When the float drops the plug is lifted, allowing increased entry of water and therefore flow. The required flow rate is adjusted using the red wheel to adjust the height of the float with respect to the height of the plug.

Figure 4.12: Sketch of Ball and Float Valve (not to scale)

Valves should be arranged to enable extensions to be connected in the future, and also to allow access for control and repairs. Good practice is to over-design the major hydraulic components of a plant at least 1.5 times the required capacity (Visscher *et al*, 1987). Huisman & Wood (1974) recommended installing pipework capable of carrying approximately 50% more than the flow required immediately. This is financially beneficial in the long term.

There are additional plumbing requirements to those pipes and valves used to control flow of water through the SSF, for example waste streams originating from the scum outlet and sand washing facility. All basins and floors should also be provided with drains. Gutters should be provided to direct flow towards drains (Hendricks *et al*, 1991).

4.2.15 Optional Components

4.2.15.1 Housing: Covers and Shading

The decision to cover a SSF will largely depend on the climate in which the SSF will operate and the trophic state of the raw water (i.e. levels of nutrients in the water). If winter temperatures consistently freeze surface water bodies in the area, then a SSF will require a cover and possibly insulation and/or heating to maintain it at a temperature that does not adversely affect the microbiological community (Section 2.2.7) and one which allows skimming to take place during the winter without icing problems. Logsdon (1994) reported cases where filter drain-down periods were lengthened as a result of the sand bed freezing when drained. In some cases the filter box was also damaged due to ice formation on the SSF structure. If temperatures drop below 6ºC for several months during the year, or below 2ºC for one month or more then Huisman & Wood (1974) recommend covering the SSFs. Low temperatures slow the metabolic rates of the microbiological community and can make the SSF less efficient at treating water as a result. Covering enables control of environmental variables that influence SSF performance (climate control) and hence greater consistency. It is reminded that maintaining constant operating and environmental conditions is fundamental to ensuring effective SSF treatment.

Covers will also be required for SSFs in areas where aquatic weeds can enter the SSF and grow in the sand's surface (Visscher *et al*, 1987). Run lengths for uncovered SSFs are usually sufficiently long to enable algal growth within the supernatant (assuming non-oligotrophic influent water). Algal growth causes problems with SSFs (Section 2.2.6). By covering a SSF (thus restricting sunlight exposure) this growth can be minimised. This in turn stabilises DO trends (Huisman, 1996) and the problems associated with low night time DO levels (Section 2.2.4). However, algae brought into the SSF via the influent water may still present problems. Therefore ensuring adequate pre-treatment of water in conjunction with covering is necessary to minimise algal issues with SSFs.

In addition to covering the SSF, pre-treated water storage tanks (e.g. balancing or header tanks) should also be covered to prevent algal growth (Visscher *et al*, 1987). This is also advised in order to prevent the encouragement of disease transmission via insect vectors, as water bodies can be breeding grounds for such vectors (Feachem & Cairncross, 1993). Covers prevent wind-borne contamination from entering the SSF and also that from bird droppings.

Operational advantages with covering include:

- Increased run lengths (providing surface loading rates are not also increased and adequate pre-treatment exists and if influent water is non-oligotrophic and algal growth rates in the supernatant were high when uncovered).
- Potential to increase surface loading rates (though at the expense of run length). This is only sustainable if adequate pre-treatment exists.
- Headloss development occurs more slowly and does not demonstrate the rapid approach to terminal headloss characteristic of uncovered SSFs. This increases the predictability of a covered SSF, which in makes it easier to manage.
- Avoidance of problems associated with removing and disposing of algae when filters are skimmed.

For community scale SSFs, covers may be costly. In cold climates the SSFs may be sunk into the ground, be roofed and then covered by a layer of soil to maximise insulation, however this necessitates an expensive load-bearing roof (Huisman & Wood, 1974). An alternative is light-weight but insulated roofing. In regions where insulation is not a necessity covers may be removable, light-weight structures (e.g. corrugated iron, grass mats) whose purpose is solely shading (Huisman & Wood, 1974). For example, Weglin *et al* (1996) reported that corrugated iron sheets were used to cover SSFs for a water treatment plant in rural Cameroon. These were easily removed for cleaning. The costs associated with these more light weight structures will be smaller.

Plate 4.14: SSF covers at the Nyabwishongwezi Water Treatment Plant, Umatara, Rwanda

Plate 4.15: Shaded SSF for a community scale SSF at the Dennery Water Treatment Plant, St Lucia

4.2.15.2 Surface Mats

Surface mats (a layer of fabric of equal size to the SSF surface area) may be placed on top of the sand's surface of an uncovered SSF in order to improve performance. A suitable fabric may be locally available. Advantages include:

- Protection of the filter media from sunlight thus preventing rapid headloss development and short run times.
- Equivalent or possibly enhanced filtrate quality (compared to a conventional SSF). The aim of the surface mat is to concentrate the purification processes in the fabric layer itself, which in turn may improve removal rates.
- Avoidance of aquatic plants rooting in the filters.
- Protection of filter bed from coarse debris (e.g. leaves, bird-droppings).
- Extended run lengths (e.g. 3-4 times longer, though this will depend on the fabric and specific operating conditions).
- The SSF is less vulnerable to variable raw water quality. For example, an increase in influent water turbidity levels may result in rapid filter clogging, however, remedial action may only entail the removal and washing of the fabric, as opposed to skimming (which would be the course of action for a SSF without a surface mat).
- Simplified filter cleaning. Only the fabric is removed, and this can be washed by hose and re-used. This may reduce cleaning costs (for relatively small SSFs).
- The SSF demonstrates almost complete recovery in terms of headloss, after the replacement of the fabric.
- It is a relatively cheap amendment to a SSF.

(Mbwette & Graham, 1987, Klein & Berger, 1994, Mbwette *et al*, 1990).

In order to achieve the above it is recommended that the fabric demonstrates:

- Open structure with high porosity (0.7-0.95).
- Pore size of approximately 0.1mm.
- Small light transmission (below 20%).
- UV light stability.
- Low specific weight per unit area.
- 1-3mm thickness.
- High resistance to breaking.
- Easy disposal after use, if not re-used (e.g. via incineration)
- Low price.

(Klein & Berger, 1994).

Suitable fabrics are often described as ‘non-woven synthetic fabric’ (geotextile, Klein & Berger, 1994). The term synthetic fabric refers to man-made textiles. This means that the components of that form the textile (i.e. fibres, webs or yarns) are artificially produced (i.e. not naturally produced such as cotton, Mbwette & Graham, 1987). The term woven refers to synthetic fabrics made from yarns or tapes, for example those produced by weaving or knitting. These are not considered suitable as they are usually very thin (usually less than 1mm, Mbwette & Graham, 1987).

Disadvantages of surface mats include:

- Not practicable for large SSFs due to difficulties in removing and disposing of the used cover.
- The advantages are only achieved if suitable fabrics are used.
- Care must be taken when removing the fabric not to disturb the surface sand layer below.
- If the SSF is uncovered then practical problems may arise in resisting the upthrust caused by trapped gas bubbles produced by algae and microbes on the fabric. This problem may be resolved by laying small stones on top of the fabric (sparingly used and evenly spaced).

(Mbwette & Graham, 1987, Clarke *et al*, 2004, Luff, 2000)

Plate 4.16: Surface mat installed onto a pilot scale SSF bed at Shalford (Surrey, UK)

Plate 4.17: Surface Mat Ready for Installation onto SSF shown in Plate 4.16


Plate 4.18: Surface mat installed onto a SSF bed at Surbiton (London, UK)

4.2.16 Cost Aspects

When building a community scale SSF, costs can be incurred in the following areas:

- Floors, under-drainage
- Media: sand and gravel (cost varies according to availability, number of grades of gravel used, depth of media, degree of washing required etc)
- Walls and possibly cover
- Mechanical parts: pipes, valves, meters, pumps (these costs can be reduced by gravity feeding flows and manually undertaking operational procedures)
- Labour (this cost will depend on the degree of mechanisation of operational procedures, local availability of labour and pay)
- Land (a cost influenced by the vicinity of the SSF to urban areas).
- Pre-treatment – pre-treatment processes are often required in order to render SSFs operationally sustainable and to increase the security of a safe water supply. The number of pre-treatment processes required (and hence the cost of the build) will depend on the raw water quality (and its variability). For example, for a multi-stage filtration plant (pre-filtration using gravel pre-filters followed by SSFs, Section 3.1) the cost of the build increases with the risk level associated with the raw water.

(Visscher *et al*, 1994, Berg *et al*, 1991, Galvis, 1999)

An engineer should be able to estimate these costs using experience and with regard to local circumstances. A review of construction, operation and maintenance costs is provided by Berg *et al* (1991), though this information is now over 10 years old and based on American SSF installations.

In addition to the estimates made for the cost of each factor listed above, Hendricks *et al* (1991) advised that a contingency of 10% should be added to this final value.

SSFs are sometimes associated with a high capital cost due to their requirement for relatively large land areas (compared to alternative treatment processes). However in rural locations land costs are usually a small proportion of the total SSF construction cost (Visscher *et al*, 1994). Furthermore, it is worth bearing in mind that although SSFs may require a higher initial capital cost compared to alternative treatment options, this expenditure is usually fed back into the local economy as local contractors, labour and materials can be used (Hendricks *et al*, 1991). In addition, operational costs are relatively low as use of chemicals and electricity can be avoided.

Visscher *et al* (1994) reported that the main area in which savings can be made is via minimising the total wall length (though this should not be undertaken at the expense of operational flexibility). This may be achieved by constructing filter units with shared walls (Berg *et al*, 1991). The type of SSF box chosen also affects costs as this determines the materials used to construct the SSF walls.

The choice of valve types can also reduce costs. For example Visscher *et al* (1994) cite an example from Colombia where locally made gate valves performed satisfactorily and cost 10 times less than the 6-in (152mm) butterfly valves available in the market.

Labour costs may be minimised by keeping the filter's design simple (Visscher *et al*, 1994).

High capital costs should always be balanced against long term maintenance cost savings. For example, covering a SSF can substantially increase the cost of a SSF (Berg *et al*, 1991), however, this will lead to operational cost savings during the SSFs operation.

Depending on the nature of the project and the (social and physical) environment in which the plant is being built, a proportion of the costs incurred (capital and/or operational) may be passed onto the consumer. Shenkut (1996) provided some cost information for a water treatment plant in Ethiopia. The cost per head of water supply to a population of 50000 was less than 15USD and operational costs were 600USD per month. Approximately 170USD/day of the operational costs were recovered by water tariffs of 0.1cents/m^3 water.

Another example is provided by Rubiano (1994) in San Felipe (Colombia) where a multi-stage filtration plant was built to serve a local community. The community decided to meter its water usage in order to enable calculation of fair tariffs (i.e. the charge imposed on a household was directly calculated from their water usage). This approach cannot be imposed however, "*it must be a community decision, according to the local water culture and obviously with institutional support in administrative and technical aspects*" (Rubiano, 1994). Water tariffs for consumers will be inappropriate for many locations due to:

- the inability of the consumer to pay for water usage
- reluctance to pay when alternative (untreated) water sources are available and the health implications of their consumption are not fully understood
- water is distributed to communal tap stands rather than households.

Obviously water tariffs are inappropriate when they will restrict access to clean water to only those consumers who can afford to pay. Tariffs should not be imposed if there is any chance that this will discourage some households from consuming treated water. Where water tariffs are within the affordability of the community, this community must be involved in the discussions leading to this decision as well as those regarding the means by which consumers will be charged and at what rate.

4.2.17 Materials and Labour

Sourcing materials locally can reduce the cost of a SSF build, and will ensure that these materials can be obtained in the future (and at a relatively low cost) during any maintenance work. Materials required include:

- SSF media (e.g. sand and gravel).
- Materials to build the SSF structure (e.g. cement, bricks, mortar, iron rods).
- Plumbing materials (pipes, connectors, valves).
- Mechanical parts (e.g. pumps, though the SSF may be entirely gravity fed)

- Instrumentation for monitoring purposes (manometer materials, flow measurement devices etc).
- Materials to build a sand washing facility.

Providing that there is adequate professional supervision from an engineer, community scale SSFs can be built using builders and plumbers sourced locally. For example, the SSF structure (box) is not very different from the construction of houses or commercial buildings and therefore within the skills of locally sourced builders (Logsdon *et al*, 2002).

Participation from the local community should also be encouraged as this cultivates a sense of ownership over the filter. By employing local labour this helps feed any expenditure on the plant back into the community.

4.2.18 Plant Layout

The ease with which a SSF is operated is influenced by the way in which the plant is laid out. Therefore the operation and maintenance procedures involved in managing a SSF site should be considered when designing the plant layout. An example of a community scale treatment works is shown in Figure 4.13.

Ideally the site should also be clear of trees, to avoid problems with roots, falling branches and canopy drip (Oxfam, 1994).

The intended method of skimming (e.g. mechanical or manual) will influence the design of the SSF and the plant layout. If mechanical skimming uses vehicles then access ramps will need to be incorporated into the design of the filter structure and roads need to provide access to every SSF. Rectangular filters of equal size are also recommended when mechanical skimming is intended (Huisman & Wood, 1974). When rectangular filters are located next to one another this layout also enables covers (Section 4.2.15.1) to span several SSFs - which may be more economical than covering the SSFs individually.

If a bridge/gantry (Section 5.2.3) is used to mechanically skim more than one SSF then these filters must be arranged in alignment and located adjacent to one another such that the same rail tracks permit the bridge to move from one filter to another.

If the SSFs are covered then easy access must be provided for operational procedures. For example if manual skimming is practiced then operatives will require a means of access into the SSF box that allows both their entry/exit and also the removal of dirty sand (Logsdon, 1994).

Plant layout also needs to consider the provision for sand storage areas and methods of washing the sand. Wash water disposal is another consideration (Sharpe *et al*, 1994). The location of the sand washing facility should be convenient to the SSFs, particularly if this sand is being transported manually (e.g. by wheelbarrow).

If monitoring equipment is located in the pipe gallery then this area must be made accessible and a safe and comfortable place in which to work.

There must also be consideration for water drainage around the SSFs. Logsdon (1994) cited one example where high levels of run-off spilled into an area of treated water, leading to the requirement for a boil notice being issued to customers.

The plant should also be designed such that there is room for future expansion (Huisman & Wood, 1974). This involves not only considering the layout of the pipes, filter walls and buildings, but also sizing pipes for future peak flows (Hendricks *et al*, 1991). With regards to pipe lengths, these should be kept to a minimum so as to reduce friction losses (Oxfam, 2004), though not at the expense of a gravity fed system.

In summary, areas should be set aside for:

- Pre-treatment units
- Raw water storage
- SSF units, with room for expansion
- Treated water storage
- Sand washing facility
- Clean sand storage area
- Dirty sand storage area
- Office (luxury not necessity)
- Laboratory
- Site roads (if vehicles used on site)
- Area set aside for toilets and wash basins away from water treatment processes and with dedicated, isolated drainage facility to dispose of waste water. If waste water is disposed of directly into a river, then this point of discharge must be downstream of the sites abstraction point (and other points where the community comes into contact with the river).

Finally, the site needs to be protected from trespasses and against intrusion of animals. Furthermore, open water bodies should be fenced to prevent accidental drowning. If work is required at night (and funds exist) then the site may also be fitted with lighting and guard rails to protect staff (Huisman & Wood, 1974).

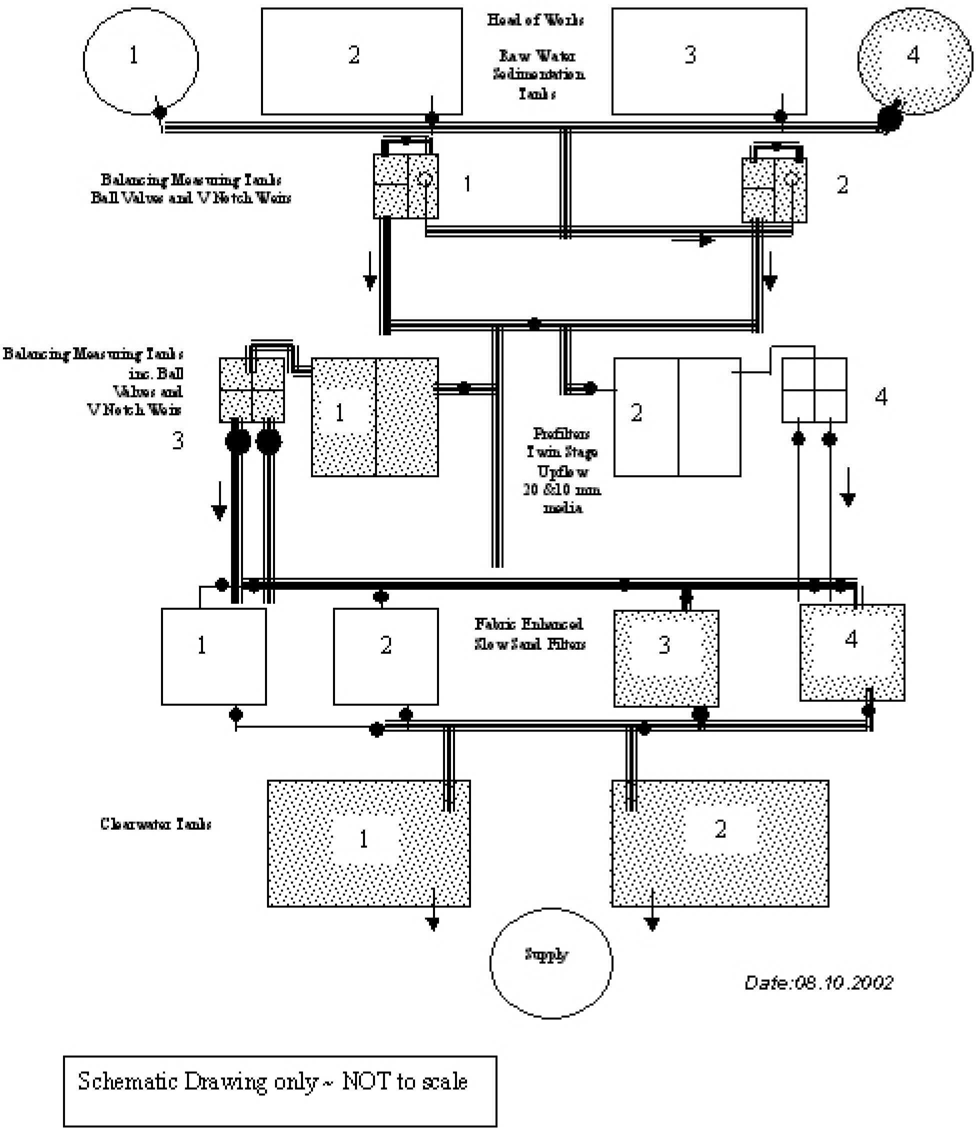


Figure 4.13: Schematic of a Community Scale SSF Treatment Works: Nyabwishongwezi, Umatara, Rwanda

4.2.19 Clear-water Reservoir

SSF filtrate is stored in a tank called the clear-water reservoir (also known as the clear-water well). Downstream storage of treated water is a necessary part of any filtration system as it permits steady surface loading rates through the SSF regardless of water demand variations. This also makes the SSF easier to operate as operational parameters remain constant. This tank is filled continuously by SSF filtrate, but treated water is supplied to customers only when demanded (by abstracting from the clear water reservoir). Logsdon (1994) recommended that a SSF treatment system should be designed with sufficient water storage so that surface loading rates require adjustment only once per day.

In order to size the clear water reservoir a graph is plotted of predicted cumulative hourly water consumption (by the community) and intended cumulative hourly water production (by the SSF) over a 24 hour period. The greatest difference between these two lines (in m^3) is the minimum storage capacity required by the clear water reservoir (Visscher *et al*, 1987). This figure will need to be increased if the clear water reservoir is to contain sufficient water for emergencies such as fire fighting (Pyper & Logsdon, 1991).

When water consumption data are not available for a community, then data from a nearby community with a water supply may be used to estimate this. If no such data are available, then Visscher *et al* (1987) recommended provision of a clear water reservoir whose volume is 40% of the daily water production by the plant.

When possible, advantage should be taken of natural slopes, by locating the clear water reservoir below the SSF tanks but above the community to be served (Oxfam, 1994). When natural slopes do not exist it may be worthwhile constructing an elevated earth platform for the whole or part of the plant, to enable gravity flow. However in order to take the weight of the tanks a gravel or concrete foundation ring may be necessary (Oxfam, 2004).

Hence, water in the clear water reservoir may be distributed directly (via gravity flow), or it may be pumped to further, elevated, storage tanks from where supply can be continuously gravity fed to the community distribution points or households (Visscher *et al*, 1987). For small communities, piped water supplies with house-connections are often not feasible economically, and a number of individual or ‘point’ sources may be more realistic (e.g. communal taps such as illustrated in Plate 4.19, Huisman *et al*, 1981).

Plate 4.19: Treated water point of distribution (tap stand) at the Nyabwishongwezi Health Centre, Umatara, Rwanda

5 Operate & Maintain

5.1 Household Scale O&M

5.1.1 Monitoring and Maintenance Requirements

Option 1: 3 Tank SSF System

- Ensuring that the header tank never empties.
- Surface loading rate control - A constant surface loading rate of $0.1m^3/h$ should be maintained. This is regulated by adjusting the floating weir. Flow needs to be checked and possibly adjusted once per day (Section 5.1.2).
- Skimming – Periodically, the SSF will require draining, skimming (Section 5.1.3), recharging (Section 5.1.4) and re-starting (Section 5.1.5). The frequency with which this must be done will depend on the raw water quality and surface loading rate.
- Sand washing - Sand that is removed during skimming will need to be washed, dried and stored for re-use (Section 5.1.8).
- Re-instatement and Refurbishment - Depending on the depth of the filter bed, complete re-instatement of the filter media will be required approximately once per year (Section 5.1.7). At this point the tanks should also be checked for leaks. Taps, hose and pipe may also need to be replaced.
- Filtrate quality testing – Ideally some filtrate quality testing should be undertaken, including microbiological analysis, turbidity testing and also possibly for specific pathogenic organisms known to be endemic in the area. This is discussed in Section 5.1.9).

Option 2: 2 Tank SSF System

- Water collection - The SSF supernatant will require topping up regularly (e.g. once per day). The filter must never be allowed to empty. Water should be carefully poured into the supernatant, directly over the stone that sits on the filter bed and serves as a splash plate (Section 4.1.2).
- Surface loading rate - A constant surface loading rate of $0.1m^3/h$ should be maintained. This is regulated by adjusting the outlet valve. Flow needs to be checked and possibly adjusted once per day (Section 5.1.2).
- Skimming - Every month or two months the SSF will require draining, skimming (Section 5.1.3), recharging (Section 5.1.4) and re-starting (Section 5.1.5). The frequency with which this must be done will depend on the raw water quality and surface loading rate.
- Sand washing - Sand that is removed during skimming will need to be washed, dried and stored for re-use (Section 5.1.8).
- Re-instatement and Refurbishment - Depending on the depth of the filter bed, complete re-instatement of the filter media will be required approximately once per year (Section 5.1.7). At this point the tanks

should also be checked for leaks. Taps, hose and pipe may also need to be replaced.
- Filtrate quality testing – Ideally some filtrate quality testing should be undertaken, including microbiological and turbidity testing. This is discussed in Section 5.1.9).

Monitoring and maintenance requirements for household SSFs are also summarised in Table 7.

Table 7: Operation and Maintenance Requirements (reprinted from Brikké & Bredero, *Linking technology choice with operation and maintenance in the context of community water supply and sanitation*, Copyright (2003), with permission from the World Health Organisation, WHO)

Activity and Frequency	**Materials and Spare Parts**	**Tools and Equipment**
Daily - fill raw-water reservoir - check flow rate	Raw Water Watch	Bucket
Approx. Every 6 Weeks - scrape off sand from top - of filter, wash, dry and store.	Water	Scraper, bucket
Occasionally - repair tap - disinfect clean water tank	Washer, spare tap Disinfectant (e.g. chlorine)	Screwdriver, spanners Bowl, spoon
Yearly or less - restore sand	Water, clean recycled and new sand	Bucket, sieve
Every Two Years - replace hoses	Hose	Knife

5.1.2 Surface Loading Rate

Surface loading rate refers to the hydraulic load (m^3/h) per unit cross sectional area (m^2) of a bed, normal to the direction of flow. Controlling the rate of flow through the SSF is fundamental to ensuring the filter produces potable water. Relatively high surface loading rates ($0.3\text{-}0.5m^3/m^2/h$) are successfully used for large scale SSFs with rigorous pre-treatment (Rachwal *et al*, 1988). However, household SSFs supplied by surface water and with limited pre-treatment, require lower surface loading rates of $0.1\text{-}0.2m^3/m^2/h$ (Visscher *et al*, 1987). If surface loading rates rise up to $0.3m^3/m^2/h$ for short periods (1-2 days) this is unlikely to cause harm, however, if such rates are sustained the SSF is likely to clog rapidly.

Option 1: 3 Tank SSF System

Surface loading rate is checked every day. The weir (bowl and tubes, Figure 4.1) is adjusted to maintain a rate of $0.1m^3/m^2/h$. Surface loading rate is measured at the outlet to the SSF tank, however, it is regulated using the weir.

The height of the water in the bowl determines the flow of water into the SSF tank and therefore the supernatant height and in turn the surface loading rate onto the sand. The height of the tube through which water enters the bowl regulates the height of water in the bowl and therefore the surface loading rate in the SSF. Hence the tube is moved downwards to increase the surface loading rate applied to the SSF.

Option 2: 2 Tank SSF System

Surface loading rate is checked every day. The outlet control valve will need to be continuously opened wider as time progresses (into the run) to maintain a surface loading rate of $0.1m^3/m^2/h$. Surface loading rate is measured using a container (of known volume) and watch/clock.

5.1.3 Skimming a SSF

When it is no longer possible to maintain the required surface loading rate through the SSF due to filter clogging, then the filter needs to be drained and skimmed. This process needs to be undertaken with care, but also in as short a time period as possible. The longer the time period that a SSF is drained during skimming, the poorer is filtrate quality during the subsequent run (Section 2.2.5).

To skim a SSF the flow into the supernatant is stopped and the filter is allowed to drain. The splash plate (stone) is removed and put to one side. The top 1-3cm of sand is scraped off the filter bed using a small hand shovel/trowel (or it may be done carefully by hand).

The dirty sand is collected in a bucket and put to one side for washing (Section 5.1.8).

Smooth the surface of the skimmed filter by hand. The SSF is now ready to be recharged (refilled with water). As soon as skimming is completed the SSF should be re-filled.

5.1.4 Recharging the SSF

To recharge a SSF simply means to refill the filter with water after it has been drained during skimming or re-instatement.

A SSF is usually carefully refilled with water backwards, by adding water from below. This allows any air trapped in the filter bed to escape as the filter is filled, which in turn helps to prevent the media from being disturbed by trapped air bubbles which rise once the filter has been completely recharged. Air bubbles may also remain in the pores of the filter media and block them, leading to a high initial headloss and loss of productivity.

If an outlet valve has been fitted to the outlet hose (e.g. Option 2) then this will need to be fully opened. Water is then slowly fed into the bottom of the filter via the outlet hose. This process will require a continuous supply of water, with sufficient head to drive the water up through the filter media. If a pump is available then water can be pumped directly into the bottom of the filter (at a low flow rate).

Back-filling should only be undertaken using water that has been filtered. Use of raw (untreated) water to backfill a SSF is not advised as this can seed the under-drainage and bottom section of the bed with potentially pathogenic organisms. If only raw water, or partially treated water is available then top-filling is recommended, as follows:

Option 1: 3 Tank SSF System

Remove the SSF tank's outlet hose from the clear water reservoir (tank 3) and secure this to the side of the SSF tank so that the end that usually feeds tank 3 is elevated above the height of the SSF filter bed. Place the splash plate (stone) onto the top of the skimmed filter bed. Begin to fill the SSF tank from the top using water from the header tank (tank 1), but ensure that this is done slowly and that the influent flow of water is directed onto the splash plate (stone) so as to avoid disturbing the sand. Completely fill the SSF tank. The filter is now ready to be re-started – which should be done immediately.

Option 2: 2 Tank SSF System

Close the SSF's outlet valve and replace the splash plate (stone) onto the SSF's skimmed filter bed. Begin to fill the SSF tank from the top by pouring water slowly onto the splash plate. Once the tank has been completely filled with water the filter should be re-started immediately.

5.1.5 Re-starting a SSF

Re-starting a SSF is necessary after skimming or re-instatement. Methods vary depending on the SSF design (Section 4.1.2).

Option 1: 3 Tank SSF System

Once the SSF tank has been completely filled with water, lower the outlet hose to a height where filtrate is allowed to flow freely from this hose, but such that the end of the hose is still at a height above the filter bed's surface. Regulate this flow by adjusting the weir in the header tank. The filter should be re-started at its normal operational surface loading rate. At this point do not feed the filtrate into the clear water reservoir. In addition, do not attempt to recycle this water into the top of the recently skimmed SSF as the filter will not ‘ripen’. Instead, let this water ‘run to waste’ (RTW). Water that is RTW is discarded and should not be consumed. The filter is allowed to RTW during the ‘ripening period’ (Section 5.1.6).

Option 2: 2 Tank SSF System

Once the SSF tank has been completely filled with water it is re-started by opening the outlet valve a fraction. The valve is only opened wide enough to allow water to filter at the desired surface loading rate. The filter should be re-started at its normal operational surface loading rate. At this point do not feed the filtrate into the clear water reservoir (tank 2), but let it ‘run to waste’ (RTW). Water that is RTW is discarded and should not be consumed. The filter is allowed to RTW during the ‘ripening period’ (Section 5.1.6).

5.1.6 The Ripening Period

The ripening period refers to the time period after re-starting the filter during which time a SSF may not effectively treat the water filtering through it. During skimming, a large portion of the filter’s microbiological community is removed by scraping away the top sand layer. The microbiological community is crucial in achieving effective water treatment, therefore by removing a large proportion of these micro-organisms the filter’s performance is adversely affected. In addition, during the time period that the sand is drained of water, the micro-organisms inhabiting the media will remain alive, but may become stressed by the stoppage of flow. Therefore once the flow of water is restored to the filter it will require some time for the microbiological community remaining in the media bed to re-establish itself and to recover from the stresses associated with the drain-down period. The time the filter takes to recover is called the ‘ripening period’.

When a SSF has been re-instated, the media bed is completely clean and has no microbiological community. In order to treat water effectively, a microbiological community must become established and develop in the filter bed (which takes time). This time period is also called the ripening period. The ripening period for a new media bed is likely to be longer than the ripening period for a skimmed bed.

Water should not be consumed until the SSF has ripened, however, this ripening period is likely to vary depending on the environmental and operational conditions. The only way to conclusively determine whether a SSF has sufficiently ripened (and is thus producing filtrate fit for human consumption) is by water quality testing (Section 5.1.9).

Ellis (1985) recommended that if filtrate quality testing was not possible and that water was not disinfected, then the filtrate should not be consumed until 48 hours had elapsed after re-starting the filter following skimming. Similarly, Visscher *et al* (1987) suggested that skimmed SSFs would take 1-2 days to ripen.

In contrast, a completely new bed of sand will take up to 3 weeks to ripen (Visscher *et al*, 1987).

5.1.7 Re-instatement

The term re-instatement refers to the complete excavation of the SSF filter bed and its replacement by a new, clean bed of sand (to the maximum filter bed depth). Other terms used to describe re-instatement include rebuilding, restoring or re-sanding the filter.

Once successive skims have reduced the sand bed to its minimum depth (e.g. 0.5-0.6m, Visscher *et al*, 1987) then the filter will require re-instatement. Re-instating a small scale SSF is only likely to be necessary once yearly, or less (Brikké & Bredero, 2003).

The flow of influent (raw) water is stopped and the SSF is allowed to drain completely. The filer bed is completely dug out and the dirty sand put to one side for washing. It is also recommended that the layer of gravel is removed for washing (though separately from the sand) and that the inside of the SSF tank and its under-drainage is rinsed through with (treated) water.

The rinsed gravel is re-laid onto the under-drainage pipes, and a clean (new or washed) bed of sand is laid (to its maximum depth) on top of the gravel. As the tank is filled with clean sand, the sand should be pressed down by hand to ensure that no large air spaces remain in the bed. Once the required depth has been laid, smooth the bed’s surface by hand so that it is approximately level. The filter is now ready to be re-started (Section 5.1.5).

5.1.8 Sand Washing

Sand that is removed from a SSF can be re-used once it has been washed. This is usually preferable to sourcing new sand. New sand will need to be purchased and/or graded and washed of fines before use, which can be costly. In addition, if new sand is purchased then the dirty sand that is discarded must be properly disposed of (Letterman, 1991).

For small scale SSFs hand stirring is an appropriate method of washing sand (Visscher *et al*, 1994). The media is placed in a container (e.g. bucket) such that only one third of the container is filled. The container is the topped up with water. The mixture is stirred by hand to encourage fines and material attached to the media to separate from the media and become suspended in the water. The denser sand settles in the bottom of the container. By allowing water to overflow from this container during the washing procedure, the fines and dirt are removed. The procedure is repeated until the water overflowing from the container appears clear.

Clean sand should be allowed to dry, ideally in a protected, clean area, but whilst maximising the sand’s exposure to sunlight. Turning the sand regularly will quicken the process. If this sand is not immediately required for re-instatement (Section 5.1.7) then it must be stored in a clean dry area until it is needed again.

5.1.9 Water Quality Testing

Access to water quality testing facilities can be limited for areas where small scale SSFs are operated. Ideally SSFs should be monitored for:

- Microbiological filtrate quality (e.g. thermotolerant coliforms)
- Influent water and filtrate turbidity levels.
- Headloss development.
- Surface loading rate.

In the absence of microbiological tests, ammonia testing can be used to assess performance. There should be no ammonia in the filtrate from a mature SSF (Ellis, 1985).

Where the funds and/or facility is not available to test these water quality parameters possible options include:

- Purchase a water quality testing kit (e.g. Oxfam-DelAgua Water Testing Kits at www.robenscentres.com/delagua/index.cfm) and any consumables required to operate it.
- Enquire about locally available water quality testing facilities/services in the area.
- Visual turbidity testing (Section 5.3).
- Operational experience and judgement. If possible an external water quality assessor should be brought in to establish the filtrate quality achieved (how long typical ripening periods are for the specific SSF etc). Subsequent water consumption is then based on these guidelines. Alternatively, the guidelines of Visscher *et al* (1987) as well as others should be followed (Section 5.2.7).

Water quality sampling, monitoring and testing guidelines, for drinking water, are provided by the WHO (1996). Information is available on the Internet (UNEP/WHO, 1996) at www.who.int/docstore/water_sanitation_health/wqmonitor/

- Click on ch08 for Field Testing Methods
- Click on ch10 for Advanced Instrumental Methods

5.2 Community Scale O&M

5.2.1 Monitoring and Maintenance Requirements

Providing that sufficient time is taken to design and construct a SSF to suit the social and environmental conditions then the SSF will be relatively simple to operate, maintain and monitor (Huisman & Wood, 1974). This is particularly important for small rural communities where the water treatment responsibilities may lie with one part-time operative only able to routinely spare several hours per day (Pyper & Logsdon, 1991). Points to consider include:

- Surface loading rates – The surface loading rate of outlet controlled SSFs must be checked daily and flows adjusted if necessary (Section 5.2.2). Inlet controlled SSFs will require less frequent attention as surface loading rate does not need checking daily.
- Headloss measurement – The headloss of every SSF should be recorded daily after surface loading rate has been adjusted (Section 4.2.14.3).
- Water Quality Monitoring – Some monitoring of raw and treated water is advised, particularly during the ripening period for a SSF (Section 5.2.9).
- Metering equipment – This equipment (e.g. flow meters) should be periodically calibrated and checked for blockages (Hendricks *et al*, 1991).
- Visual Inspection - SSF operatives would also be expected to keep the site clean and to remove floating scum from the SSF (Huisman & Wood, 1974). By visually inspecting the SSFs on a daily basis, operatives will become familiar with the characteristics of each filter, with what to expect during the length of a SSF run and also with what to expect at different times of the year.
- Fish - It is not unusual to find fish in the supernatant water of SSFs operating in tropical areas. Fish will cause no harm to the operation of the SSF if the fish are top feeders (e.g. *Tilapia*). Carp and other bottom feeders, however, must be removed as they will disturb the schmutzdecke and upper sand layer, potentially resulting in poor filtrate quality (Huisman & Wood, 1974).
- Maintenance Schedules - This lays out the daily, weekly and monthly monitoring and maintenance requirements of the filter(s). The requirements of the schedule will be influenced by the raw water quality, plant size, source of supply and prevailing government norms and regulations (Visscher *et al*, 1994). Table 8 is a suggested schedule of activities for operators of SSFs provided by Visscher *et al* (1987).
- Site Operating Manuals (SOMs) – SOMs should be provided as reference material. These will provide information regarding site layout, valve locations, pipeline arrangement, sample tap locations, hydraulic profiles, design specifications, operational parameter values and step

by step instructions for operational procedures (e.g. skimming, recharging, re-starting a SSF).

- Site Manager – Relatively small community scale SSFs will require the attention of only one operative for perhaps only one hour per day (Logsdon *et al*, 2002). Larger sized SSFs may need one or more operatives (particularly during cleaning) to ensure that the SSF is operated, monitored and maintained according to the schedule, within the funds available. It is recommended that where more than one operative is employed, that one be appointed as a site 'manager'. This places the responsibility onto one individual for ensuring that the plant operates smoothly and that operational procedures are carried out according to the SOMs and with attention to safety. The manager should also be responsible for the economic running of the plant and for planning ahead with regards to scheduling SSFs for skimming and hiring labour (Huisman & Wood, 1974). Planning ahead ensures that no more than one SSF is out of service at any one time (Pyper & Logsdon, 1991).
- Operative Training - Training is an important aspect of ensuring the proper operation of a SSF. This should not be restricted to the operational monitoring and maintenance procedures regarding the SSF. The operator should also have an understanding of health education and the basic theory behind SSF treatment. This ensures that he/she understands fully his/her responsibility and thus the importance of properly maintaining and operating the SSF. Although formal education is an advantage in an operator, it is not necessarily essential for the correct operation of the SSF (Visscher *et al*, 1994). SSFs can be successfully operated by personnel who have little training in chemistry and microbiology (Logsdon *et al*, 2002), but a lack of basic training and incentives to provide a professional service were factors contributing to problems with small rural SSF plants in Peru in 1988 (Lloyd *et al*, 1988). Incentives for SSF operatives include:
    - Adequate wages
    - Long term employment
    - Receiving the respect of the community
    - Training.
- Supervision - Providing adequate supervision and support to the operator is also important for ensuring that he/she is successful in operating and maintaining a SSF (Visscher *et al*, 1994). If supervision is periodic then this should be frequent, irregularly timed and can be the responsibility of the regional or national authority whose responsibility it is to oversee the operation of numerous small treatment works (Ellis, 1985).
- Operative Health - Operatives should be given regular health checks to ensure that they are not carriers of enteric diseases which could then be passed into the SSF during routine operations (e.g. during skimming, Visscher *et al*, 1987).
- Record Keeping – A log book should detail changes made to the operation of the site and any unusual events. Records should also be kept for the results of water quality testing and operational data. Depending on the scale of the treatment facility, this may require a

room designated as an office. Office furniture (filing cabinet, desk) and ideally also a computer provide the facility to record and process data (i.e. produce plots) and therefore co-ordinate the operation of the plant effectively (Hendricks *et al*, 1991). Such facilities are a luxury, however, rather than a necessity and an organised system for logging and filing paperwork will suffice. Data trends can be plotted on paper. Record keeping allows the site to plan ahead (e.g. skimming schedule) as well as to learn from previous experiences.

Table 8: Schedule of Activities for Operators (reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply*, Technical Paper No. 24, Copyright, (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

Frequency	**Activity**
Daily	Check raw-water intake Visit SSF - check and adjust surface loading rate - check water level in filter - check water level in clear-water well - sample and check filtrate quality Check all pumps Keep log book of plant
Weekly	Check and grease all pumps and moving parts Check the stock of fuel and order, if needed Check the distribution network, taps and repair if necessary Communicate with users Clean the site of the plant.
Monthly or less frequently	Skim SSF(s) Wash dirty sand and store retained sand
Yearly or less frequently	Clean clear-water well Check the filter and clear-water well for water-tightness
Every two years or less frequently	Re-sand filter units

5.2.2 Surface Loading Rates

Surface loading rate refers to the hydraulic load (m^3/h) per unit cross sectional area (m^2) of a bed, normal to the direction of flow. Controlling the surface loading rate is fundamental to the ensuring the SSF performs well. Surface loading rates should be kept as constant as possible. Intermittent operation disrupts the SSF's microbiological community and causes filtrate quality problems.

For example, if at any time the supply of SSF treated water is interrupted (e.g. during maintenance work in the distribution system) then the SSF should continue to operate and fill the clear water reservoir. If the capacity of the clear water reservoir is reached before supply can be resumed then the SSF should still continue to operate and its filtrate should be run to waste. It is preferable to waste this water rather than to stop and re-start the SSF (Huisman & Wood, 1974).

Surface loading rate is controlled using the flow control systems. It is reminded that SSFs may be outlet or inlet controlled (Section 4.2.14.1). The degree of (surface loading rate) monitoring required varies depending on how flow in controlled through the SSF.

For outlet controlled SSFs the surface loading rate is controlled by the outlet valve and will need to be continually opened through the course of the run as the filter becomes clogged. Checking the surface loading rate of a SSF is usually a daily requirement for outlet controlled SSFs, but may only take several minutes. If the surface loading rate is not checked on a daily basis then when the SSF surface loading rate is finally checked and adjusted, this can lead to a large step change in surface loading rate being necessary. This in turn can result in unacceptable filtrate quality (Letterman, 1991). Once the outlet valve can be opened no further and surface loading rate is declining through headloss development then this indicates that the SSF requires skimming.

For inlet controlled SSFs the supernatant level starts low and climbs during the SSF run as the filter becomes clogged. The inlet valve is set at the beginning of the run and does not require regular adjustment, which is an advantage (Pyper & Logsdon, 1991). Once the supernatant reaches the maximum level then this indicates that the SSF requires skimming.

The appropriate ‘nominal’ surface loading rate for a SSF will depend on its design and the outcome of pilot plant testing. SSF surface loading rates may be categorised as follows:

- High Rate Mode: The SSF is operated at relatively high surface loading rates of between 0.3-0.5$m^3/m^2/h$. The high rate mode for ‘ramping up’ involves bringing the bed back into supply (e.g. after skimming) in as short a time as possible (e.g. 3 days). This aims to encourage SSF ripening whilst avoiding SSF penetration. Whilst research has shown that elevated surface loading rates are associated with poor filtrate quality (Hazen 1908, Pyper & Logsdon, 1991), other sources (Huisman & Wood, 1974) conclude that surface loading rates do not influence SSF performance within defined limits (0.1-0.45m/h) and further research (Rachwal *et al,* 1988) has reported that surface loading rates up to 0.5$m^3/m^2/h$ are sustainable for SSFs, providing adequate pre-treatment processes are employed. However, it is stressed that the high rate mode will only be sustainable operationally when raw water is of sufficient quality, or adequate pre-treatment of this water ensures minimal suspended solids loads in influent water (Section 3.3). Benefits of the high rate mode include: faster bed ripening, less problems with algal growth (as runs are shorter), increased productivity and higher and less variable DO levels. Higher surface loading rates, however, will result in shorter run lengths. Pilot plant tests (Section 3.9) can be used to determine whether high surface loading rates are appropriate. SSFs should be designed and operated in such a way that under the worst conditions of raw water quality, run lengths still do not drop below 2 weeks (Huisman & Wood, 1974). High surface loading rates are usually only appropriate for highly pre-treated water.

- Moderate Rate Mode: The bed is brought back into supply in as short a time period as possible, but at nominal surface loading rates between 0.2-0.3$m^3/m^2/h$.
- Low Rate Mode: The bed is maintained at a surface loading rate below 0.2$m^3/m^2/h$. SSFs kept to a low rate mode are usually preceded by little pre-treatment. A low surface loading rate enables longer running times. The low rate mode may be most appropriate for use of SSFs to supply rural communities where little pre-treatment is possible and skimming is undertaken manually (and is thus time consuming and labour intensive).

Surface loading rates between 0.1 and 0.15$m^3/m^2/h$ are recommended for SSFs supplied by surface water (e.g. rivers, lakes, streams, Visscher *et al*, 1994). If surface loading rates rise up to 0.3$m^3/m^2/h$ for short periods (1-2 days) this is unlikely to cause harm and may be necessary whilst another filter unit is out of service (e.g. for skimming, Visscher *et al*, 1994).

Pilot plant studies (Section 3.9) can be used to determine the maximum surface loading rates at which a specific SSF performs effectively (given the conditions under which it operates). As a guideline, Hendricks *et al* (1991) reported that SSFs should be expected to maintain run lengths of over 30 days, whilst run lengths of several months should be considered fortunate. Huisman *et al* (1981) reported that if filter runs much longer than 2 months prove possible (as demonstrated by pilot plant testing), then the nominal surface loading rate may be increased and hence the number of SSF units decreased (which decreases costs).

5.2.3 Skimming Method

Skimming, scraping and cleaning are all terms used to refer to the removal of the top few centimetres of sand (including schmutzdecke) of a SSF filter bed. This practice is undertaken when the filter bed becomes clogged with material to the extent that surface loading rates are unsustainable (i.e. terminal headloss is reached). Alternatively, a SSF may be drained and skimmed when monitoring indicates an ongoing problem with filtrate quality. Other reasons for skimming include: excessive algal growth, evidence of media scouring and low DO conditions (when monitored). SSFs are more likely to need skimming when the media grain diameter (ES) is small, the available head is low, raw water contains high turbidity levels and temperatures are warm (Letterman, 1991).

A site with more than one SSF (as recommended) should organise its skimming schedule such that only one SSF is out of service at any one time.

This may require SSFs to be skimmed before they reach their terminal headloss (Ellis, 1985). Whilst a SSF is out of service, adjustments need to be made to the regulating valves on those SSFs remaining in service in order to continue to achieve the same volume of treated supply water (assuming adequate clear water reservoir capacity exists, Visscher *et al*, 1987).

Before an outlet controlled SSF is drained for skimming, the supernatant level is allowed to rise until it reaches the scum outlet so as to remove as much floating scum as possible before it is drained. This is not possible for inlet controlled SSFs and floating dirt may be removed manually (Visscher *et al*, 1987).

Filter drain down is initiated by stopping the flow of water into the supernatant (e.g. by closing the inlet valve to the filter). For SSFs with the inlet structure illustrated in Figure 4.5, the supernatant can subsequently be drained quickly by opening the bottom valve. If this facility is not available then the supernatant water is allowed to drain through the filter under gravity. For large filters this is often carried out overnight such that skimming can begin early the following morning. If possible, SSFs should not be completely drained for skimming. Ideally a shallow water table should be maintained below the sand's surface (i.e. the SSF is drained to approximately 0.2m below the sand's surface). This practice minimises the adverse impact of the drain-down period on of the microbiological community within the media bed (Lloyd, 1974, Lloyd, 1996).

Skimming methods vary and may be mechanical or manual. Skimming should be undertaken as quickly as possible to minimise the stress placed on the filter's biological community during the drain-down period. This reduces bacteriological counts in filtrate water during the onset of the subsequent run (MWB, 1969-70, Section 2.2.5).

Manual Skimming

Manual skimming has the advantage of keeping the SSF design simple, for example vehicular ramps are not required and there is less mechanical equipment to maintain (e.g. skimming vehicles/equipment). Manual skimming is widely practiced at small installations around the world (Letterman, 1991). As it is important to minimise the time period during which the SSF is drained, manual skimming may require extra operatives to be brought in solely on days when a SSF is skimmed. If possible, members of the local community should be encouraged to participate as this cultivates a sense of ownership over the filter and feeds money back into the local economy.

The boots of those skimming the SSF should be cleaned prior to them entering the bed. It is also important that a convenient toilet facility be provided and that supervisors stress to operatives that this should be used and not a corner of the SSF unit (Letterman, 1991).

During manual skimming the influent flow into the SSF is stopped, or diverted onto an adjacent SSF and the filter to be skimmed is allowed to drain. As soon as the filter is drained, operatives should enter the filter box. If necessary a ladder can be used to access the SSF bed. If the SSF is uncovered then any weed lying on the SSF should be removed first. This should not be allowed to lie in heaps on the SSF, but should be removed as quickly as possible for disposal.

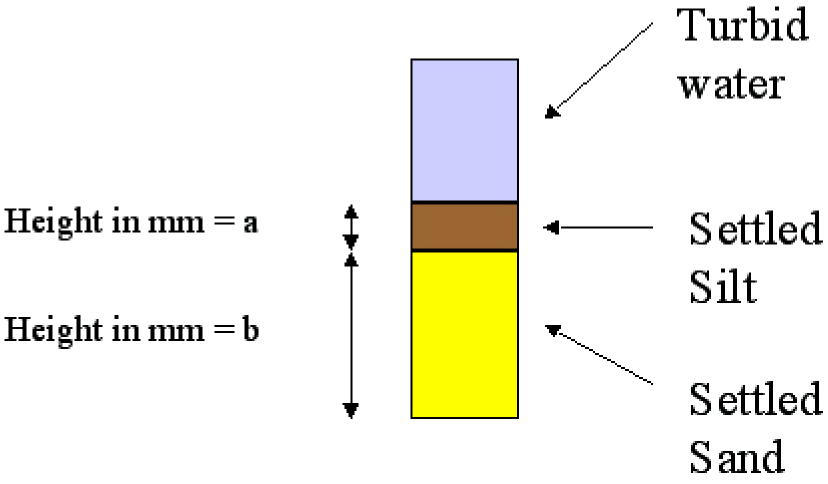
The top 1-3cm of sand is carefully and evenly scraped from the whole filter bed area, using square-bladed shovels (Huisman & Wood, 1974). It may be possible to determine the depth that requires removal by the colour of the top sand layer (as an approximation, it will appear brown to the depth where silt has penetrated). Boards or planks can be laid on the sand’s surface to enable access to all areas of the filter. This prevents media disturbance and allows the use of wheel barrows to remove weed and sand.

A deeper skim (e.g. 6cm) is used when a problem has been experienced with the filter, or if one is anticipated in the subsequent run, for example, due to an operational problem whilst skimming (e.g. prolonged drain down, for example more than 72 hours).

The appropriate skim depth may be determined by a silt analysis. This involves calculating the percentage silt content for media scraped from the SSF surface. Silt content can be assessed by placing a 100ml sample of the sand into a measuring cylinder (or glass container of known volume) and adding water to the 200ml mark. This is shaken vigorously and then allowed to settle (for approximately 20 minutes). Three layers will be formed:

1. turbid top water
2. silt (settles in the middle of the container)
3. sand media (settled at bottom of container)

The silt content is calculated by measuring the height of the band of settled silt (Figure 5.1). This can be converted into a percentage of the total media sample height. The filter is skimmed to a depth where the silt content of sand samples falls under 5-10%.



% Silt Content = (a/b) x 100

Figure 5.1: Calculating Silt Content of Media Samples (not to scale)

Once the SSF has been skimmed the sand's surface is levelled (smoothed). This can be done using a rake or by dragging a metal mesh (cyclone fence section) across the sand's surface (Letterman, 1991).

The removed dirty sand should be placed into containers that can be easily lifted out of the SSF box (e.g. wheel barrow if there is ramp access or large buckets if access is by ladder). Dirty sand is taken directly to the sand washing facility, or to an allocated area on the site until it can be washed.

The time taken to manually skim a SSF varies. Hendricks *et al* (1991) reported that at one treatment works where manual skimming was practiced and sand removed in buckets, this was performed at a rate of 19m^2/person/hour. A review of manual skimming rates by Letterman (1991) reported that on average the labour requirement was 4.2 person-hours per 100m^2 of filter bed area. For manual skimming, the deeper the skim, the longer this process takes.

Plate 5.1: Manually skimming a SSF at the Walton treatment works in the 1940s, London (UK)

Mechanical Skimming

Mechanical skimming is a faster process than manual skimming, and one that requires less man power for large scale SSFs. Disadvantages include the higher capital cost incurred in purchasing the skimming equipment and the time and costs involved in maintaining this equipment. Use of vehicles in mechanical skimming is only appropriate for large SSFs and this will also require the SSFs to be fitted with ramps to permit vehicular access. Alternatively, removable ramps may be purchased. If the SSF is covered by a permanent roof then use of skimming vehicles is only an option if adequate consideration has been given to the extraction of vehicle fumes.

If vehicles are used to skim the SSF, these will need to be tracked or wide-tyre wheeled vehicles in order to permit them to drive over the media without disturbing the sand’s surface (Ellis, 1985). Such measures are also required to prevent compaction of the SSF media (which would result in high starting headlosses and shortened run lengths). To prevent media compaction vehicles should be adapted to ensure that soil pressure is kept below $33kN/m^2$ (Huisman & Wood, 1974).

Once drained, algae are removed from the bed and a vehicle fitted with a mechanical scraper is driven around the filter removing the top 1-3cm of sand. A vehicular scraper (Plate 5.2) is typically fitted with a horizontal twin auger screw device which both picks up the (preset) top layer of sand and pushes it towards the centre line of the vehicle from where it is picked up by a wide scraper flight and transported rearwards by rubber conveyor belt to the back of the vehicle and dropped into a dumper truck that follows the scraper (Ellis, 1985).

A deeper skim of 6cm is used when a problem has been experienced with the filter, or if one is anticipated in the subsequent run, for example due to an operational problem whilst skimming (e.g. prolonged drain down, for example more than 72 hours). The appropriate skim depth can significantly impact filtrate quality during the onset of the subsequent run. For example, if a filter is not properly skimmed then an inoculum of algae may remain, causing rapid growth of algal populations in the subsequent run, which in turn shortens its run length (Bellinger, 1979).

A bed must be skimmed uniformly to avoid differential flow velocities occurring through the bed when it is re-started. Uneven flow through the filter can result in uneven supply of DO, substrate and nutrients to the microbiological community, which in turn can result in locally reduced microbiological activity in the filter and poor performance (Bayley, 1999).

If sufficient funds are available, a site may invest in a laser sand leveller. This is used to ensure a level surface and also to make sure that a minimum sand depth is maintained. Once this minimum sand depth has been reached, the bed must be re-instated with clean media (Section 5.2.4). The sand leveller is driven around the bed in a circular pattern, automatically adjusting the sand level by scooping excess sand into a box. In the absence of a mechanical leveller, the sand's surface can be smoothed using a rake or by dragging a piece of metal mesh (cyclone fence section) across the sand's surface (Letterman, 1991).

Plate 5.2: Mechanically skimming a SSF at the Hampton Advanced Water Treatment Works in London (UK).

Another means of mechanically skimming a SSF is the use of a bridge/gantry and mechanical scraper (Plate 5.3). The bridge itself runs on rails fixed to the top of the walls on both sides of the filter, along its full length. The bridge is therefore able to straddle the filter and can move down its length. If more than one SSF exists on the site then these filters must be arranged in alignment and located adjacent to one another such that the same rail tracks permit the bridge to move from one filter to another. Attached to the bridge is a mechanical scraper, which is lowered to the sand's surface once the filter is drained. This then moves across the entire area of the filter, removing the required depth of sand. The dirty media is carried up onto the bridge and dropped into an adjacent dump truck. Dirty sand is taken directly to the sand washing facility, or stored in an allocated area until it can be washed.

Some water treatment companies operating SSFs skim their filters whilst they are still filled with water (so-called wet skimming). This requires specialised machinery, however, and will be unsuitable unless there are the funds and expertise to purchase, maintain and operate these systems.

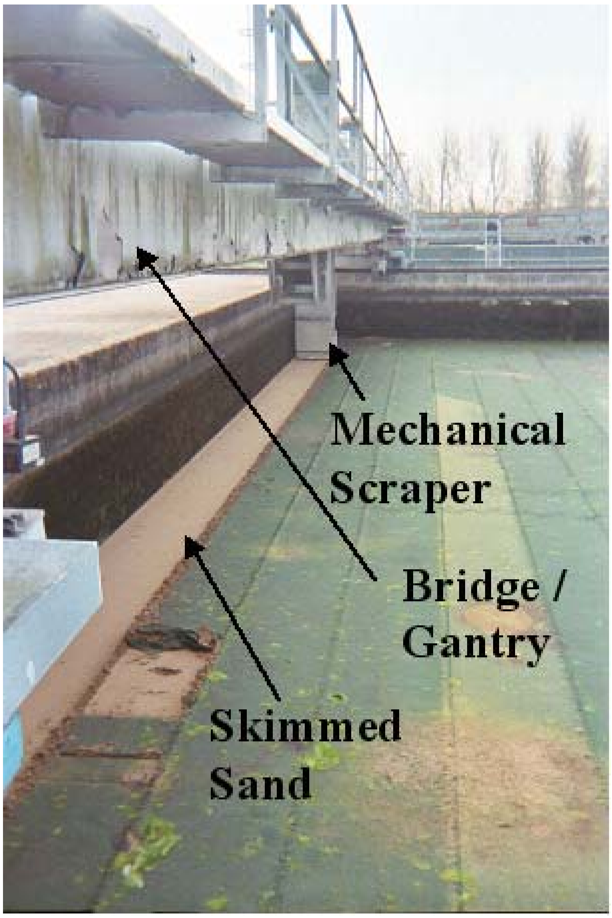


plate 5.3: Mechanically skimming a SSF (after algal mat removed) using a bridge/gantry (Fobney Advanced Water Treatment Works, Berkshire, UK)

Once a SSF has been skimmed, it should be recharged and re-started as soon as possible.

The choice of skimming method (manual vs. mechanical) will depend on the available funds and the cost of hiring labour. Huisman & Wood (1974) estimated that manual skimming of a SSF (of area 2000m^2) required 75 man-hours of labour compared to mechanical (vehicular) skimming which required only 20. With these estimates, if this SSF were skimmed 15 times per year then this would leads to a saving of 300 man-hours per annum. Whether it is appropriate (and economical) to undertake mechanical skimming will depend on:

- Local pay rates for labourers
- Design period (over which costs are calculated)
- Available (future) funds for operating costs, maintenance and repair of vehicles
- Area of the SSFs
- Skimming frequency (dependent on raw water quality, covering etc)

In rural communities where relatively small SSFs are used and there is no shortage of labour, manual skimming is likely to be most appropriate. The fewer mechanical parts in the system that require servicing the more likely it is that these systems will continue to operate in the long term. Manual skimming also has the benefit of providing some local employment.

5.2.4 Topping-up, Trenching and Re-instatement of the Bed

The term re-instatement refers to the complete excavation of the SSF filter bed and its replacement by a new, clean bed of sand (to the maximum filter bed depth). Other terms used to describe re-instatement include rebuilding, restoring or re-sanding the filter.

Once successive skims have reduced the sand bed to its minimum depth (e.g. 0.5-0.8m, Huisman & Wood, 1974) then the filter bed depth will need to be restored to its maximum (starting) bed depth. This is an operational procedure that needs to be undertaken only once every couple of years, though its frequency will depend on the conditions under which the SSF operates and the operational practices (Letterman, 1991). The decision to re-instate a SSF should be planned in advance as the SSF is out of service for an extended time period.

Simply topping up the filter bed with new sand to its maximum (starting) bed depth is a relatively quick process compared to re-instatement, however it has several disadvantages. After several filter runs, the bottom layers of the media begin to accumulate deposits which could cause a ‘breakthrough’ of turbidity, high starting headloss and short run lengths, despite regular skimming. Hence, topping up a bed is a relatively quick procedure, but the SSF bed will not be as productive in the long term and will eventually need the whole bed replaced in order to maintain the required filtrate quality and operational sustainability. Monitoring (media silt content, filtrate quality, headloss and run length) should ascertain whether a SSF requires a completely new bed of sand once it reaches its minimum bed depth, or whether topping up the sand is sufficient. If a SSF has already been topped up once it is likely that the next time it reaches its minimum bed depth it will require re-instatement.

An alternative procedure to topping up and re-instatement is trenching (described below).

Topping Up the Media Bed

The flow of influent (raw) water is stopped (e.g. by closing the inlet valve) and the SSF is allowed to drain completely. The filter is skimmed (Section 5.2.3) and then clean sand laid on top of the bottom sand until the total bed depth is restored to its maximum (starting) filter depth.

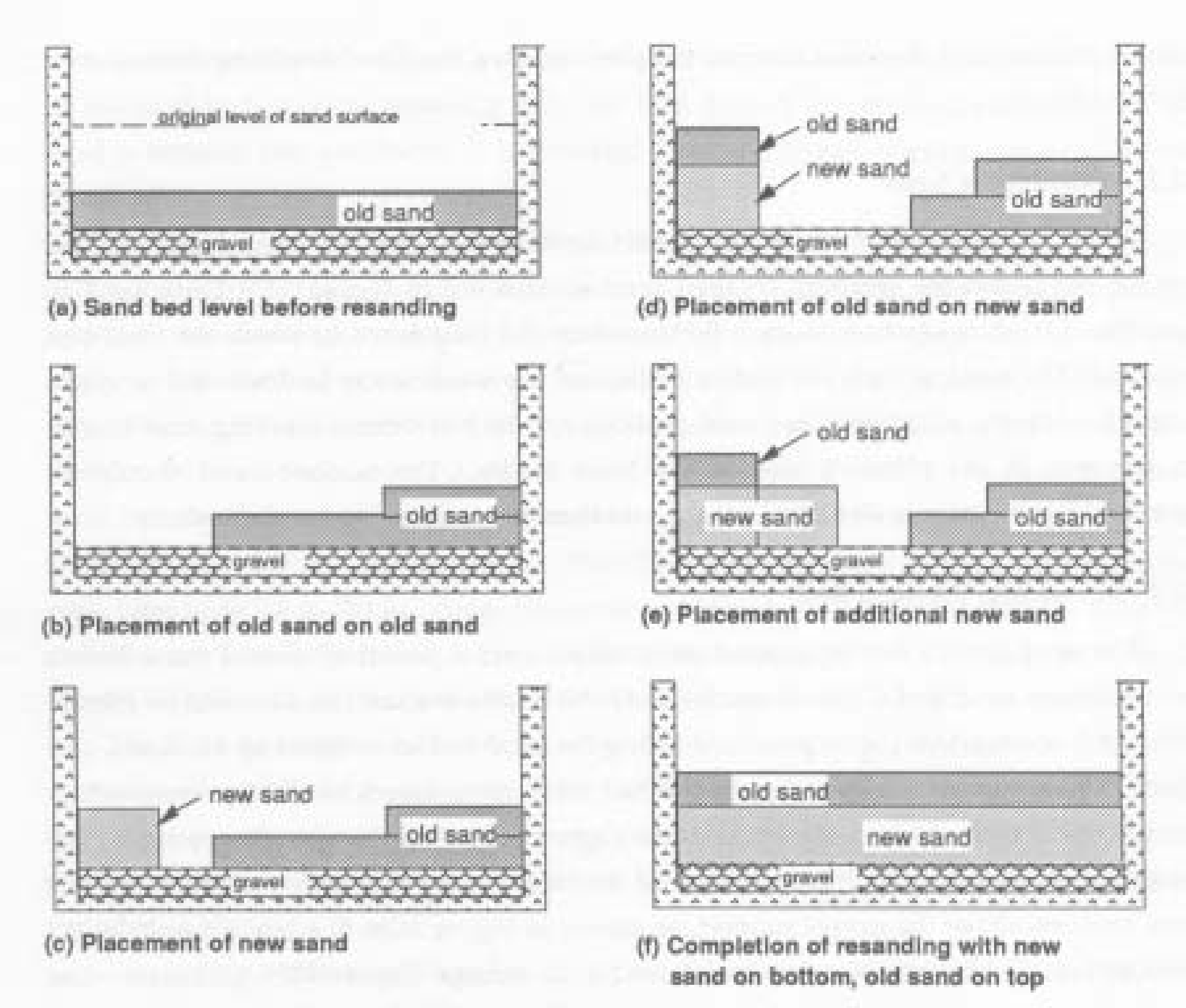
The SSF area should be filled with sand in layers such that one layer is evenly spread across the SSF area at a time and to ensure that no large air spaces remain in the bed. Methods of doing this will depend on the size of the filter and the equipment available. Layers of sand are laid until the maximum (starting) sand depth is reached.

Plate 5.4: Re-sanding a SSF at the Ashford Common Advanced Water Treatment Works in London (UK).

Once the required depth has been laid, a sand leveller may be used to ensure that the bed's surface is level. This leveller is driven around the bed in a circular pattern, automatically adjusting the sand level by scooping excess sand into a box. In the absence of a mechanical leveller, the sand's surface can be smoothed using a rake or by dragging a piece of metal mesh (cyclone fence section) across the sand's surface (Letterman, 1991). Operatives should use their judgement, and make sure that the filter bed is as level as possible before the filter is recharged. Marking the required starting bed depth on the inside of the SSF walls can assist in this process. Once recharged, the filter is ready to be re-started (Section 5.1.5).

Trenching ('throwing-over')

This involves first skimming the SSF (Section 5.2.3). Then the remaining old bottom sand is removed and put to one side. The appropriate depth of clean sand is placed on top of the gravel layer and then the old bottom sand is put back into the bed, over the top of the clean sand (Figure 5.2). The end result is a clean bed of sand underlying a layer of biologically active (old) sand. The advantage of trenching is that the old sand, which now lies on top of the filter bed, is still biologically active and hence the SSF will ripen more quickly after it is re-started compared to if a completely new bed of sand was used (Letterman, 1991). This biologically active layer will increase the starting headloss through the SSF compared to a re-instated SSF, however this layer is also removed relatively quickly as it is the first media to be removed by skimming (by which time the whole bed has become biologically active).



(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 5.2 Trenching (Hendricks *et al*, 1991, adapted from Huisman & Wood, *Slow Sand Filtration*, Copyright (1974), reprinted with permission from the publisher, World Health Organisation, WHO)

Re-instatement

The flow of influent (raw) water is stopped (e.g. by closing the inlet valve) and the SSF is allowed to drain completely. The filer bed is completely dug out and the dirty sand transported to the sand washing facility or an allocated area for storage until it can be washed.

Every 5-10 years it is recommended that the layer of gravel is removed for washing (though separately from the sand) and that the inside of the SSF tank and its under-drainage is inspected and repaired as necessary. Clean gravel is then re-laid over the under-drainage.

A clean bed of sand is then laid (to its maximum depth) on top of the gravel layer. The SSF area should be filled with sand in layers such that one layer is evenly spread across the SSF area at a time and to ensure that no large air spaces remain in the bed. Methods of doing this will depend on the size of the filter and the equipment available.

Once the required depth has been laid, a sand leveller may be used to ensure that the bed's surface is level. This leveller is driven around the bed in a circular pattern, automatically adjusting the sand level by scooping excess sand into a box. When a leveller is not available, a rake may be used, or a piece of metal mesh (cyclone fence section) can be dragged over the sand's surface (Letterman, 1991). Operatives should use their judgement, and make sure that the filter bed is as level as possible before the filter is recharged (Section 5.2.5). Marking the required starting bed depth on the inside of the SSF walls can assist in this process. Once recharged, the filter is ready to be re-started (Section 5.1.5).

5.2.5 Filter Recharge

To recharge a SSF simply means to refill the filter with water after it has been drained (e.g. for skimming or re-instatement). This is usually done by slowly backfilling the filter. Backfilling allows any air trapped in the filter bed to escape as the filter is filled (Letterman, 1991), which in turn helps to prevent the media from being disturbed by trapped air bubbles which rise once the filter has been completely recharged. Backfilling must be undertaken slowly in order to avoid disturbing the media. Ideally, the pipes used to backfill the SSF should be fitted with a flow meter to ensure that backfilling is undertaken at the required rate (e.g. 0.1-0.2m/h, Hendricks *et al*, 1991). Alternatively, once an appropriate backfill rate has been determined for the specific SSF, this rate can be regulated (in future backfilling operations) by the number of valve turnings, or similar.

When more than one large scale SSF exists, the filtrate from one SSF can be used to backfill another, providing the correct valve configuration has been provided in the design (Figure 4.11). When only one SSF exists (not recommended), then backfilling using treated water is obviously not possible. Use of raw (untreated) water to backfill a SSF is not advised as this can seed the under-drainage and bottom section of the bed with potentially pathogenic organisms. It is preferable for raw water to be used to recharge the SSF via solely top filling when no alternative exists. Alternatively, partially water may be taken from the outlet of any pre-treatment processes (Visscher *et al*, 1987). If sufficient head has been incorporated into the system at the design stage then the movement of this water may be possible under gravity. Alternatively water may be pumped.

When filtered water is available, the filter undergoing recharge is backfilled until a minimum water level (e.g. 0.1m) is observed above the sand's surface. This minimum supernatant level exists to prevent scour when influent water is allowed to enter from above (Huisman & Wood, 1974). Once the minimum supernatant level is reached, top-filling can begin. This enables the SSF to be recharged more rapidly. As the supernatant fills, the top-fill rate can be accelerated because the sand becomes increasingly protected by the volume of water above it. In order to prevent any influent water turbulence from disturbing the sand during recharge, a filter should have a concrete slab or protective device at the inlet (Huisman & Wood, 1974). It is not unusual for flow to be started through the filter before top-filling is completed, although care must be taken to maintain top charge flow rates above initial surface loading rates whilst avoiding scour of media close to the inlet.

When the SSF design does not allow backfilling to take place (or when filtered water is not available for recharge), a SSF can be recharged solely by top-filling, though this must be done with care and requires a concrete slab or protective device to be fitted at the inlet (to prevent media scour). Water fills the chamber at the inlet. It is then allowed to slowly overflow this chamber and water spreads across the filter bed and down into the media. Top-filling continues at a slow rate to allow any air bubbles trapped in the media to escape before the sand it completely saturated.

5.2.6 Re-starting and Ramping up a Community Scale SSF

For SSFs that have been skimmed, the SSF should be re-started immediately (once recharged). At this stage the filtrate should not contribute to the clear water reservoir (assuming chlorination is not possible) and should be run to waste (discarded), or recycled (diverted onto the supernatant of another SSF). However, the filtrate from the ripening SSF should not be recycled onto itself as this slows the ripening process. Filtrate water will not meet drinking water quality requirements immediately after it is re-started (as it is 'ripening', Section 5.2.7). Bacteriological and turbidity testing will ascertain when water is ready for supply. Headloss measurements and visual inspection (e.g. schmutzdecke growth in an uncovered SSF) will also assist in determining the rate of ripening. If treated water is chlorinated then the SSF may be allowed to contribute to supply soon after it is re-started, providing it is adequately chlorinated and the chlorine residual checked regularly (Visscher *et al*, 1987). However, this practice may be unsafe where diseases carried by aquatic vectors are endemic to an area.

The method for re-starting a SSF will depend on its design (Section 4.2.14.1). The term 'ramping-up' refers to the gradual increase in surface loading rate through a SSF as it is re-started. Several approaches are identified:

- The SSFs are started at their nominal surface loading rates. This maximises the supply of substrate (‘food’), DO and nutrients to the filter’s microbiological community, which in turn may quicken its recovery. This method will only be suitable for SSFs operating at low surface loading rates (<0.2m^3/m^2/h) and the filtrate must be RTW during this period.
- Gradual increments to surface loading rate throughout the first day. For example, if a SSF operates at nominal rates of 0.2m^3/m^2/h the surface loading rate is progressively increased until this value is reached at the end of the first day (e.g. 0.02m^3/m^2/h increments each hour over 10 hours).
- Surface loading rate is ramped up in step changes. This method is suitable for SSFs operating at high surface loading rates. For example, if a SSF operates at nominal surface loading rates of 0.3m^3/m^2/h, the whole skimming and return to service process may proceed as follows (though these timings will obviously depend on the size of the SSF and the time it takes to complete each procedure):

  DAY 1 18:00 begin to drain SSF

  DAY 2 07:00-17:00 skim then recharge SSF

  DAY 2 17:00 start SSF at 0.1m^3/m^2/h

  DAY 3 08:00 ramp-up SSF to 0.2m^3/m^2/h

  DAY 3 12:00 ramp up SSF to 0.3m^3/m^2/h

When valves are operated automatically, they can be programmed to progressively increase the surface loading rate through the SSF during re-start until the nominal surface loading rate is reached.

With manually operated valves, the operative should start the SSF at a fraction of its nominal surface loading rate, leave this for a period of time and then return to the SSF and open the regulating valve a fraction more, and repeat this process until the desired surface loading rate is reached.

With an outlet controlled SSF the outlet valve is only partially opened during the start up of a filter. Operatives should be able to view the flow meter as they adjust the outlet valve.

With an inlet controlled SSF, the inlet valve is opened a little until the filtration rate is 0.02m^3/m^2/h. Every subsequent hour the inlet valve should be opened a little further until the design flow is reached (Visscher *et al*, 1987). As with outlet controlled SSFs, operatives should be able to view the flow meter as they adjust the inlet valve.

Water quality monitoring during the ramp-up period should also be undertaken to determine the optimum procedure for re-starting the SSF given the specific conditions under which it operates. For SSFs that operate at 0.2 $m^3/m^2/h$ or lower, optimum performance may be achieved by starting the SSF directly at these surface loading rates. Operational experience will enable operatives to ascertain the best operating practices (BOP) for their site. Water quality monitoring will also enable operatives to determine when a sufficient ripening period has elapsed to allow filtrate to begin contributing to the clear water reservoir (Section 5.2.7).

5.2.7 The 'Ripening' Period

The term 'ripening period' refers to the time period after re-starting the SSF during which time it may not effectively treat the water filtering through it (in comparison to an identical mature SSF treating water from the same source).

During skimming a large portion of the filter's microbiological community is removed by scraping away the top sand layer. The microbiological community is crucial in achieving effective water treatment, therefore by removing a large proportion of these micro-organisms the filter performance is initially adversely affected. In addition, during the time period that the sand is drained of water, the micro-organisms inhabiting the media will remain alive, but may become stressed by the stoppage of filtering water. Therefore, once the flow of water is restored to the filter, it will require some time for the microbiological community remaining in the media bed to re-establish itself and to recover from the stresses associated with the drain-down period. The time the filter takes to recover is called the 'ripening period'.

Skimmed SSFs will usually take less than a week to ripen and possibly only 1-2 days (Visscher *et al*, 1987). Ellis (1985) recommended that if filtrate quality testing was not possible and water was not disinfected then the water should not be consumed until 48 hours had elapsed after re-starting the filter following skimming. Similarly, Huisman and Wood (1974) stated that if the drain-down period was relatively short and the filter bed only partially drained, then the SSF may be ripe enough to contribute to supply after only one or two days (Huisman & Wood, 1974).

When a SSF has been re-instated, the media bed is clean and has no microbiological community. In order to treat water effectively, a microbiological community must become established and develop in the filter bed, which takes time. This time period is also called the ripening period, however the ripening period for a new bed is likely to be longer than the ripening period for a recently skimmed bed, as the skimmed filter already has an established microbiological community. A completely new bed of sand may take up to 3 weeks to ripen (Visscher *et al*, 1987). If it has been trenched then a SSF should ripen within 3-7 days in tropical conditions and up to two weeks in temperate regions (Visscher *et al*, 1987). A SSF will take longer to ripen when operating at low temperatures (Huisman & Wood, 1974).

Water should not be consumed until the SSF has ripened, however the ripening period is likely to vary according to the environmental and operational conditions. The only way to conclusively determine whether a SSF has sufficiently ripened (and is thus producing filtrate fit for human consumption) is by water quality testing (Section 5.2.9). Operational experience is also valuable in this decision-making process and operatives will learn which practices provide optimum results and also the typical ripening period for their SSFs. If intensive and comprehensive water quality monitoring is not possible every time a SSF is skimmed then a fixed ripening period can be used (Letterman, 1991). It is recommended that this approach err on the side of caution. In addition, some water quality testing will be required initially to establish what constitutes a typical ripening period for the specific SSFs (under the environment and operating conditions in which they operate). Once a routine ripening period is defined, some basic water quality analyses (e.g. turbidity measurements) during a SSF's return to service can assist in determining whether the SSF is ripening as usual, or whether an extended ripening period is required.

During the ripening period the SSF filtrate should be discarded (run to waste, RTW). In order not to waste this water it may be diverted onto the supernatants of other filters. In order to do this a pump may be required. Alternatively ample head may be incorporated into the design of the SSFs to enable it to gravity feed its filtrate into the supernatants of other filter units (Sharpe *et al*, 1994).

5.2.8 Sand Washing

Sand that has been removed from the SSF (e.g. during skimming) must be washed, dried and appropriately stored until its reuse. Reusing sand is preferable to sourcing new sand, particularly with large SSF installations. New sand will need to be purchased and/or graded and washed of fines before use, which can be costly. In addition, if dirty sand is discarded it must be properly disposed of (Letterman, 1991).

Large sites that wash and reuse large volumes of sand (and which have sufficient funds) may choose to invest in mechanical washing equipment. Hendricks *et al* (1991) refer to cyclone or concrete mixers. Huisman and Wood (1974) provide examples of ejector type sand washers where sand is placed in a tank into which water is ejected into the bottom. The sand sinks and the dirt attached to the sand becomes suspended in the water and is carried up to the surface of the tank, where it overflows and is thus removed.

In the absence of resources to buy equipment or built a sand washing facility then hand stirring is an appropriate method (Visscher *et al*, 1994) and one that may be more appropriate if relatively small volumes of sand are being washed at relatively infrequent intervals.

For small scale hand washing, media is placed in a container/tank which is continuously filled with water. The mixture is stirred to encourage fines within the media to become suspended, whilst the denser sand settles in the bottom of the container. By allowing water to overflow from this container, the fines are removed. The procedure is repeated until the water above the media is clear. The media is then drained, spread out on a clean surface to dry and transferred to a clean sand storage container.

Alternatively a sand washing facility can be built for this purpose. This can comprise a platform (e.g. 3.5m x 1.5m) with an inclination of 5° (Plate 5.5). The platform is surrounded by a wall 0.6m high at the head of the slope and 0.3m high at the lower end (Visscher *et al*, 1987). Sand is placed onto the platform (0.5-1.0m^3) and water sprayed at the sand using a hose. The sand is stirred to encourage the dirt to detach from the sand grains. At the end of the platform is a weir over which the dirty water flows and runs to waste, but which also holds the sand inside the platform. This process reportedly takes about an hour, after which time the weir is removed to allow the water to drain, and the sand is spread out to dry (Visscher *et al*, 1987). A similar method was also described by Huisman & Wood (1974).

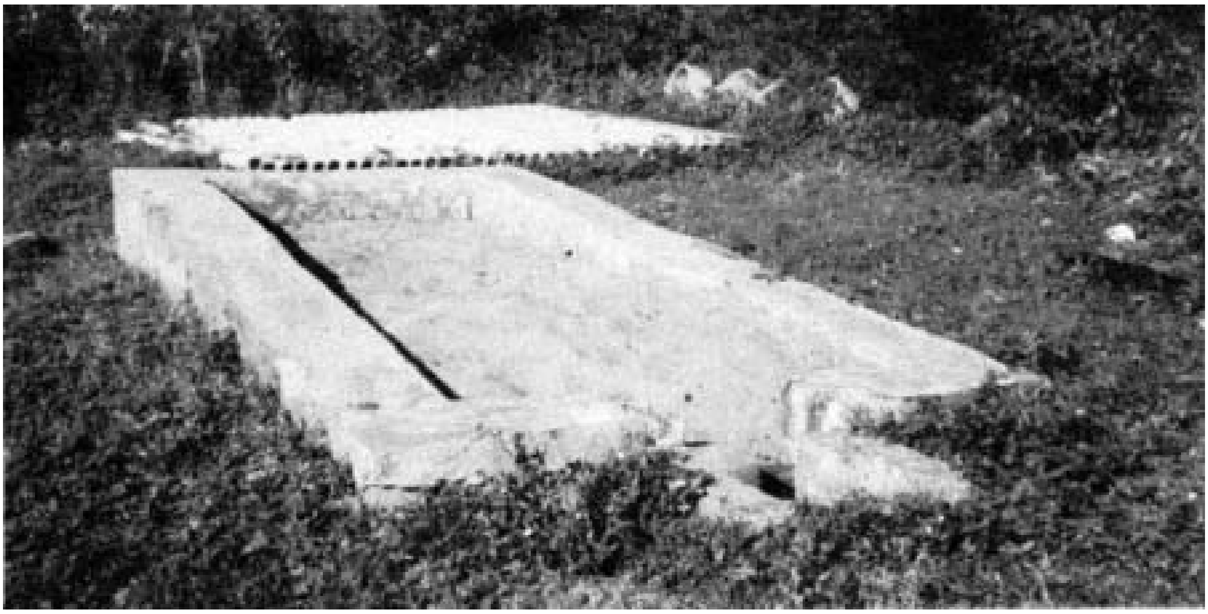


Plate 5.5: Sand Washing Platform (reprinted from Visscher *et al*, *Slow Sand Filtration for Community Water Supply*, Technical Paper No. 24, Copyright (1987), with permission from the publisher, International Reference Centre for Community Water Supply and Sanitation, IRC)

For larger scale SSF works (processing more sand) the facility shown in Plate 5.5 may be inadequate. An alternative is the use of ‘bottle washers’ (usually used in succession). These consist of cones into which the sand is loaded from the top. Water enters from the bottom and washes the media within the cone. Cleaned media drops down to the bottom of the cone and is carried away to the next bottle washer (where the process is repeated). The dirty water overflows over the top of the cone and is discharged to waste. Bottle washers were used by the Metropolitan Water Board to clean SSF sand at London’s SSF works. This is illustrated in Plate 5.6.

Plate 5.6: Bottle washers used to wash sand at a London SSF works

It is highlighted that washing the sand results in the loss of its finer particles which in turn increases the effective diameter of the media and possibly decreases the ability of the bed to remove impurities (Huisman & Wood, 1974). Therefore the media may need to be periodically assessed to ensure it maintains the design specifications (Section 4.2.10).

5.2.9 Water Quality Testing and Monitoring

Daily monitoring (and recording) of surface loading rate and headloss measurements is important for effective operation the SSFs (particularly outlet controlled SSFs). Additional information that should be recorded includes:

- Number of days a SSF has been running since its last skim (i.e. run length)
- Date of each skim, depth of sand removed and the depth of sand remaining.

In addition to operational parameters, some water quality testing is advised. This is particularly useful during the start of a SSF run, and will assist in deciding when the SSF is ripe enough to allow it to contribute to the clear water reservoir (i.e. supply). Recommended tests include:

- Microbiological tests, (e.g. thermotolerant coliforms, *E.coli*)
- Turbidity.

If possible these parameters should be monitored once per day for each individual filter's filtrate. More intensive monitoring is advised during a SSF's ripening period (Section 5.2.7). It may also be appropriate to analyse filtrate for pathogenic organisms known to be endemic to an area, such as aquatic vectors of pathogens. The frequency of filtrate quality testing will depend on the number of SSFs contributing to supply and the volume of water being treated. For large works with multiple filters, a greater degree of protection is provided against an individual filter performing poorly since its filtrate will be diluted by a large number of other SSF filtrates.

In the absence of microbiological tests, ammonia testing is another tool that may be used to assess performance. There should be no ammonia in the filtrate from a mature SSF (Ellis, 1985).

Other useful parameters for SSF monitoring include particle counters and dissolved oxygen (DO) measurements. DO can be measured by dedicated monitors, or via the Winkler (laboratory) method. Though these tests require sufficient funds to purchase and maintain the instrumentation. Monitors may also require a computer to down load and analyse data. Obviously the level of monitoring undertaken will depend on the available resources. Particle counters and DO monitors are a luxury rather than a necessity. Turbidity and microbiological monitoring are more important and often a drinking water requirement of regulatory agencies.

Plate 5.7: Water quality testing at the Water and Sewage Authority laboratory near Castries (St Lucia)

Plate 5.8: Water quality testing training (using the DelAgua Membrane Filtration kit) with staff from the Nyabwishongwezi Water Treatment Plant, Umatara, Rwanda

All monitoring should be recorded in an organised fashion and also provide the following information:

- Date and time of sampling.
- Name of sampler.
- Reason for sampling.
- Sample point (influent, treated water etc).
- Details of the analysis, including date, laboratory, analysis method and name of the analyst.
- Results of the test.

(Hendricks *et al*, 1991)

Water quality monitoring should be possible in a dedicated laboratory. Ideally this should be stocked with the instruments and reagents necessary for turbidity and microbiological testing. As a minimum the laboratory should contain a turbidimeter, clean sample bottles, turbidity standards and sterile plastic sampling bottles (e.g. to enable sampling for microbiological testing, Hendricks *et al*, 1991). If facilities are limited, as a minimum SSF operatives should be trained to check the following:

- Turbidity of raw water (at the intake) and whether abstraction should be stopped as a result.
- Turbidity of the influent water and filtrate of the SSF and whether the SSF is performing properly.

(Visscher *et al*, 1987).

When turbidity measurement using turbidimeters is not possible, visual assessment of influent and filtrate turbidity may be useful (Visscher *et al*, 1987). This is reviewed in Section 5.3.

If chlorination is practiced then operatives should also be trained in testing chlorine residual. It is also recommended that periodically a higher-level agency perform a complete set of physico-chemical and bacteriological tests on raw and treated water. Furthermore, it is advised that sanitary surveys be routinely conducted to identify potential sources of contamination to water undergoing treatment as well as poor practices regarding the treatment processes (Lloyd & Helmer, 1991, Rubiano, 1994). The remedial action advised (based on the sanitary survey) can assist in improving treatment and it is also preventative. Guidelines on how to undertake a sanitary survey as well as example sanitary survey forms and case studies are provided by Lloyd and Helmer (1991).

Where the funds and/or facility is not available to test these water quality parameters possible options include:

- Purchase a water quality testing kit (e.g. Oxfam-DelAgua Water Testing Kits at www.robenscentres.com/delagua/index.cfm) and any consumables required to operate it.
- Enquire about locally available water quality testing facilities/services in the area.
- Visual turbidity testing (Section 5.3).
- Operational experience and judgement. If possible an external water quality assessor should be brought in to establish the filtrate quality achieved (how long typical ripening periods are for the specific SSF etc). Subsequent water consumption is then based on these guidelines. Alternatively, the guidelines of Visscher *et al* (1987) as well as others should be followed (Section 5.2.7).

Water quality sampling, monitoring and testing guidelines, for drinking water, are provided by the WHO (1996). Information is available on the Internet (UNEP/WHO, 1996) at www.who.int/docstore/water_sanitation_health/wqmonitor/

- Click on ch08 for Field Testing Methods
- Click on ch10 for Advanced Instrumental Methods

All operational monitoring and water quality test results should be recorded and filed in an organised system. Basic records should include:

- Quality parameters that have been tested (ideally turbidity and bacteriological testing undertaken at the same time each day)
- Operational parameters that have been monitored - surface loading rate, changes in the supernatant level and headloss measurements (on a daily basis if possible, measured at the same time each day)
- Interruptions to the intake of raw water
- Cleaning of the inlet and sump
- Interruptions to filter operation.
- Skimming records (date, time, sand depth, date and time the filter was re-started and date and time of its return to service).
- Daily volume of water treated.
- Flushing of the distribution network (if one exists).

(Huisman & Wood, 1974, Visscher *et al*, 1987)

When analysing the results of water quality monitoring, it is important to assess the *level* of the parameters being measured in comparison to the *level* of these parameters in alternative water sources. For example, thermotolerant coliforms (also referred to as faecal coliforms) may still be present in treated water, however this may still be a preferable source of drinking water compared to alternatives (Huisman *et al*, 1981). Ideally no thermotolerant coliforms should be present in drinking water (WHO, 1996), however in practice, in the absence of alternative sources (and given that a relatively large dose of any one pathogen is usually required to cause illness) it may be necessary to supply water which does not conform to WHO standards. It is usually accepted that the lack of water to ensure a minimum of hygiene entails even more problems than does the consumption of relatively poor quality water (Delmas & Courvallet, 1994).

5.3 Visual Turbidity Assessment

Two methods of visual turbidity assessment are reviewed in this section:

1. Turbidity Tube (Lloyd & Helmer, 1991)

This requires the purchase of a 'turbidity tube'. This was developed by Lloyd for the DelAgua kit (www.robenscentres.com/delagua/index.cfm) in 1985.

The water being tested is slowly added to the turbidity tube. Care must be taken not to allow bubbles to form. The tube is only filsled until the mark at the bottom can no longer be seen from above. The turbidity can then be read from the scale at the side of the tube. The turbidity of the water is the value closest to the height of the sample water in the tube. Since this scale is not linear, interpolation of values between the lines is not advised (Lloyd & Helmer, 1991).

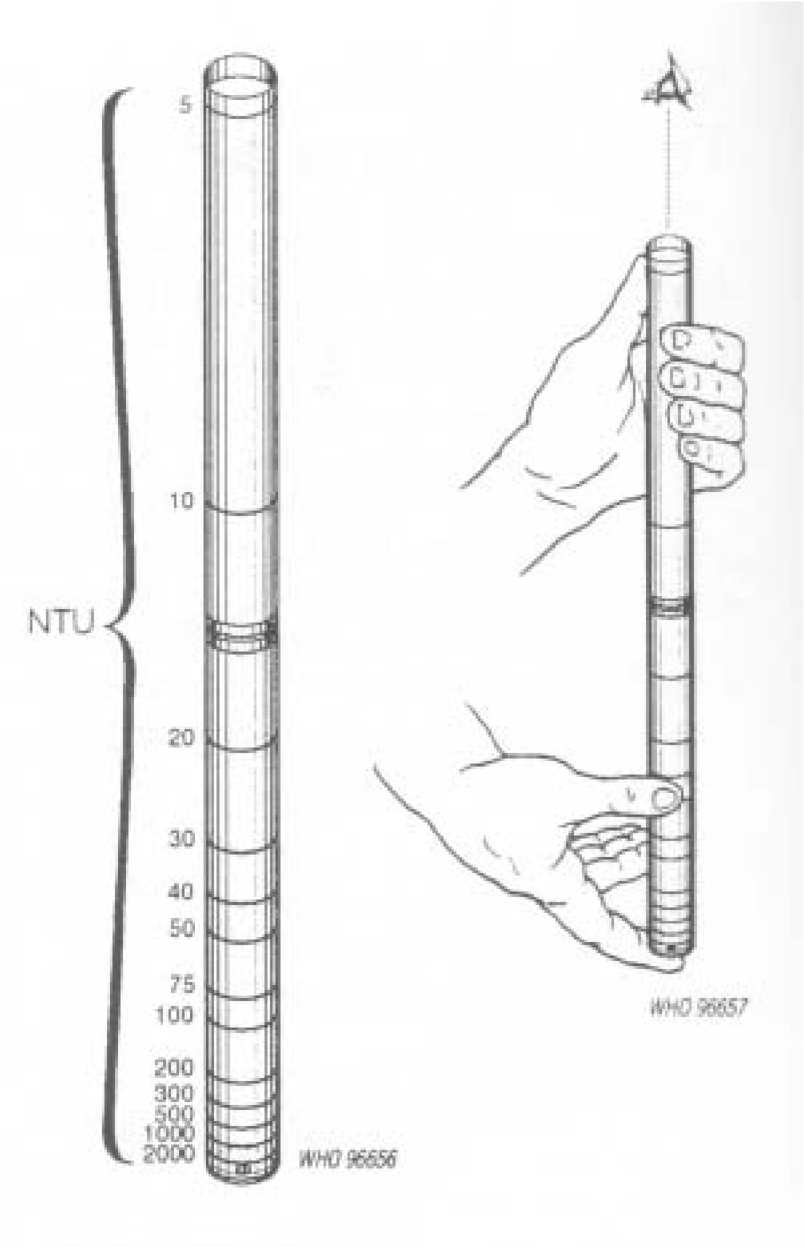


Figure 5.4: Turbidity Tube (reprinted from *Guidelines for Drinking Water Quality - Health Criteria and other Supporting Information* Second Edition, Copyright (1996), with permission from the publisher, World Health Organisation, WHO).

Plate 5.8: Measuring treated water turbidity, using a turbidity tube, at the tap stand at the Nyabwishongwezi Health Centre, Umatara, Rwanda.

Plate 5.9: Water quality improvement throughout the multi-stage treatment system at the Nyabwishongwezi Water Treatment Plant (Umatara, Rwanda) on 05/Oct/2002. From left to right: raw water tank inlet: 647NTU, raw water tank effluent: 220NTU, pre-filter effluent: 40.2NTU, and slow sand filter effluent: 12.2 NTU (Dorea *et al*, in press 2004).

2. Secchi Disc

The secchi disc can be used to quantify the transparency (colour and turbidity) of lakes and reservoirs. The disc itself is made of rigid plastic or metal and may be 20-30cm (or larger) in diameter (UNEP/WHO, 1996). The disc is usually either white, or has black and white quadrants painted onto it. The disc is suspended by a light rope and a small weight is tied to its bottom to encourage it to sink when submerged in the water body.

Measurements should be taken between 10am and 2pm. The secchi disk is lowered into the water until it disappears from view. The depth to which it is submerged (i.e. the length of rope) is measured. The procedure is repeated twice and the average calculated. (UNEP/WHO, 1996). This measurement can be converted into turbidity units (see link below), although these are subjective measurements and should be treated as guideline turbidity values. When possible a turbidity meter or turbidity tube should be favoured.

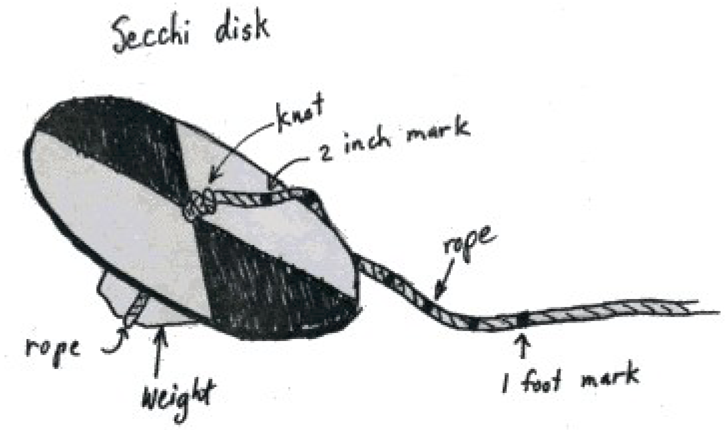


Figure 5.5: Secchi Disk (reprinted from Adams, *Turbidity and Water* Copyright (1998), with permission from the Northern Essex Community College)

Guidelines on how to make a secchi disk, as well as tables for converting measurements into Jackson turbidity units are provided by Adams (1998) at the website below. Note that in practice Jackson turbidity units (JTU), nephelometric turbidity units (NTU) formazin turbidity units (FTU) and formazin nephelometric turbidity units (FNU) are interchangeable (WHO, 1996).
www.necc.mass.edu/mrvis/mr2_14/start.htm#p4

6 Common Problems

Clogging of the filter by turbid water

- Avoid using SSFs when raw water is clay-bearing.
- Install pre-treatment processes to reduce turbidity levels.

(Logsdon, 1994)

Water in the filter freezes

- Cover the SSF.
- Insulate the SSF (e.g. using earth).
- Heat the environment inside the filter building.

(Logsdon, 1994)
Filtrate is initially turbid

- If locally sourced media is being used, wash the fines from this media before laying it in the filter (Logsdon, 1994).
- Use pilot plant studies to select optimal media source.

Operational flexibility of the Plant is Limited by Single Filter Unit

- Subdivide the existing unit and design the piping accordingly.

(Logsdon, 1994)

Piping arrangements restrict plant operating flexibility

- Review piping arrangements to ensure that flow patterns are flexible

(Logsdon, 1994)

No Pilot Plant was Studied before Design of Full Scale Plant

- Undertake monitoring to ensure successful treatment.
- Undertake a pilot plant study before designing the actual plant.

(Logsdon, 1994)

A SSF has inadvertently drained

- How long has the filter been drained?
- If this is less than 72 hours then the filter can be skimmed, recharged and re-started, though treated water will not be fit for consumption for the period immediately afterwards (i.e. it requires a ripening period, Section 5.2.7).
- If the SSF has been drained for over 72 hours then it may require re-instatement.

Algal Growth is a Problem for Operation and Quality

- Pre-treat SSF influent water (e.g. river bed filtration, gravel pre-filtration).
- Cover/shade all water storage tanks (pre and post SSFs).
- Cover/shade the SSF.
- Manual removal of filamentous algae may be appropriate (Visscher *et al*, 1987).

7 Useful SSF References

Bellinger, E.G., (1979), “Some Biological Aspects of Slow Sand Filters” Journal of the Institution of Water Engineers and Scientists, Vol. 33, No. 1, pp. 19-30.

Collins, M.R., Eighmy, T.T., Fenstermacher Jr. J.M., & Spanos, S.K., (1992), “Removing Natural Organic Matter by Conventional Slow Sand Filtration”, American Water Works Association, May, pp. 80-90

Collins, M.R. & Graham, N.J.D. (Ed.s), (1994) Slow Sand Filtration – an international compilation of recent scientific and operational developments, American Water Works Association, Denver, USA, A collection of papers discussing principles of SSFs, SSF case studies, design and construction experiences, pre-treatment techniques, removal of micro-organisms and organic material, modelling and process control, operating and maintenance experiences, research needs.

Collins, R. & Graham N. (Ed.s), (1996) Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, Inc. A selection of papers reviewing research undertaken in the 1980 and 90s regarding SSFs.

In particular:

- Lloyd, B.J., (1996), “The Significance of Protozoal Predation and Adsorption for the Removal of Bacteria by Slow Sand Filtration”, in Collins, R. & Graham N. (Ed.s), Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, Inc.
- Graham, N.J.D., Clarke, B.A., Jones, C.J., & Lloyd, B.L., (1996), “Effect of Reduced Depth Fabric-Protected Slow Sand Filters on Treated Water Quality” in Graham, N., & Collins, R., (Ed.s), Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, pp. 233-243.
- Shenkut, M., (1996), “Experiences with Slow Sand Filters in Ethiopia”, in Graham, N., & Collins, R., (Ed.s), Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, pp. 379-387.
- Li, G.B., Ma, J., & Du, K.Y., “Multi-stage Slow Sand Filtration for the Treatment of High Turbid Water”, in Graham, N., & Collins, R., (Ed.s), Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, pp. 371-378. Application is China.
- Weglin, M., Zimmermann, & Burgthaler, B., (1996), “Rehabilitation of Slow Sand Filters and New Treatment Plant Designs in Rural Cameroon”, ”, in Graham, N., & Collins, R., (Ed.s), Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, pp. 359-369.

Ellis, K.V., (1985), “Slow Sand Filtration”, CRC Critical Reviews in Environmental Control, Vol. 15, Issue 4, pp 315-354.

Galvis, G., Latorre, J., & Visscher, J.T., (1998), “Multi-stage Filtration: an innovative water treatment technology”, Technical Paper No. 34, Order Code TP 34-E, ISBN 90-6687-028-1, www.irc.nl/page/1894 A technical paper reviewing multi-stage filtration (MSF, the use of gravel pre-filters in combination with SSFs). This text describes each treatment stage, its design criteria, removal efficiencies, operation and maintenance requirements and costs. Guidelines are also provided for selecting the appropriate combination of MSF treatment processes based on the quality of the raw water.

Graham, N.D.J. (Ed.), (1988), “Slow Sand Filtration – Recent developments in slow sand filter technology”, Ellis Horwood Series. A selection of papers reviewing research undertaken in the 1980s regarding SSFs.

In particular:

- Mbwette, T.S.A., & Graham, N.J.D., (1988), “Pilot Plant Evaluation of Fabric Protected Slow Sand Filters”, in Graham, N.J.D., (Ed.), Slow Sand Filtration – recent developments in water treatment technology, Ellis Horwood Ltd., pp. 305-329.
- Lloyd, B.J., Pardon, M., & Wheeler, D., (1988), “The Performance of Slow Sand Filters in Peru”, Slow Sand Filtration: Recent Developments in Water Treatment Technology, Graham, N.J.D., (Ed.), Ellis Horwood Ltd., pp. 393-411.
- Visscher, J.T., (1988), “Water treatment by slow sand filtration considerations for design, operation and maintenance”, in Graham, N.J.D., (Ed.), Slow Sand Filtration – recent developments in water treatment technology, Ellis Horwood Ltd., pp. 1-10.
- Toms, I.P. & Bayley, R.G., (1988), “Slow Sand Filtration: an approach to practical issues”, in Graham, N.J.D., (Ed.), Slow Sand Filtration – recent developments in water treatment technology, Ellis Horwood Ltd., pp. 11-28.

Hendricks, D., (Ed.), (1991), “Manual of Design for Slow Sand Filtration”, Barrett, J.M., Bryck, J., Collins, M.R., Janois, B.A. & Logsdon, G.S., (authors), published by AWWA Research Foundation and American Water Works Association, Denver, Colorado. A comprehensive review of factors to consider when planning, designing, constructing, operating and maintaining a SSF system. Small and large scale scenarios discussed.

Huisman, L., & Wood, W.E., (1974), “Slow Sand Filtration”, World Health Organisation, Geneva. Comprehensive review of SSF treatment theory, design and construction, operation and maintenance and artificial recharge. This document is on line at http://whqlibdoc.who.int/publications/9241540370.pdf

Jordan, T.D. Jnr., (1980), “A Hand-book of Gravity-Flow Water Systems for Small Communities”, Intermediate Technology Publications, UNICEF. A manual detailing pre-design procedures (e.g. feasibility studies, topographic surveys, estimating design period and population water demands) as well as the steps required for full scale design of gravity-flow water systems (e.g. pipeline construction, design of the intake and treatment processes, flow control systems etc). Hydraulic theory is explained and construction materials reviewed.

Lloyd, B., & Helmer, R., (1991), “Surveillance of Drinking Water Quality in Rural Areas” published on behalf of the World Health Organisation and the

United Nations Environment Programme, Longman Scientific and Technical, Longman Group UK Ltd. A comprehensive review of water surveillance methods (e.g. how to undertake a sanitary survey). This reference also reviews bacteriological and physico-chemical water analyses, provides water surveillance case studies, explains how water surveillance results can be analysed and reviews remedial action.

Logsdon, (Ed.) (1991), “Slow Sand Filtration – a report prepared by the Task Committee on Slow Sand Filtration” published by American Society of Civil Engineers. A selection of papers discussing SSF theory, raw water quality appropriate for treatment and concepts for pre-treatment, removal of micro-organisms, design and operation of SSFs, construction and maintenance costs and pilot plant studies.

Logsdon, G.S., Kohne, R., Abel, S., & LaBonde, S., (2002), “Slow Sand Filtration for Small Water Systems”, Journal Environ. Eng. Sci. Vol. 1, No. 5, pp. 339-348.

Smet, J., & van Wijk, C., (2002), “Small Community Water Supplies – Technology, People and Partnership”, Technical Paper Series 40, International Water and Sanitation Centre, www.irc.nl/page/2481

Visscher, J.T., Paramasivam, R., Raman, A. & Heijnen, H.A., (1987), “Slow Sand Filtration for Community Water Supply – planning, design, construction, operation and maintenance”, Technical Paper Series 24, June 1987, International Reference Centre (IRC) for Community Water Supply and Sanitation, The Netherlands. Principles of slow sand filtration, the design process, costs, planning a SSF, structural design considerations, design examples, construction guidelines, operation and maintenance procedures.

WHO, (1996), “Guidelines for Drinking-Water Quality – Health Criteria and other Supporting Information”, Second Edition, World Health Organisation, Geneva. This information is made available by the WHO in pdf format at http://www.who.int/water_sanitation_health/dwq/gdwq2v1/en/index.html

8 Useful Links

Slow Sand Filter Design and Construction Guidelines for Household and Small Community Scale SSFs

- WELL www.lboro.ac.uk/well/resources/technical-briefs/technical-briefs.htm (‘Water Treatment 2’,Technical Brief 42).
- Brikké & Bredero (2003) at www.who.int/water_sanitation_health/hygiene/om/en/linkingchap6.pdf
- Medair www.medair.org/sandfilter/default.htm
- Centre for Affordable Water and Sanitation Technology CAWST www.cawst.org/technology/waterteatment/filtration-biosand.php

9 Glossary of Terms

Air Binding - the presence of gas bubbles in the media bed, causing increased headloss and possible disruption of the bed on their release (Hendricks, *et al*, 1991).

Algal bloom – prolific algal growth that arises due to the provision of ideal environmental conditions for algal growth (e.g. temperature, sunlight hours, sunlight intensity, nutrient supply etc). Algal blooms typically occur in temperate regions in the spring and late summer months. Algal blooms can cause problems with the operation of the SSFs and may shorten run lengths (Section 2.2.6).

Bacteria - bacteria are the primary colonisers of the media surfaces in a SSF and will usually dominate the microbial community found in the biofilm. The presence of bacteria living in the SSF bed is fundamental (i.e. beneficial) to the treatment of filtering water. Bacteria living on the sand grains feed on impurities in the water as it filters passed. However presence of bacteria in treated (filtered) water is undesirable as some are pathogenic (disease-causing).

Bed – a term used to describe the media (as a whole) in a SSF.

Biofilm – the biologically active film that coats the media grains of a SSF and consists of micro-organisms and EPS. The biofilm enables a greater variety and number of micro-organisms to exist in the SSF and therefore assists in removing contaminants.

Design Flow – the maximum daily flow for a projected population (Hendricks *et al*, 1991).

Diatom – the common name for a member of a group of microscopic one-celled algae with the cell wall composed of two overlapping valves (containing silica) that fit together like the two halves of a box (Robinson & Davidson, 1996).

Drain-down period – the time period during which the supernatant is drained for maintenance procedures. The drain-down period should be minimised in order to minimise the ripening period.

Effective Size (ES) or Effective diameter (d_{10}) - the size of aperture through which 10% by weight of the material (e.g. sand) will pass (Hazen, 1980). See Table 6 for typical ES values for SSFs.

Eutrophication – when a water body becomes enriched with nutrients (e.g. phosphorous and nitrogen) this induces excessive growth of aquatic plants.

Eutrophication results in oxygen depletion of the water body, which is undesirable for water being treated for drinking water supply.

Extracellular polysaccharides (EPS) – a ‘slimy’ substance produced by most bacteria in order to protect themselves (e.g. against famine and desiccation) and which assists in their attachment to the media grains. EPS together with a microbiological community make up the biofilm that surrounds the media grains and assists in the treatment of filtering water.

Fermentation - The breakage of the bonds in organic molecules results in the release of energy (O’Neil, 1998).

Fines – the smallest particles in unwashed sand (Hendricks *et al*, 1991).

Headloss – the loss of media permeability due to filter clogging. Headloss increases the resistance to flow and increases with the time elapsed into a filter run. Eventually the headloss through the bed prevents the SSF from being operable at nominal surface loading rates and the filter must be drained and skimmed. The headloss at the end of a filter run is the ‘terminal headloss’.

Inlet chamber – the front end of the SSF system, where flow control systems are located on an inlet controlled SSF. It usually comprises a box, with water entering from a pipe (fitted with regulating valve) on one side. The water level in the inlet box is allowed to rise up to a level at which it flows over into the SSF box (Figure 4.5). Another valve located on a pipe exiting the bottom of the inlet box allows rapid drainage of the supernatant (Ellis, 1985). This set up also allows the supernatant water level to be controlled (Visscher *et al*, 1994). For inlet controlled SSFs the inlet structure must incorporate a device to enable flow measurement.

Insect vector route – the spread of disease by insects that either breed in water, or bite near water (Feachem & Cairncross, 1993). As with water-based diseases, potable water supply can reduce transmission of these diseases by reducing the need to frequent untreated surface water sources. Covering water treatment processes such as SSFs and sedimentation ponds is necessary to prevent the encouragement of disease transmission via the insect vector route.

Interstices – the pore spaces in the media bed (spaces in between the media grains).

Manometers – clear plastic tubing used to enable headloss measurement in SSFs (Section 4.1.4.1). Sometimes also described as piezometers.

Media – the material through which water is filtered, for example in the case of SSFs this is usually sand.

Micro-organism – a microscopic (not visible to the naked eye) organism consisting of a single cell, a cell cluster, also including the viruses. Size varies, for example a single cell may only have a diameter of 1µm, whereas a rod-shaped micro-organism may be 5µm long and 1µm across (Brock *et al*, 2000).

Negative Pressure – when the pressure in the SSF drops to the extent that gases that are dissolved in the filtering water precipitate (i.e. forming of gas bubbles). These can then cause problems with air-binding (and possibly media disturbance). Negative pressure is undesirable in a SSF and can be avoided by ensuring that the tail water of the SSF rises to an elevation above the surface of the sand bed.

Nominal – theoretical, rather than actual (Robinson & Davidson, 1996). The value of some property (e.g. surface loading rate) of a device at which it is supposed to operate, under normal conditions, as opposed to actual value (Parker, 1994). Nominal surface loading rates refer to those that prevail for a given filter at a given site.

Outlet chamber – the tail end of a SSF system, where the flow control systems are located on an outlet controlled SSF. It usually comprises two sections separated by a wall on top of which a weir is located such that the overflow of water is slightly above the level of the filter bed's surface (Visscher *et al*, 1987). See Section 4.2.13.

Photosynthesis – the process by which the sun's energy is converted into chemical energy by some organisms thus enabling them to grow and carry out normal functions. Oxygen is produced during this process. Photosynthesis is a process restricted to daylight hours only.

Pilot Plant Filter – a small scale version of a proposed full scale filter used to investigate optimal design parameters in advance of the full scale build. This is a pre-design recommendation (Section 3.9).

Porosity - typically in the region of 37-40% for SSF sand media. If a SSF sand bed is saturated with water (assuming water completely fills the interstices), then the porosity may be defined as the percentage of the total volume of the sand bed that is occupied by water. A porosity of 37% causes water travelling onto the filter bed at a rate of v m/h to have an increased velocity of ((100/37) x v) m/h whilst passing through the interstices of the sand grains.

Protozoa – Organisms found in the SSF bed that assist in the removal of impurities from filtering water and which prey upon other micro-organisms in the filter bed. They are usually comparatively large in size and may be motile (Brock *et al*, 2000). Their presence in the SSF is beneficial to the treatment process, however they are undesirable in filtrate water as some are pathogenic (disease-causing).

Ramping up – an operational term used to describe the stepped increase in SSF surface loading rate after it has been stopped (usually for skimming or other maintenance).

Re-instatement – the complete excavation of a SSF bed and its replacement by a clean bed of media.

Respiration – the process by which some organisms obtain energy by oxidising chemical compounds. During aerobic respiration (in the presence of oxygen), oxygen levels in the filtering water are depleted. Most micro-organisms in a SSF respire in this way. During anaerobic respiration (which occurs in a SSF when DO levels for the filtering water are low) alternatives to oxygen are used to respire. The products of anaerobic respiration in filtrate are highly undesirable, therefore DO levels in a SSF must be kept high enough to ensure respiration is predominantly aerobic (i.e. filtrate DO levels >3mg/l, Huisman & Wood, 1974).

Ripening – the period of time immediately after a SSF is re-started, during which time the filtrate water is of poor quality and must be discarded. Ripening periods vary with environmental and operational factors. This is discussed in Section 5.1.6 and Section 5.2.7.

Run/Run length – the period of time (usually in days) for which a SSF operates between skimming. The period of time after a SSF is started that it takes to reach terminal headloss.

Shear stress – shear stress in a flowing liquid is the force exerted by one layer as it moves past another. In biofilms, the term shear stress is often used to describe wall shear stress, which is the shear stress at the wall (biofilm surface) caused by the liquid moving past it (CBE, 2004).

Skimming – the process of scraping off the top 1-3cm of a SSF bed in order to maintain its operation. Skimming is necessary when terminal headloss has been reached.

Supernatant – the water that sits above the bed and provides the driving head for flow through the media. Also termed top-water.

Surface loading rate – the hydraulic load (m^3/h) per unit cross-sectional area of a filter bed (m^2), normal to the direction of flow. Also sometimes described as filtration rate and flow rate, although these terms quantify the velocity of filtering water.

Terminal Headloss – see Headloss.

Throughput – the volume of water treated by the water treatment process(es). For example, daily site throughput is the volume of water treated by the site within a 24 hour period.

Trenching - This involves first skimming the SSF (Section 5.2.3). Then the remaining old bottom sand is removed and put to one side. The appropriate depth of clean sand is placed on top of the gravel layer and then the old bottom sand is put back into the bed, over the top of the clean sand (Figure 5.2). Trenching is discussed in Section 5.2.4.

Turbidity – turbidity quantifies the degree to which light travelling through a water column is scattered and absorbed by suspended organic (e.g. algae) and inorganic (e.g. clay, silt) particles (WHO, 1996). In simple terms it is a measure of the clarity of water. High turbidity levels in raw water require it to be pre-treated in advance of SSFs (Section 3.3).

Uniformity coefficient, UC, d_{60}/d_{10} – the ratio of the sieve size through which 60% of the media (e.g. sand) will pass, to the size through which 10% will pass (Hendricks *et al*, 1991). For most SSFs this is below 2 (Kiely, 1998). See also Table 6.

Venturi flume – a tube or duct which is narrow in the middle and wider at both ends, used in measuring the flow rate of fluids. Named after Italian physicist G.B. Venturi (1746-1822, Robinson & Davidson, 1996).

Water-borne – a route by which disease may be transmitted from one person to another where the pathogen is in water which is drank by a person, which then may become infected (Feachem & Cairncross, 1993).

Water-washed – a transmission route for a disease (e.g. of the intestinal tract, skin, eyes or disease carried by lice) where improvements in hygiene significantly reduce its transmission between people. Hence the transmission depends on the quantity of water used rather than the quality (Feachem & Cairncross, 1993).

Water-based disease – a water-based disease is one whose pathogen spends part of its lifecycle in a water snail or other aquatic animal. Providing a potable water supply reduces the incidence of these diseases by reducing the need for contact with untreated water sources (e.g. river water, Feachem & Cairncross, 1993).

Weir – A device for measuring the flow of a liquid in an open channel. The rate of flow is proportional to the head (i.e. height of water) over the weir. A weir re-oxygenates filtrate water, and also helps prevent negative pressure conditions from developing in the filter bed (Visscher *et al*, 1987).