16 Multi-stage filtration technology

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16.1 Introduction

The technology of multi-stage filtration (MSF) presented in this chapter is a combination of coarse gravel filtration (CGF) and slow sand filtration (SSF). This combination allows the treatment of water with considerable levels of contamination, well above the levels that can be treated by SSF alone. MSF retains the advantages of SSF in that it is a robust and reliable treatment method that can be maintained by operators with low levels of formal education. It is much better suited than chemical water treatment to the conditions in rural communities and small and medium-sized municipalities in the South and in more remote areas in the North. Other treatment processes such as simple sedimentation, sand traps and screens can precede MSF technology. Wherever possible, terminal disinfection needs to be included as a safety barrier after the MSF. This chapter provides a summary description of the components of MSF systems. It gives an overview of indicative cost implications and ends with a selection guide.

16.2 Slow sand filtration technology

There are some typical operational differences between SSF and rapid filtration (RF) units. Filtration rates are around 50-150 times lower for SSF. Flow retention periods are about 30-90 times longer for SSF. Filter run lengths are about 30-90 times longer for SSF, and the surfaces of the SSF units are usually scraped at the end of the filter runs, whereas RF units are cleaned by backwashing. These differences originate from the most distinctive feature of SSF, its biological life. The water treatment in SSF is the result of a combination of physio-chemical and biological mechanisms that interact in a complex way.

Inorganic and organic matter enter the SSF units in the raw water. Photosynthesis gives rise to another fraction of organic matter. Soluble matter in the sand bed is utilised by bacteria and other micro-organisms. Zooplankton grazing occurs and respiration of the entire biomass is continuous.

The principal physical mechanisms contributing to particle removal are surface straining, interception, transport, and attachment and detachment mechanisms. Physical particle removal in SSF is not exactly the same as in RF since in RF the particles have previously been destabilised by chemical coagulants and the biological activity is not so relevant.

Design characteristics of slow sand filtration units

In an SSF treatment plant at least two units should operate in parallel for continuous supply. A unit basically consists of a structure that contains flow control and drainage systems, a supernatant water layer and a filter bed (Fig. 16.1).

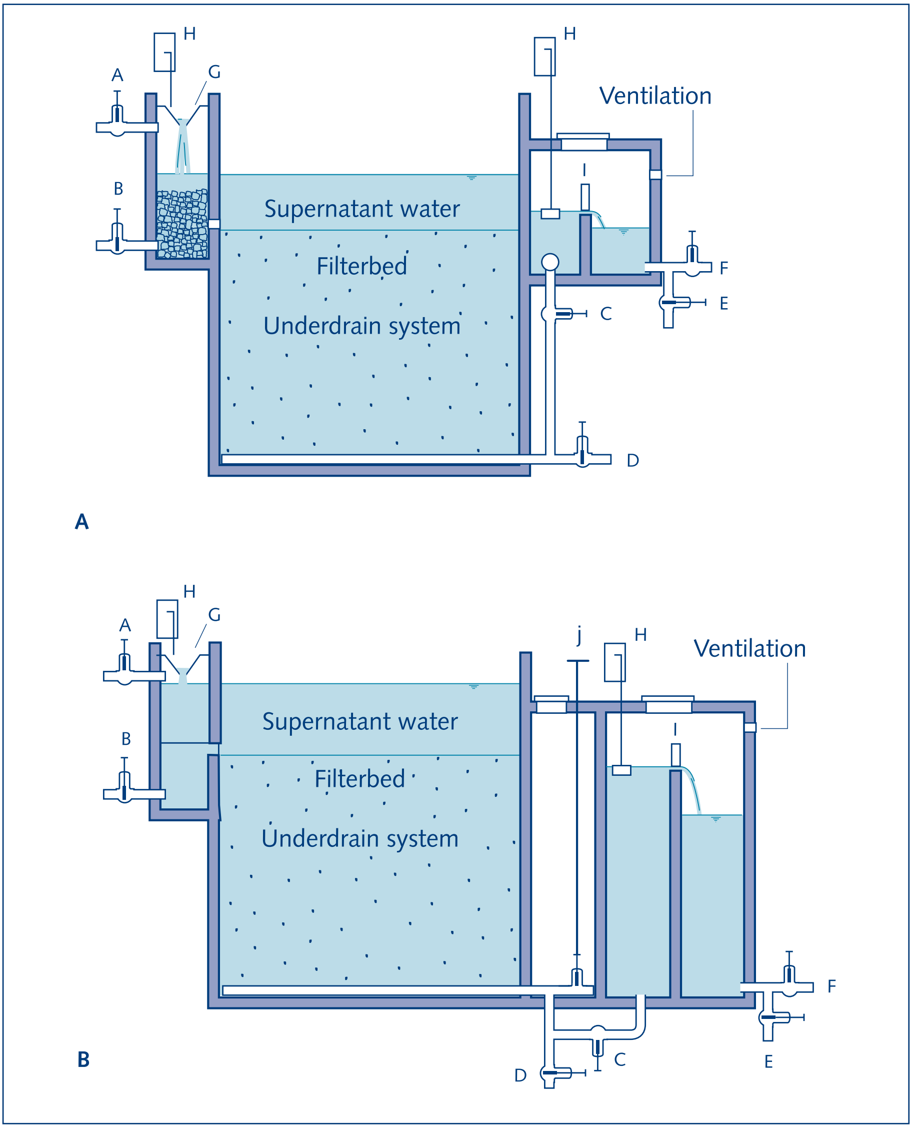


Fig. 16.1. Basic components of SSF units with inlet (A) and outlet (B) flow control

A: Inlet valve to regulate filtration rate

B: Valve to drain the supernatant layer of water

C: Valve for backfilling unit with filtered water

D: Valve to drain the filter bed

E: Valve to waste filtered water

F: Valve to contact tank or water storage

G: Inlet weir

H: Calibrated flow indicator

I: Outlet weir

J: Outlet control valve

Flow control systems

Controlling the flow in SSF units is necessary to maintain the proper filtration rate through the filter bed and the submergence of the media under all conditions of operation. Abrupt filtration rate increases should be avoided. Two types of flow rate control are used, outlet- and inlet-controlled flow.

In an outlet-controlled filter the supernatant water level is kept close to the maximum desired level above the filter bed. To control the flow rate, the outlet valve is gradually opened to compensate for the increase in the head loss over the filter media. This is the usual control method in Europe and has been adopted in some of the units built in the Americas. The storage capacity above the sand bed provides for some equalisation of the influent water quality, sedimentation of heavier particles, and time for some biological activity, as well as some buffer capacity.

In inlet-controlled filters any increase in head loss is compensated by an increase in the height of the supernatant water. Some researchers have found similar performance in terms of effluent water quality, head loss in the filtering bed, and filter run times for inlet- and outlet-controlled SSF units run in parallel, with filtration velocities in the range of 0.13-0.5 mh^{-1}. In the inlet flow control option, the inlet box has several purposes. It provides flow control, reduces excess energy to protect the filtering bed from scouring, facilitates flow distribution to the SSF units filtering in parallel, and permits possible overflow.

The drainage system consists of a principal drain with lateral branches, usually constructed in perforated pipes, brickwork or tiles and covered with a layer of graded gravel and a layer of coarse sand. The drainage system of SSF has to achieve the following functions:

- Support the filter material and prevent it from being drained from the filter
- Ensure uniform abstraction of the water over the filter unit
- Allow for the backfilling of the filter and drive out possible air pockets

The main drain should discharge the filtered water freely at atmospheric pressure into the outlet box. A flow indicator is required at both inlet and outlet side of the units to facilitate operational procedures and to verify water balance, as an indication of possible water losses in the main filtering boxes. The outlet weir is also necessary to maintain the supernatant water layer above the maximum level of sand, protecting biological activity, preventing pressure drops in the filter bed, and ensuring the functioning of the units independently of the level fluctuations in the contact or storage tanks.

Supernatant water layer

The layer of supernatant water provides the static head necessary for the passage of water through the sand bed. In a clean bed the initial head loss is usually below 0.1 m and it gradually increases until the maximum level is reached. In units with outlet control, variations of the supernatant depth for small systems have been reported in the range of 0.6-1.2 m. At the Weesperkaspel plant in Amsterdam, where the SSF units deal with highly pre-treated water, the average supernatant water height is 2 m. Filter shading may contribute to improve filter runs if significant production of filter-blocking algae is occurring on the filter skin or in the supernatant water layer, but few definitive advantages in terms of filtrate quality have been reported.

Filter bed

The adequate selection of sand includes size grading, characterised by the effective size diameter d_{10}, and the uniformity coefficient, uc = d_{60}/d_{10}. Huisman and Wood (1974) advise that d_{10} should be small enough to produce safe water and to prevent penetration of clogging matter to such depth that it cannot be removed by surface scraping. Experiences in the USA report a total coliform removal reduction from 99.4% at d_{10} of 0.1 mm to 96% at d_{10} of 0.6 mm.

Deeper sand beds should result in improved removal of particles. However, due to the development of the filter skin and the biological activity concentrated mainly in the upper sand layers, particle removal is more effectively accomplished in this part of the SSF units. Experimental evidence supports the practice of having a minimum sand depth of 0.3-0.5 m in the SSF units to achieve more than one log reduction of indicator bacteria. This is relevant for small systems working with low flow rates (0.1-0.2 mh^{-1}), but having to filter at higher rates during short periods due to their lower buffering capacity when one of the units is out of operation.

The sand to be put into the SSF units should be clean and free of clay, earth and organic material. The presence of dust or fine material produces high initial head losses and seems to limit the essential development of an active and effective microbial population in the filter bed. Placing dirty sand in the filter may interfere with the treatment process and makes it necessary to remove the sand earlier for correct washing.

Operation and maintenance procedures

SSF units must operate continuously, since this contributes to better quality effluents and a smaller filtration area is required for a given daily water production. Declining-rate filtration can be applied, but intermittent operation should be avoided, since oxygen depletion in the bed compromises biological activity. Research carried out in India reports deterioration of effluent bacteriological quality when filters recommence operation after 5 hours. In the USA, initial ripening periods in the range of 35-100 days were identified before the effluents of the SSF units became stabilised for parameters such as viruses, indicator bacteria and turbidity.

After several weeks or months of running, the SSF unit will gradually become clogged as a result of the accumulation of inorganic and organic material, including the biomass that is formed on top of the filter bed. The major increase in head loss occurs in this top layer. By scraping off this layer, the hydraulic conductivity is restored to the level at the beginning of the filter run. Classically, this is achieved by scraping the top 1-3 cm of the filtering bed. After several scrapings, when the filter bed reaches its minimum depth (0.3-0.5 m), resanding is required.

Manual cleaning has been the option for most small SSF units. In general, a high frequency of scraping is associated with one or more of the following factors: high solids concentration in the raw water; growth of algae in the supernatant water; small media grains; low available head; and high water temperature. The filter runs (periods between scrapings) of small SSF units in the USA range from one week to one year, with the average about 1.5 months. There, manual scraping labour requirements are in the range of 1.3-8 (average 4.2) person-hours per 100 m^2 of area scraped. The labour requirement increases significantly when the depth scraped is greater than about 2.5 cm. Filter runs for small systems could vary in the range of 20-60 days and, for cycles shorter than 1.5 months, labour costs will escalate and operator satisfaction with the plant will diminish.

After scraping the sand surface, a secondary ripening period may be necessary for the SSF units to recover their previous treatment capacity. Values in the range of 0-10 days have been recorded for this secondary period. The most important factor affecting the duration of a secondary ripening period appears not to be the removal of the filter skin, but the dewatering of the sand bed. The cleaning is best done in warm periods and by keeping the water table within 10 cm of the sand surface. This procedure ensures that spirotrichs and peritrichs protozoa are retained in the sand (inoculation); they are susceptible to desiccation and are unable to re-establish themselves at less than 3°C.

Scraped sand should be washed and stored. After several filter runs this activity leads to a gradual reduction of the sand bed depth until a minimum value, usually in the range of 0.3-0.5 m, is reached. Then re-sanding becomes necessary. For resanding, the remaining sand in the filtering bed should be lifted to become the top portion, with the stored and washed sand becoming the bottom. In this way the sand on top of the filtering bed should provide seed organisms to shorten the ripening period. Resanding in the USA requires around 50 person-hours per m^2.

The wet-harrow cleaning technique uses a horizontal and sometimes vertical pressurised water flow below the sand surface for washing across the filter skin being harrowed, without dewatering the sand beds. The wash water is passed out via a surface overflow weir. Shorter cleaning and ripening periods have been recorded with this technique in the USA, where it is applied in SSF units treating clear raw waters with low turbidity.

Design guidelines

Great differences exist in the application of SSF technology around the world, as it depends on drinking water quality standards, raw water quality, the type and level of pre-treatment specified; and the local conditions. These conditions include institutional development and support capacity to community-based organisations, availability of materials and financial resources, user income, and willingness to contribute to capital investment and running costs of the water supply infrastructure.

Design criteria presented by various authors and based on different experiences and conditions are summarised in table 16.1. Those recommended by Visscher et al. (1987), although oriented worldwide, were considered adequate for small systems in the USA, where the experience with SSF was being re-established. The last column in table 16.1 corresponds to the design criteria proposed by Cinara - IRC based on planning, design, monitoring and evaluation of over 100 SSF systems built in Colombia and other Latin American countries.

Table 16.1 Comparison of design criteria for slow sand filtration from various authors

Design criteria	Recommendation			
	Ten states standards USA (1987)	Huisman and Wood (1974)	Visscher, et al. (1987)	Cinara – IRC (1997)
Design period (years)	Not stated	Not stated	10 -15	8 - 12
Period of operation (hd^{-1})	24	24	24	24
Filtration rate (mh^{-1})	0.08 - 0.24	0.1 - 0.4	0.1 - 0.2	0.1 - 0.3
Sand bed: Initial height (m)	0.8	1.2	0.9	0.8
Minimum height (m)	Not stated	0.7	0.5	0.5
Effective size (mm)	0.30 - 0.45	0.15 - 0.35	0.15 - 0.30	0.15 - 0.3
Uniformity coefficient:	Not stated	< 3	< 5	< 4
Acceptable	≤ 2.5	< 2	< 3	< 2
Support bed. Height including drainage (m)	0.4 - 0.6	Not stated	0.3 - 0.5	0.25
Supernatant water. Maximum height (m)	0.9	1 - 1.5	1	0.75
Freeboard (m)	Not stated	0.2 - 0.3	0.1	0.1
Maximum surface area (m^2)	Not stated	Not stated	< 200	< 100

Water quality limitations of slow sand filtration

Slow sand filtration has been recognised as a simple, reliable and efficient treatment technology and a most effective unit treatment process in improving water quality. However, SSF does not necessarily remove all harmful substances to the extent required by relevant drinking water quality standards. Table 16.2 presents typical treatment efficiencies that SSF can achieve. The reported efficiencies have normally been achieved in filter units operated at filtration rates in the range of 0.04 and 0.20 mh^{-1}, temperature above 5°C, and sandbed depths greater than 0.5 m.

The efficiencies in table 16.2 cannot always be achieved though, because much depends on the nature, composition, and concentration of the components in the influent waters; and the effect of design parameters, and ambient and operating conditions. Even if high removal efficiencies can be obtained, SSF alone cannot always produce water of a high standard. Raw water sources in many countries are already so deteriorated that a combination of treatment processes is required to meet water treatment objectives or national drinking water standards

Clearly, SSF, like all other treatment processes, is not a panacea for every water quality problem. In general, two situations can be identified under which SSF presents limitations:

- Levels of contamination in the raw water may exceed the treatment capacity, or may result in short filter runs to comply with existing standards;
- Conditions that inhibit or reduce the efficiency of the treatment process.

Levels of contamination that exceed the treatment capacity

Suspended solids or turbidity. The most frequently mentioned limitation of SSF when it is used as a single treatment step is its inability to treat water with a high level of suspended solids or turbidity. These solids can create major increases in head loss and adverse conditions for the biomass active in the filtering bed. Even short peaks of solids may bury the large number of bacterial predators present in the sand bed and thus reduce their capacity to remove harmful micro-organisms. This important potential reduction in biological performance is, however, rarely cited in the technical literature, despite the fact that it may have a very negative effect on the quality of the treated water. The literature seems to focus instead on the difficulties of treating water sources with small particles of a colloidal nature or the impact of high concentrations of particulate matter on the duration of filter runs.

To prevent high effluent turbidity, frequent blockage of the filter bed (filter runs shorter than one month) or an environment that is unfavourable for microbiological activity, upper limits are usually specified for the influent turbidity. The limits vary, however, between < 5 NTU and < 50 NTU. Furthermore, the majority of the references accept higher values in the range of 50-120 NTU, provided these are of short duration, i.e. less than few hours to 1-2 days, though they recognise these high limits as undesirable. Nevertheless, turbidity alone is not sufficient to identify the limitations associated with the duration of filter runs.

Table 16.2 Treatment efficiencies of slow sand filters (Galvis et al., 1992a; Fox et al., 1994; Lambert and Graham, 1995)

Water quality parameter	Performance or removal capacity	Comments
Enteric bacteria	90-99.9%	Reduced by low temperatures; increased hydraulic rates; coarse and shallow sand beds; and decreased contaminant level
Enteric viruses	99-99.99%	At 20°C: 5 logs at 0.2 mh^{-1} and 3 logs at 0.4 mh^{-1} At 6°C: 3 logs at 0.2 mh^{-1} and 1 log at 0.4 mh^{-1}
Giardia cysts	99-99.99%	High removal efficiencies, even directly after cleaning (removal of the filter skin)
Cryptospori-dium	> 99.9%	Cryptosporidium oocytes. Pilot scale studies
Cercaria	100%	Virtually complete removal
Turbidity	< 1 NTU	The level of turbidity and the nature and distribution of particles affect treatment capacity
Pesticides	0-100%	Affected by the rate of biodegradation
DOC[1]	5-40%	Mean around 16%. Removal appears to be site specific and varies with raw water and O&M
UV-absorbance (254 nm)	5-35 %	A slight, but not significant difference in treating upland and lowland water sources. Mean 16-18% Colour associated with organic material and humic acids.
True colour	25-40%	Colour associated with organic material and humic acids. 30% being the average
UV-absorbance (400 nm)	15-80%	Colour (°Hazen). Mean 34%, but upland water sources 42% and lowland water sources 26%
TOC[2]; COD[3]	< 15-25%	Total organic carbon; chemical oxygen demand
AOC	14-40%	Assimilable organic carbon. Mean about 26%.
BDOC	46-75%	Biodegradable dissolved organic carbon. Mean 60%
Iron, manganese	30-90%	Fe levels > 1 mgl^{-1} reduce the filter runs

1. DOC = dissolved organic carbon
2. TOC = total organic carbon
3. COD = chemical oxygen demand

Turbidity is accepted as an indirect indicator of the presence of particulate matter, because of its ease of application. This parameter does not always properly reflect the load of solids that the filter receives though, particularly if the particles are of an organic nature such as algae. In addition, very few recommendations exist about the maximum load of suspended solids (SS) an SSF can accept. Technical literature suggests a SS load below 5 mgl-1 but without evidence related to the impact of this level of SS on SSF units.

Iron and manganese. Bacteria that contribute to the oxidation of iron and manganese are present in the filter bed. Small quantities of iron deposits improve the removal capacity for organic components. On the other hand, high concentrations of iron (above 1 mgl^{-1}) may contribute significantly to the clogging of the SSF unit.

Algae. Algae may grow in rivers, lakes, storage reservoirs, or even in the supernatant of the SSF. The presence of algae in moderate quantities is usually beneficial for functioning of the SSF units. Most algae are retained by the SSF, but under certain conditions occasional and significant algal growth or algal blooms may develop. This massive growth can cause a quick reduction of the permeability of the filtering bed, greatly reducing the filter run. Algae may also play an important role in the production of high concentrations of soluble and biodegradable organic material in the water, which in turn create smell and taste problems, and contribute to microbial growth in the distribution system. Furthermore, as a result of photosynthesis, algae may affect the buffer capacity of the water and increase the pH to levels of 10 or 11. This can result in the precipitation of magnesium and calcium hydroxides in the sand bed (calcification) and contribute to the obstruction of the filter bed, increase the effective diameter of the sand, and reduce the efficiency of the process.

Controlling algae is difficult, but possible methods are based on reducing the nutrient content of the raw water, or creating a storage system or a supernatant environment in which algae can be controlled by the exclusion of light. This is done by covering the filters. Before investing in covers for the SSF, it is prudent to check if standard operation and maintenance procedures are not enough to manage moderate quantities of algae by occasional harvesting. Different levels have been established for the concentration of algae and other parameters (table 16.3).

Organic colour and organic carbon. A limitation of SSF is its low efficiency in the removal of organic colour and organic carbon. In fact, some studies report no removal at all and others indicate TOC and COD removal in the range of 15-19%. However, there are also studies reporting COD removals in the range of 50-68%. The discrepancy lies in the diverse composition of organic compounds, which are grouped together under surrogate parameters such as COD or TOC. SSF units generally remove between 5 and 40% of DOC, although the mean value is only 16%, and the difference between upland and lowland water sources is not significant (data from wide literature review).

True colour. True colour removal, as colour units of Pt-Co in filtered or centrifuged samples, includes only colloidal and soluble substances, especially natural organic matter. The removal of true colour is normally reported to be in the range of 25-30%. Because of the potential formation of disinfection by-products in the presence of organic material, low colour levels are desirable. The colour level, however, should not determine the application of final disinfection, as the risk of acute microbiological contamination is far more significant.

Heavy microbiological contamination. In some communities the only source available for water supply may be so heavily contaminated with harmful micro-organisms that SSF alone will not be able to produce a good quality effluent. Whilst long-term efforts are directed at protecting catchments, pre-treatment of the raw water may be necessary before SSF can be properly applied.

Conditions that inhibit or reduce the efficiency of the treatment process

Various circumstances can interfere with the treatment process in the SSF units and prevent the expected efficiencies from being obtained. Some of these are related to the short filter runs considered in the previous item. Other important inhibiting conditions are low temperatures, low nutrient content and low dissolved oxygen content.

Low temperature. Low temperature increases the viscosity of water and reduces the biochemical activity in the sand bed, affecting the treatment efficiency. E. coli removal may be reduced from 99 to 50% when the temperature falls from 20°C to 2°C. The strategy in countries that face cold periods during the year has been to cover the filters or to build them underground to prevent the freezing of the units and reduce the impact of low temperatures. This, of course, has considerable economic implications. Reducing the filtration rate is another way to reduce the impact of low temperature on the treatment process.

Nutrients. The micro-organisms active in the sand bed require nutrients such as carbon, nitrogen, phosphorus and sulphur for their metabolism and growth. Humic and fulvic acids are rich in carbon but low in the other elements. This may be part of the explanation for the low removal of natural colour in SSF treating water sources that are well protected. In experimental SSF units, adding nutrients has been shown to increase the biological activity and improve removal efficiency for turbidity and microbiological contamination.

Dissolved oxygen. When the flow velocities and the dissolved oxygen level in the water source are low, particularly if this is combined with a high amount of biodegradable material, the oxygen in the water can be depleted, resulting in anaerobic conditions in the filter skin. This anaerobic condition in the filter must be avoided because it may create serious water quality problems such as bad smell and taste, as well as re-suspension of heavy metals, with aesthetic implications and interference with the final disinfection stage.

In summary, in spite of the potential of the SSF process illustrated in table 16.2, surface waters presenting relatively moderate to high levels of contamination could not be treated directly by conventional SSF units. Far too great a strain would be placed on the terminal disinfection, limiting its role as a final safety barrier. This is critical in most developing countries, where the reliability of disinfection is low.

Table 16.3 Some water quality guidelines that permit direct slow sand filtration treatment

Water quality parameters	Quality limitations based on references of 1991		
	Spencer, et al.	Cleasby	Di Bernardo
Turbidity (NTU) [1]	5 - 10	5	10
Algae (units/ml)	200[2]	5 $\mu g l^{-1}$ [3]	250
True colour (PCU)	15 – 25		5
Dissolved oxygen ($mg l^{-1}$)	> 6		
Phosphate (PO_4) ($mg l^{-1}$)	30		
Ammonia ($mg l^{-1}$)	3		
Total iron ($mg l^{-1}$)	1	0.3	2.0
Manganese ($mg l^{-1}$)		0.05	0.2
Faecal coliforms (CFU/100ml)			200

(1) The type of turbidity and the particle distribution may produce changes in the water quality of the effluent of the SSF.

(2) Both the number and the type of species present in the water source are important. This reference suggests covered filters.

(3) This limit corresponds with chlorophyll-a in the supernatant water as an indirect measure for the algae content.

16.3 Overcoming the water quality limitations of slow sand filtration

Multi-stage and integrated water treatment concepts take advantage of the great potential of SSF technology. They have made it possible to overcome many of the water quality limitations previously identified and to meet drinking water quality requirements. In practice they are not new concepts as can be seen from the gradual evolution of water treatment in two important European cities.

London

By the beginning of the twentieth century, SSF was already accepted as a vital barrier in the provision of safe drinking water in London. A few years later, long-term storage reservoirs and terminal disinfection with chlorine were incorporated as additional treatment steps. Each of these treatment stages was fundamental in contributing to improve drinking water quality. Nevertheless algal growth in the reservoirs and the increased load of suspended solids gradually created premature clogging problems in the SSF units. This problem was overcome in 1923 when the Metropolitan Water Board introduced its first "rapid" sand filter (without coagulants). This double filtration was used without major modifications until the 1980s. The gradual microbial improvement of each step in this four-stage treatment is illustrated in figure 16.2. In the 1990s, to comply with the requirements of the European Community, the treatment plants were improved by including ozone treatment and a layer of activated carbon in the filter bed to increase the biodegradability and the removal of organic compounds and improve the reliability of disinfection.

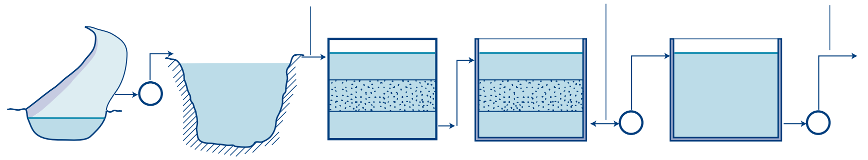


Fig. 16.2. Gradual removal of microbes indicating pollution (Escherichia coli) from a half pint glass (284 ml) of water at each stage of a typical London water treatment plant, based on a 10-year (1961- 1970) average. (Adapted from Windle-Taylor, 1974)

Zurich

The city of Zurich draws its water from three sources: Lake Zurich, groundwater and springs. The first treatment plant with SSF began operation in 1871. Gradually other processes were added due to water quality deterioration and higher water quality standards setting lower acceptable levels of organic contamination. Today lakewater provides 70% of the water supply and is treated in two water treatment plants. In 1975, SSF became the seventh of an eight-stage treatment system comprising: pre-oxidation in the lake water collectors, coagulation/flocculation, pH adjustment, rapid sand filtration, ozone treatment, activated carbon filtration, SSF, and disinfection (Fig. 16.3). Velocities up to 0.7 mh-1 are now applied in the SSF. One of the benefits of SSF in this treatment plant is to contribute to removal of the organic compounds that support biofilm growth in the distribution system, reducing the requirements for high levels of disinfectant residuals.

So, SSF continues to be used as a treatment process in large European cities, but today it is one of the final treatment stages, after quite complex pre-treatment stages. As a result the SSF units receive water of very good quality. Hence, these systems, with reliable operation, maintenance, and management conditions, can operate at high filtration rates of around 0.3-0.7 mh^{-1}. In these European cities the multiple barriers

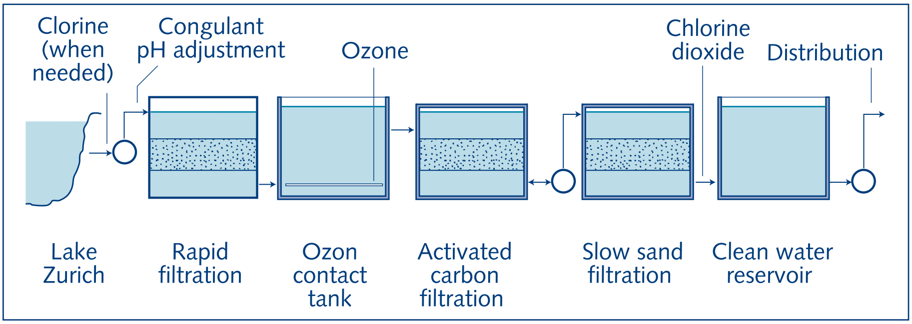


Fig. 16.3. Flow diagram of the water treatment system in Lengg, Zurich (Adapted from Huck, 1988)

strategy and basic water treatment concepts gradually developed from field experience and under the pressure of tighter regulations. To extend the possibility of surface water treatment to rural areas and small towns, these same concepts can be used in identifying, developing and promoting pre-treatment alternatives in harmony with the simplicity of operation and maintenance of SSF.

The search for pre-treatment alternatives for small water supply systems

The adequate use of SSF technology in small systems has often been determined by the availability of good quality water resources, as is apparent from the application of SSF in the USA. Pre-treatment appears to be the *technical* link missing from the SSF technology for small communities with lower raw water qualities. During the last few decades pre-treatment alternatives have been developed to extend the application of SSF to poorer water sources without requiring skilled staff, complex mechanical equipment, or chemical supplies. Some of these methods, such as riverbank filtration (infiltration wells) and riverbed filtration (infiltration galleries), are oriented towards improving surface water quality at the abstraction point. Other methods, using plain sedimentation, are long- and short-term storage, and tilted plate settling. Others are based on coarse filtration, such as dynamic filtration, and horizontal flow, downflow, and upflow gravel filtration.

Infiltration wells

One of the oldest pre-treatment techniques is filtration in infiltration wells or riverbanks along a river or stream (Fig. 16.4). Depending on the surface water quality and the abstraction soil strata, the abstracted water may be acceptable for direct human consumption or to be feed water for SSF units. Experiences with river Rhine water showed that riverbank filtration reduced turbidity from a range of 1-6 NTU to a range of 0.2-0.8 NTU. Trace metals, DOC and COD were also significantly reduced. However some problems were reported with the re-suspension of iron and manganese oxides when the oxygen level in the river fell below 1 mgl^{-1}. Changes in sediment transport in the river may also affect the capacity of the wells. One possible disadvantage of this system is that changes may occur underground, and can be difficult to remedy by maintenance activities.

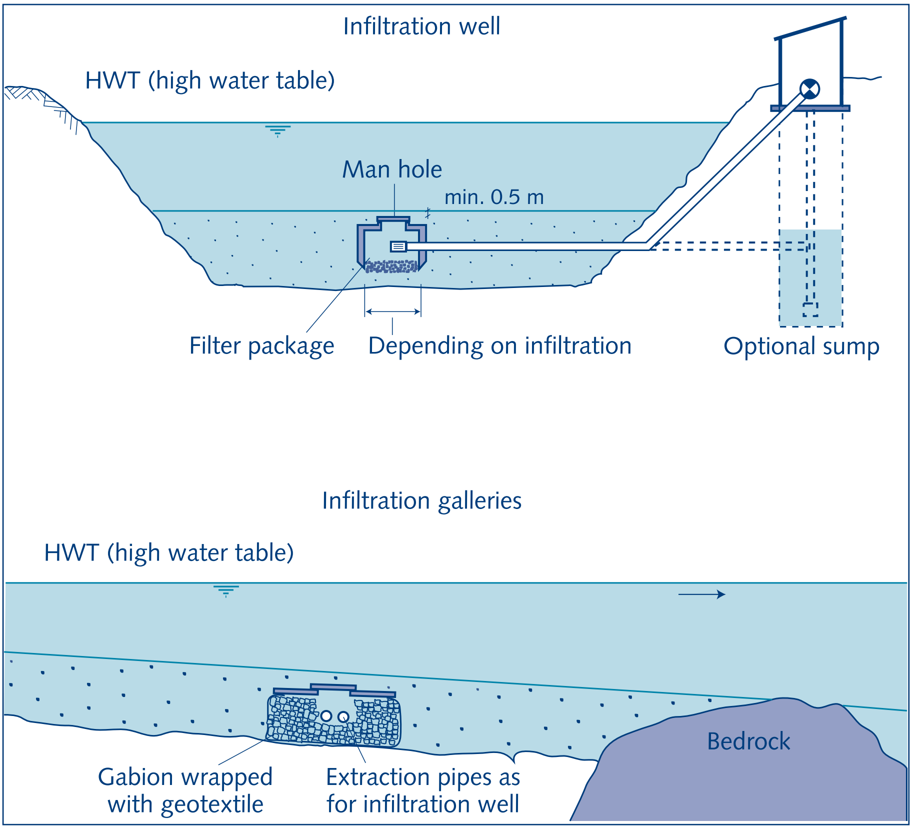


Fig. 16.4. Infiltration wells and infiltration galleries
Source: Wehrle, personal communication; and Galvis and Visscher, 1987

Infiltration galleries

In infiltration galleries or riverbed filtration, water is abstracted using perforated pipes through the natural riverbed material, or if the permeability is too low, through an artificial bed of coarse sand and gravel. Riverbed filtration systems include longitudinal and lateral drain systems, modular sub-sand abstraction, and river dam filtration systems. Flow velocity through the filtering bed ranges from 0.25-1.5 mh^{-1}, depending on turbidity levels and effluent requirements. Removal efficiencies up to 98% have been reported for riverbed dam filtration from rivers with turbidity levels in the range of 48-200 NTU. However, in a field evaluation the efficiencies were found to be around 20%. This may be due to difficulties in implementing periodic cleaning or repositioning of the clogged filtering material, particularly during the rainy season, when the rivers have high flows and high solids transport capacity. Because clogging of the infiltration area can mean reconstruction of the riverbed filter or the infiltration area, pre-treatment filtration alternatives completely separated from the surface water source are receiving more attention.

Plain sedimentation

Exposing the water to very slow or non-moving conditions allows suspended matter to be removed by the action of gravity and natural particle aggregation without the use of coagulants. This process is called plain sedimentation. Ideally, the clarification efficiency of a settling basin, for a particular suspension of discrete particles, depends only on S_0, the surface charge (relation between the flow and the settling surface area). In practice, however, disturbing factors such as turbulence and short-circuiting reduce the effective settling velocity. Plain sedimentation is described in detail in chapter 15.

Tilted plate settlers

Improved flow conditions in the settling zone (laminar and stable flow) and lower values of S_0 (greater surface area for a given flow) can be obtained in a given conventional sedimentation tank by introducing parallel plates set a short distance apart (5-10 cm). To achieve self-cleaning, these plates are tilted or inclined at an angle of 50-60° to the horizontal. Tilted plate settlers may reduce the required area of a conventional settler (without plates) by some 65%. They are widely used in chemical water treatment, but their application with non-coagulated water is very limited. Besides, in small systems, if area is not a critical issue, this option may have comparable capital costs to conventional settling, but higher running costs, since more frequent attention and cleaning is needed because of its lower sludge storage capacity. Tilted plate settlers are also described in chapter 15.

Prolonged storage basins

Plain sedimentation may have long retention times, measured in days or weeks. In this case other factors are important, including wind, thermal, and photosynthetic effects. This usually makes it an expensive solution to be adopted exclusively for water supply purposes in small systems. A classical goal of storage basins is to provide supplies during periods of low rainfall in multipurpose projects, and off-channel storage can provide a source during short-term pollution events. Storage basins can be used as preliminary treatment. Indeed, for extremely turbid waters, above 1000 NTU, storage provides the best pre-treatment. In England the water depth in pumped storage reservoirs is typically about 10-20 m and the theoretical retention time ranges from about 10-50 days. In London, in long-term storage prior to SSF, turbidity reductions from around 30 NTU to below 4 NTU have been reported. As shown in figure 16.2, the average *E. coli* faecal coliform counts were reduced by 96%. However, the periodic blooms of algae made it necessary to introduce microstrainers or rapid filters before the SSF units. Management techniques have been developed to minimise algal blooms and other detrimental water quality effects in the reservoirs. These techniques include pumping devices to control the thermal stratification. The potential of long-term storage to protect SSF in small systems directly or in combination with other treatment steps needs to be evaluated under local conditions, introducing the possibility of a multipurpose reservoir.

Coarse media filtration (CMF)

Porous media such as gravel and sand are old water clarification processes with documented applications in several European countries since the 1800s. Development and promotion of this technology was interrupted with the arrival of chemical and mechanised water treatment technologies. Since the 1970s the use of SSF technology in small WS systems has gained increasing attention because of the potential of CMF to improve the quality of deteriorating surface waters. During the 1980s it became clear that CMF was a good option to condition the water before it reached the SSF units, based on studies conducted in Africa, Asia, Europe, and Latin America. These technologies and new ones are still being developed.

Coarse media filtration as a pre-treatment step for slow sand filtration

Short-term plain sedimentation may be the first conditioning stage of surface waters that transport relatively large and heavy particles, such as grit or sand. However, rivers usually transport a wide range of particles, including those with sizes of less than 10-20 µm. Most streams or small rivers in the tropics have peaks in suspended solids for short durations, giving a high load on the water treatment system; these can happen in the absence of the water treatment plant caretaker.

CMF is considered to be a promising pre-treatment technique for small water supply systems since it is more effective in removing suspended particles than short-term plain sedimentation and because of its ability to maintain treatment simplicity comparable to that of SSF. CMF units are easier to operate and maintain than long-term storage reservoirs and are not dependent on the hydraulic behaviour of streams or rivers, as are riverbank and riverbed filtration, particularly during the rainy seasons in tropical countries.

Classification of coarse gravel filters

Different CMF alternatives using gravel as the filter media are described in the following sections and schematically illustrated in figure 16.5. CMF alternatives have been classified according to the main application purpose and the flow direction as shown in figure 16.5.

Dynamic gravel filters (DyGF)

Dynamic gravel filters include a shallow layer of fine gravel in their upper part and coarse gravel that covers the underdrains. The water enters the unit and passes through the fine gravel to the drainage system. With moderate levels of suspended solids in the source water, the DyGF gradually clogs. If quick changes in water quality occur, the clogging may be much faster. Eventually the gravel bed will be blocked and the total water volume will just flow over the clogged surface area to waste, protecting the subsequent treatment steps that are more difficult to maintain.

Depending on the flow direction in the layer of gravel, the second treatment step – the gravel filters – are called upflow (UGF), downflow (DGF) or horizontal flow (HGF) systems. A comparative study of these alternatives showed that the option of UGF was technically and economically preferable over the DGF and HGF, although these also achieve good removal efficiencies.

Upflow gravel filters (UGF)

Upflow gravel filters consist in principle of a compartment in which the gravel layer reduces in size in the direction of flow. A drainage system placed on the bottom of the structure serves to distribute the flow during the filtration period or to drain the gravel layers during periods of cleaning, discharging the water through the drainage system. There are two alternatives: upflow gravel filters in layers (UGFL) when the gravel layers of different size are installed in the same unit and upflow gravel filters in series (UGFS) when the gravel layers are installed in two or three different units, each having a main gravel size that decreases in the direction of flow.

Downflow gravel filters in series (DGFS)

Downflow gravel filters (as used Colombia) consist usually of three compartments with the coarsest gravel in the first unit and less coarse in subsequent units. The functioning or performance of the DGFS is similar to the UGFS in terms of removal efficiency, but maintenance is more difficult because the sludge tends to accumulate on the surface of the first unit. Cleaning is more difficult than for the UGFS units, where the sludge is accumulated basically in the bottom part close to the drains.

Horizontal-flow gravel filters (HGF)

Horizontal-flow gravel filters consist of at least two parallel modules constructed basically in three compartments separated by perforated walls. In the beginning this option was very voluminous, because it did not include a drainage system for hydraulic cleaning. Nowadays a drainage system is included. Although it is possible to reduce the size of the units, the activities of operation and maintenance in an HGF are more demanding in terms of manpower and water consumption. Research on HGF in series gives promising results in terms of hydraulic performance and the gain is a substantial reduction in the length of the gravel bed, while maintaining similar efficiency levels as the conventional HGF.

General considerations

Effluent water quality

Coarse gravel filters (CGF) have normally been specified to produce an effluent with turbidity $< 10\text{-}20$ NTU, or suspended solids < 5 mgl^{-1}, although the impact of these or other values on the SSF performance or maintenance is not clearly established. Besides, other parameters such as high levels of faecal contamination or natural organic matter

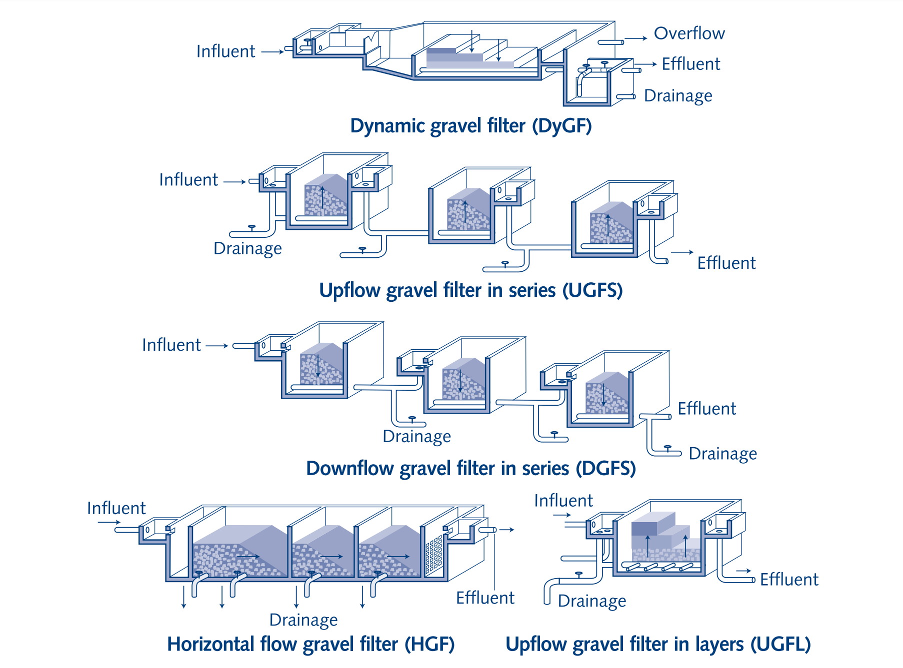


Fig. 16.5. Schematic view of coarse gravel filtration alternatives (Based on Galvis and Visscher, 1987)

that could limit the application of SSF, are not normally considered as critical factors in the specification of this technology.

Head loss and flow control

Final head loss in CMF units is small, usually a few centimetres, with a maximum value around 0.30 m. Because of these low values, CMF units usually have inlet flow control. The inlet structure should include facilities for energy dissipation, flow control, flow measurement, and overflow. A well-designed inlet box facilitates the operation and control of the system. A weir or a raised effluent pipe maintains the water above the filter bed level. Flow measurement devices are recommended at the inlet and outlet sides to control the operation and to verify that the filter boxes are watertight. Since the CMF units in small water supply systems deal with low flow and low pressure values, some simplified valves, gates, and weirs can be used together with more commercial hydraulic devices.

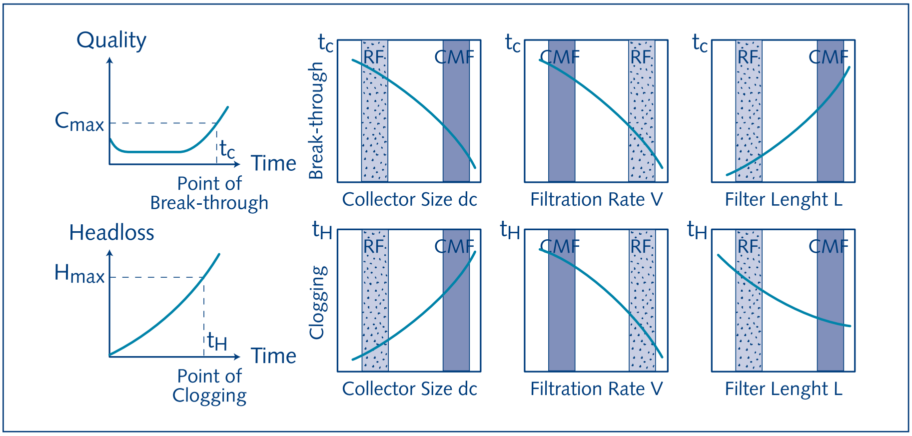
Design criteria and filter run time

The main criteria for CMF design have been removal efficiency and head loss related to particle retention in the filtering bed. Process variables such as particle nature and size distribution, collector size (d_c), filtration rate (v), and filter length (L) determine the filter run time up to the breakthrough, related to a maximum concentration value (C_m) in the effluent, or up to a clogging point, related to a maximum head loss (H_m).

A qualitative illustration of the impact of some process variables on breakthrough and clogging in RF and CMF is illustrated in figure 16.6. As predicted by the trajectory approach in filtration theory, removal efficiencies in coarse filtration will be smaller due to its greater collector size. This limitation is partly overcome by lower filtration rates and longer filtering beds in CMF.

Biological activity

Biological activity takes place in the coarse filtration units when they are processing natural waters and synthetic waters with organic matter or nutrients. Most probably, with mechanisms similar to those present for SSF, bacteria and other micro-organisms may form sticky layers in some areas of the filter media or produce exocellular polymers that contribute to particle destabilisation and attachment. Macro-biological creatures inhabiting the coarse filters are thought to contribute to the sloughing off of stored material or biofilm observed. There is evidence of organic matter decomposition during cleaning procedures of full scale HGF, calling for frequent maintenance of units susceptible to high biological activity.



Note: Although effluent water quality is expected to be lower in the CMF, its tc (breakthrough) value should be higher than for the RF

Fig. 16.6. Effects of some process variables on the breakthrough and clogging points in rapid (RF), and coarse media filters (CMF). (Adapted from Boller, 1993)

Flow conditions and coarse media filtration efficiency

Research was carried out with vertical flow filter columns of 1 m depth filled with gravel varying from 1-64 mm in size and filtration rates from 0.5-8 mh^{-1}. The turbidity of the raw water mixture was maintained at around 60 NTU. Good turbidity reductions were obtained at filtration rates < 2 mh^{-1}. This experience shows that significant solids removal efficiency is only achieved under laminar flow conditions (see fig. 16.7).

Further laboratory and field tests with UGF and HGF confirmed that effluents with a turbidity below 10 NTU were achieved only at filtration rates of 0.5-1.0 mh^{-1}.

The filtering media

The filtering media should have a large surface area to enhance particle removal and a high porosity to allow the accumulation of the separated solids. Filtration tests with kaoline clay suspensions revealed that neither the roughness nor the shape of the filter material had a great influence on filter efficiency. Any inert, clean and insoluble material meeting the previous criteria could be used as filtering media. Gravel is the commonly used material, but broken bricks, palm fibre, and plastic material have also been reported in different experiences. In a review of CMF performance with different filter media, a filter filled with palm fibre achieved better turbidity removal than a gravel filter. This is the result of the greater porosity (92% versus 37%), resulting in a lower effective velocity. However, since the use of palm fibre causes a considerable drop of dissolved oxygen along with odour and taste problems, this filtering medium has serious limitations. The use of plastic material may be an alternative, but the uplift forces of the water have to be overcome.

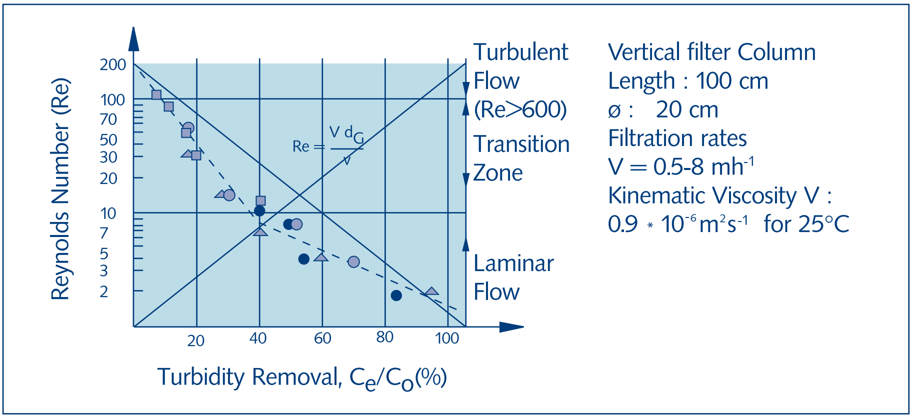


Fig. 16.7. Influence of flow conditions on coarse filtration efficiency
Source: Wegelin and Mbwette (1989); Wegelin et al., (1991)

Operation and maintenance (O & M).

Operation of CMF units requires a frequent (at least daily) control of the influent and effluent flow and the quality of the raw and filtered water. Maintenance is associated mainly with the cleaning process, which tries to restore the initial head loss. To facilitate maintenance, a minimum of two units should be constructed in parallel. Frequent cleaning of the CMF units is recommended to limit head loss development and to avoid operational or maintenance difficulties due to solids consolidation or organic decomposition inside the filter media. CMF units are cleaned both manually and hydraulically. Manual cleaning involves media removal, washing and replacement, which is time consuming and labour intensive. So, hydraulic cleaning facilities for in-place media flushing become a key component of the units to ensure a long-term sustainability of this treatment technology.

Initially only surface raking was used to clean dynamic gravel filters (DyGF). Later it was combined with filter bed drainage. Only manual cleaning was initially used to clean HGF and gradually fast drainage of the filter bed compartments has been incorporated in its application. Fast or moderate drainage velocities, combined in some cases with some surface raking, are being applied to maintain DGF and UGF. The area and the height of the filter boxes should be limited to facilitate both frequent hydraulic cleaning and eventual manual cleaning.

The drainage system

In the case of DyGF, HGF and DGF, the drainage system collects and provides an outlet for filtered water during normal operation, as well as for washing water during hydraulic cleaning by fast drainage. In the case of UGF, the drainage system distributes the water to be filtered, and collects and provides an outlet for washing water during hydraulic cleaning. The system may consist of a small trough, a false filter bottom, or perforated pipes or manifolds. One small trough would have limitations to produce an even flow distribution across the entire filter bed compartment. A good false bottom would ensure an even water collection or distribution but imply additional hydraulic structures. A properly designed manifold should have a good hydraulic efficiency with lower construction costs, although it requires an additional gravel layer to embed the pipes. The decision between false bottom and manifolds should be taken after analysing local conditions.

16.4 Considerations about multi-stage filtration

The combination of coarse gravel filtration and SSF is what in this publication is called multi-stage filtration (MSF).

The MSF technology has received a lot of positive response in Colombia and other Latin American countries, where over 100 systems are already in operation today. Ten of these built in Colombia date from the middle 1980s, each producing effluents with low sanitary risk before terminal disinfection and with low operation and maintenance costs that are to a large extent covered by the users. They pay a tariff of some 2 USD/month, in a country with a minimum official salary of some 140 USD. All systems are administered by community-based organisations with some technical support from sector institutions.

MSF does not compromise the advantages of an SSF system in terms of ease of operation and maintenance and the production of good water quality. It is an option that is applicable to many rural communities and small- and medium-sized municipalities, where treatment with chemical products has very little potential.

Table 16.4 presents a summary of the considerations concerning MSF treatment and figure 16.8 shows a layout of MSF with three components, DyGF, UGF and SSF.

The following combinations of CGF and SSF can be made:
DyGF + SSF
DyGF + UGFL + SSF
DyGF + UGFS2 + SSF
DyGF + UGFS3 + SSF

The criteria for selection of each combination will be discussed in chapter 16.6.

Table 16.4 Summary of considerations concerning MSF treatment

Issue	Comment concerning MSF treatment
Quality of treated water	It is a good alternative to improve the physical, chemical and bacteriological quality of the water. In many areas and particularly those with a less developed infrastructure, MSF is the only feasible treatment option.
Ease of construction	The relatively simple design facilitates the use of local materials and local manpower. There is no need for special equipment.
Construction cost	The construction in local materials and with local labour reduces the cost. Usually there is no need for imported materials.
Ease of operation and maintenance	After a short period of training, local operators with a minimum of formal education can operate and maintain the system.
Cost of operation and maintenance	The cost of operation and maintenance and the requirements in electrical energy are minimum and less than required for other systems. There is no need for chemical products for coagulation.
Reliability	A low risk of mechanical problems or problems related to the changes in the raw water quality, as these can be absorbed without interrupting the service in the majority of cases.
Cleaning	The cleaning process is simple although laborious, but almost always involving low cost, as in many countries labour is relatively cheap.
Requirements of surface area	A conventional RSF plant in respect to storage zones, management of chemicals etc., may require comparable areas to an MSF system.
It is not a panacea	There are levels of contamination that limit the efficiency or interfere with the treatment.

Performance of multi-stage filtration systems

The number of full-scale MSF plants in the world is limited. Most comprehensive research on functioning and performance has been carried out in Latin America. The following observations on performance are therefore mainly from that region. In general, performance findings are very satisfactory. Nevertheless, the performance may be different, that is higher or lower, in other regions of the world. Much depends on the characteristics of the raw water in terms of turbidity, suspended solids, particle size distribution, true colour and temperature. Climatic seasonal fluctuations also influence the performance of MSF.

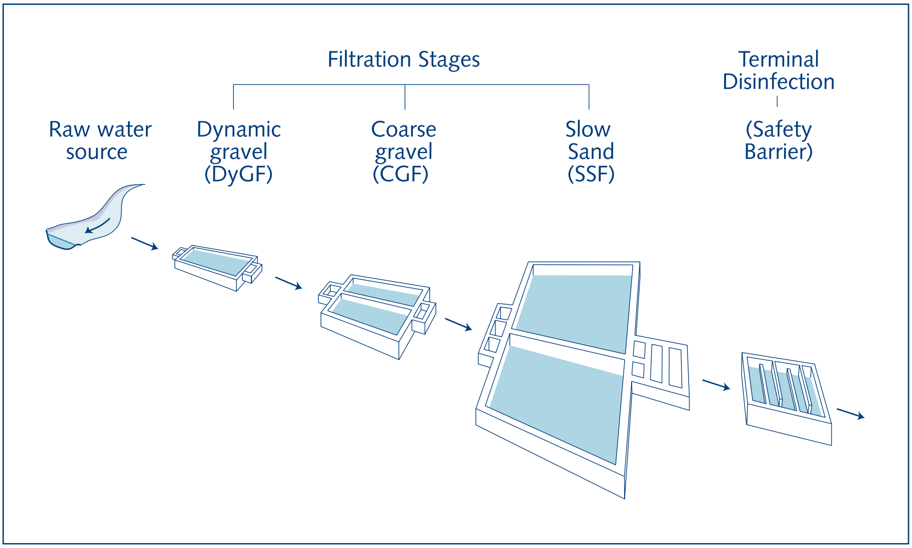


Fig. 16.8. Components of multi-stage filtration systems

The characteristics of the different coarse gravel media filter units are presented in table 16.5. The gravel filters were evaluated for filtration rates of 0.30, 0.45, 0.6, 0.7 and 1.0 m/h. The research included physical, chemical and bacteriological parameters and established the limits under which each unit could still operate. The last step in each treatment line was an SSF operated at 0.15 m/h.

The removal efficiencies of basic water quality parameters in MSF pilot system at Puerto Mallarino are shown in tables 16.6 and 16.7. Four different periods were evaluated, each with a different filtration rate.

The HGF, having a larger sludge storage capacity and similar removal efficiencies, may be an alternative for surface water high in suspended solids, even though it is more expensive.

Table 16.5 Characteristics of the treatment units in Puerto Mallarino Research Station, Cali, Colombia

Treatment Unit	Number of units in series	Filtration area (m^2)	Filter medium	
			Size (mm)	Length (m)
DyGF	1	0.75	6-25	0.6
URGS3	3	3.14	25-1.6	4.55
HGF	1	1.54	25-1.6	7.2
HGFS	3	1.54	25-1.6	4.55
UGFS2	2	3.14	25-1.6	3.1
UGFL	1	3.14	25-1.6	1.55
SSF	1	3.14	Uc = 1.57 D_{10} = 0.23 mm	max.: 1.0 min.: 0.6

Uc: Uniformity coefficient.
D10: Effective diameter

The results show that the combination of two stage gravel filters (DyGF + CGF) very much improves the performance of the SSF. Nevertheless, in cases of highly contaminated surfaces water sources, particularly if the levels of suspended solids are high (above 100 mg/l), a very critical selection of treatment barriers is required and has to be in coherence with the risk level in the water source and its variation over time. The preferred option would be to select an alternative water source. If this is not possible detailed pilot studies are needed to ensure the viability of the solution.

Performance of full-scale MSF systems in Colombia

Seven community managed MSF systems in the Cauca Valley have been monitored for a period of seven years. The systems receive water from catchment areas with low or moderate levels of human intervention. Water quality of the different sources indicates mean turbidity levels between 0.9 and 15 NTU, faecal coliform counts between 52 and 51,916 FCU/100 ml, and true colour levels between 3 and 30 PCU. The mean removal efficiencies of basic water quality parameters in full-scale MSF plants are shown in table 16.6 and 16.7. The wide ranges are due to different CMFs applied and the different local operations.

The composition of the systems matches the multi-barrier concept that implies that more than one stage of treatment is needed, combined in such a way that together the barriers have a removal efficiency that is sufficient to ensure low dose disinfection as the final and efficient safety barrier.

All systems produce water with turbidity below 1 NTU, with a frequency between 65 and 98%, and below 5 NTU in more than 98% of the samples. Faecal coliforms were below 25 FCU/100 ml, with a frequency above 97%, and true colour below 15 TCU in more than 98% of the samples. With these water qualities, constant dose disinfection with chlorine as suggested by WHO (1996) becomes an effective safety barrier.

Table 16.6 Individual (at each treatment stage) and cumulative (up to the end of SSF stage) mean removal efficiencies of basic water quality parameters in MSF pilot system at Puerto Mallarino.

Filtration		Period	Influent mean values			Individual mean efficiencies		
Stage	Rates (mh^{-1})		Turbidity (NTU)	Colour (PCU)	Faecal coliforms (CFU/ 100 ml)	Turbidity (%)	Colour (%)	Faecal coliforms (log. units)
DyGF stage								
DyGF	(0.9-1.4)	I	109	81	41,184	32	11	0.2
	(1.4-2.5)	II	59	54	31,800	41	15	0.6
	(1.4-2.5)	III	51	35	97,779	43	14	0.8
	(1.9-2.8)	IV	52	57	108,796	40	16	0.6
CGF stage								
UGFS	0.3	I	74	72	24,758	84	69	2.6
	0.45	II	35	46	8843	77	54	2.3
	0.6	III	29	30	16,823	77	53	2.4
	0.75	IV	31	48	26,226	75	63	2.3
UGFL	0.3	I	74	72	24,758	70	44	1.8
	0.45	II	35	46	8843	54	28	1.3
	0.6	III	29	30	16,823	55	30	1.4
	0.75	IV	31	48	26,226	61	46	1.3
SSF stage								
SSF 1	0.1	I	12	22	65	64	73	2.8
	0.1	II	8.1	21	45	75	67	2.7
	0.55	III	6.6	14	64	82	57	2.1
	0.15	IV	7.8	18	127	74	67	1.8
SSF 2	0.1	I	22	40	369	85	88	3.1
	0.1	II	16	33	452	79	70	2.2
	0.15	III	13	21	637	89	67	2.6
	0.15	IV	12	26	1226	77	69	2.0
Treatment lines		Period	Effluent mean values			Cumulative mean efficiencies		
DyGF + UGFS + SSF1		I	4.3	6	0.1	96	93	5.6
		II	2.0	7	0.1	97	87	5.5
		III	1.2	6	0.5	98	83	5.3
		IV	2.0	6	2.2	96	89	4.7
DyGF + UGFL + SSF2		I	3.2	5	0.8	97	94	5.1
		II	3.3	10	2.7	94	81	4.1
		III	1.4	7	1.7	97	80	4.8
		IV	2.8	8	10.7	95	86	4.0

Table 16.7 Individual (at each treatment stage) and cumulative (up to the SSF stage) mean removal efficiencies of basic water quality parameters in full-scale MSF plants.

Filtration		Filter bed	Influent mean values			Individual mean efficiencies		
Stage	Rates (mh^{-1})	length (m)	Turbity (NTU)	Colour (PCU)	Faecal coliforms (CFU/ 100 ml)	Turbidity (%)	Colour (%)	Faecal coliforms (log.units)
DyGF stage								
DyGF	0.9 – 1.6	0.3 – 0.6	3.8 – 24	15 – 30	2895 – 51,916	21 – 57	10 – 24	0.2 – 0.7
CGF Stage								
CGF	0.5 – 0.9	0.9 – 4.0	2.8 – 17	5 – 27	330 – 10,063	30 – 71	17 – 41	0.7 – 1.0
SSF Stage								
SSF	0.08 – 0.17	1.0 – 1.2	0.8 – 4.9	4 – 16	52 – 2008	50 – 87	25 – 75	1.7 – 3.3
Treatment plant			Effluent mean values			Cumulative mean efficiencies		
DyGF + CGF + SSF			0.4 – 0.9	3 – 6	0.7 -	79 – 96	40 – 87	2.6 – 4.7

MSF treatment can adapt itself to the type of raw water and the concentration of contamination. The systems give higher removal efficiencies for water that is higher in contamination. This implies that the barriers become more effective if the water to be treated has a higher risk and still can produce a water with a low sanitary risk level. MSF technology has a great potential to reduce the physical-chemical and bacteriological risk associated with surface water sources. However, the MSF technology is not a panacea and has its limitations, particularly with high levels of contamination, not always producing water of a quality that can be properly disinfected.

16.5 Cost considerations

Some components of a filtration system have the greatest impact (about 80%) on the construction cost. These include civil works, filter media, the excavation and the valves. The cost efficiency increases with the size of the system. Nevertheless, for this type of filtration systems the economy of scale is limited, which favours a relative short design period of some ten years.

The operation and maintenance cost of MSF systems is mainly determined by labour cost; in Colombia staff costs made up 85% of the total.

16.6 Selection of MSF alternatives

Different combinations of filtration stages are identified to treat raw water types. In general, filter bed lengths increase with the contamination levels in raw water types while filtration rates decrease. Unsurprisingly, capital and running costs of MSF plants increase with increasing contamination levels in their raw water types. Table 16.8 gives a selection guide based on the parameters faecal coliforms densities, turbidity and colour. All these MSF alternatives fulfil proposed water treatment objectives.

Table 16.8 An example of a selection guide for MSF alternatives fulfilling established treatment objectives for removing turbidity, faecal coliform bacteria and colour, based on experiences in the Andean Colombian Cauca Valley.

Faecal coliforms (CFU/100ml)	Y	Y4 Mean < 15,000 Max. < 45,000	DyGF$_{2.5}$ UGFS(3)$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFS(3)$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFS(3)$_{0.6}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.45}$ SSF$_{0.15}$	DyGF1.5 UGFS(3)$_{0.3}$ SSF$_{0.15}$
		Y3Mean < 5000 Max. < 15,000	DyGF$_{2.5}$ UGFS(2)$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFS(2)$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFS(3)$_{0.6}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.45}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.3}$ SSF$_{0.15}$
		Y2Mean< 1500 Max.< 5000	DyGF$_{2.5}$ UGFL$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFL$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFS(3)$_{0.6}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.45}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.3}$ SSF$_{0.15}$
		Y1Mean< 750 Max.< 2500	DyGF$_{2.5}$ UGFL$_{0.75}$ SSF$_{0.20}$	DyGF$_{2.0}$ UGFL$_{0.6}$ SSF$_{0.15}$	DyGF$_{2.0}$ UGFS(3)$_{0.6}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.45}$ SSF$_{0.15}$	DyGF$_{1.5}$ UGFS(3)$_{0.3}$ SSF$_{0.15}$
Turbidity (NTU)	X	Mean <	5	10	16	20	25
		$P_{95\%}$ <	15	30	50	60	70
		Max. <	50	100	150	225	300
			X_1	X_2	X_3	X_4	X_5
Colour (PCU)	Z	Mean <	10	13	16	18	20
		Max. <	30	40	50	55	60
			Z_1	Z_2	Z_3	Z_4	Z_5

Explanation of the selection guide in table 16.8:

1. The number between brackets indicates the number of filtration steps in UGFS alternatives. The sub-index means filtration rates in mh^{-1}.
2. Raw water may be directly disinfected (without filtration) if turbidity and faecal coliform levels are below 5 NTU and 20 CFU/100 ml in 95% of samples respectively. These low contamination levels must be confirmed periodically with sanitary inspections and analyses in the watershed area.
3. DyGF + SSF (without CGF stage) could be applied if turbidity and faecal coliform levels are below 10 NTU and 20 CFU/100 ml in 95% of samples respectively. These low contamination levels must be confirmed periodically with sanitary inspections and analyses in the watershed area.
4. Turbidity treatment objectives ($\leq$ 10 and 5 NTU in CGF and SSF effluents respectively) should be obtained with 95 percentile (P_{95}) turbidity values. It is expected that maximum (peak) turbidity values can be treated thanks to the protection capacity of the DyGF stage, combining flow reductions with higher removal efficiencies.
5. Faecal coliform treatment objectives ($\leq$ 1000 and 10 CFU/100 ml in CGF and SSF effluents respectively) should be obtained with maximum faecal coliform levels. With medium faecal coliform levels in raw water sources SSF effluents should have effluents with mean values $\leq$ 3 CFU/100 ml before terminal disinfection).
6. Colour treatment objective ($\leq$ 15 PCU in SSF effluents) should be obtained with maximum colour levels. This is a secondary treatment objective and should not compromise previous treatment objectives or terminal disinfection as a safety barrier.

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