2. Filtration of water supplies

History

As far as is known the first instance of filtration as a means of water treatment dates from 1804, when John Gibb designed and built an experimental slow sand filter for his bleachery in Paisley, Scotland, and sold the surplus treated water to the public at a halfpenny per gallon\(^1\). He and others improved on the practical details, and in 1829 the method was first adopted for a public supply when James Simpson constructed an installation to treat the water supplied by the Chelsea Water Company in London. By 1852 the practice had become so established, and its advantages so evident, that the Metropolis Water Act was passed requiring all water derived from the River Thames within 5 miles of St Paul's Cathedral to be filtered before being supplied to the public.

At that time the existence of pathogenic bacteria was unknown, and the slow sand filter was regarded as a mechanical means of straining out turbidity and suspended solids. John Snow, however, in his studies of cholera transmission, had come to the conclusion that the disease was waterborne, and he postulated the existence of *materies morbi* - a material derived from previous cases that could transmit infection to those who ingested it. This *materies morbi* was removed, with other solids, by filtration, or could be avoided by drawing the supply from a point upstream of any sewer discharge. As a result the first regular examinations of water supplies, including chemical analyses, were initiated in London in 1858. In 1885, following the discoveries of Pasteur, Koch, Escherich, and others during the 1860s and 1870s, they were extended to include bacteriological examination.

The most convincing proof of the effectiveness of water filtration was provided in 1892 by the experience gained in two neighbouring cities, Hamburg and Altona, which drew their drinking-water from the River Elbe, the former delivering it untreated except for settlement, while the latter filtered the whole of its supply. When the river became infected from a camp of immigrants, Hamburg suffered from a cholera epidemic that infected one in thirty of its population and caused more than 7,500 deaths, while Altona escaped almost unscathed. Subsequent waterborne epidemics in many parts of the world have confirmed this experience; in every case infection has been almost entirely confined to people drinking unfiltered water.

In 1885 the first mechanical filters were installed in the USA, and in 1899 automatic pressure filters were first patented in England. Since then a number of modifications and improvements have been introduced and have attained varying degrees of popularity, particularly in highly industrialized countries. Most of these improvements relate to constructional details - the reduction of the amount of land required for construction or the introduction of automatic operation and control-rather than to the quality of the delivered water. Even today, the performance of the biological or slow sand filter in producing high-quality water has not been surpassed, and there are a number of cities in industrial countries where filters of this type are being (or have recently been) constructed; examples include Amsterdam, Antwerp, London, Paris, Springfield (Mass.), and various cities in Sweden and Japan.

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Comparison of filter types

Filters may be divided into two types - pressure and gravity. Pressure filters consist of closed vessels (usually steel shells) containing beds of sand or of other granular material through which water is forced under pressure. These filters are frequently used in certain industrial situations, and a number have been installed for public water supplies. They are especially suitable in plants where a high degree of automation is necessary, in remotely situated treatment plants that have to operate with only occasional attendance, and in systems where for some reason it is desirable to have only a single pumping stage between the inlet and the distribution system. As their initial cost may be high, especially when their component parts have to be imported, their principal use is in the industrialized countries where they are manufactured; they will not be described here in detail as their operation is adequately explained in standard textbooks on water treatment.

A gravity filter consists essentially of an open-topped box (usually made of concrete), drained at the bottom, and partly filled with a filtering medium (normally clean sand). Raw water is admitted to the space above the sand, and flows downward under the action of gravity. Purification takes place during this downward passage, and the treated water is discharged through the under-drains. In turn, gravity filters are subdivided into slow and rapid types, the latter operating at rates 20-50 times faster than those of the former, and hence requiring (in theory) only some 2-5% of the area needed for slow filters. In practice the reduction in space requirements is partially offset by the additional pretreatment stages needed for rapid filtration, and the figure is likely to be nearer 20%.

On the assumption that both types of gravity filter are equally efficient in removing suspended matter, it would appear that the rapid filter must become choked and require cleaning 20-50 times as often as the slow. However, the comparison is not as straightforward as this.

In slow filtration, a fine sand is used, and the designed rate of downward flow of the water under treatment normally lies between 0.1 and 0.4 m³/h per square metre of surface. Unless the water to be treated is of exceptional turbidity, a filter of this type may run for weeks or even months without cleaning. The suspended solids and colloidal matter are deposited at the very top of the bed, from which they can be removed by scraping off the surface layer to a depth of one or two centimetres. This infrequent operation may be carried out by unskilled labourers using hand tools or by mechanical equipment such as that described in Chapter 5.

The medium used in rapid filtration is considerably coarser, with an effective grain size of 0.6 - 0.2 mm. The interstices between the grains are larger, providing less resistance to the downward flow, and thus emitting higher velocities, usually in the range 5-15 m³/m²/h. Not only are the impurities deposited more rapidly, but they are carried more deeply into the medium. Some catalytic action also takes place, encouraging deposition of iron and manganese within the bed. As a result, the necessity for cleaning occurs at frequent intervals (often only one or two days), and, in order to restore the capacity of the filter and the quality of the effluent, the medium has to be cleaned throughout its whole depth. The only practical method so far developed of achieving this is by backwashing, a process in which high-pressure water is forced upwards through the whole bed and compressed air or mechanical agitation is used to scour the individual grains so that the accumulated impurities can be flushed away.

Raw water entering a slow sand filter lies for several hours (on average) in the space above the medium, during which time there is some separation and settlement of the larger particles. It then percolates through the sandbed (a process taking 2 hours or more), and as it does so it is subjected to a number of purification processes that will be described later. In contrast, water is in contact with the bed of a rapid gravity filter for a few minutes only. If rapid filtration were the only
treatment to be given, little effective bacterial purification and only limited chemical improvement could take place during this short time, and even the mechanical straining action would be less efficient owing to the larger water channels between the grains. However, rapid filters are frequently used in conjunction with earlier stages of chemical treatment, flocculation, and sedimentation, which remove most of the impurities in the raw water before it reaches the filter. The few that do reach the filter-bed are easily removed in their coagulated state, the finer flocculi forming a film on the sand particles.

To this film further particulate impurities in the water adhere, and a certain degree of bacterial purification is believed to take place within its thickness, but in view of the frequency with which it is necessary to wash the coating from the grains it is unlikely that this bacterial action contributes significantly to the overall process.

A similar film builds up on the grains of a slow sand filter, but because it is not regularly washed away the purifying bacteria become well established and play an important part in the treatment process. It is because of this difference that slow filters are often referred to as "biological" filters.

**Elements of a slow sand filter**

Fig. 1 shows, in diagrammatic form, the various elements that go to make up a slow filter. Essentially these consist of:

1. a supernatant (raw) water reservoir, the principal function of which is to maintain a constant head of water above the filter medium, this head providing the pressure that carries the water through the filter;
2. a bed of filter medium (nearly always sand), within and upon which the various purification processes take place;
3. an under-drainage system, which fills the dual purpose of supporting the filter medium while presenting the minimum possible obstruction to the treated water as it emerges from the underside of the filter-bed; and
4. a system of control valves to regulate the velocity of flow through the bed, to prevent the level in the raw water reservoir from dropping below a predetermined minimum during separation, and to permit water levels to be adjusted and backfilling the place when the filter is put back into operation after cleaning.

![Diagram of a Slow Sand Filter](image)

The control devices are shown in greater detail in Fig. 18.
metres in depth, and built wholly or partly below ground. To save space (particularly in larger installations) the walls are normally vertical or near-vertical, and may be made of stone, brick, or concrete according to which is most easily obtainable at the site. Sloping sides and a variety of lining materials may be found in the more remote locations where land is plentiful and economy of construction is the first consideration.

At the bottom of the box is the under-drainage system which may consist of a false floor of porous concrete or a system of porous or unjointed pipes, surrounded and covered with graded gravel to support the sand-bed and prevent fine grains being carried into the drainage pipes.

Above the under-drainage system is the sand itself, to a thickness of 0.6-1.2 m, above which the raw water will lie to a depth of 1-1.5 m. Various refinements, such as scum removal channels, inlet, outlet, and drainage devices, will be described later.

Special mention should, however, be made of the outlet weir and valve to control the rate of flow. For reasons that will be fully explained it is most undesirable that the water level in the filter box should drop below the surface of the filter medium during operation. To eliminate the possibility of this happening, a weir is incorporated in the outlet pipe system. It accomplishes the dual purpose of maintaining a minimum water depth within the filter box and of aerating the outgoing water to some extent, so that oxygen is absorbed and dissolved gases, which might otherwise impart unpleasant tastes or odours to the treated water, are released. Moreover it renders the operation of the filter independent of fluctuations in the water level in the clear water reservoir.

The general appearance of a slow sand filtration plant is shown in Fig. 2.

**Purification in a slow sand filter**

The various processes that take place in a slow sand filter are described in some detail in Chapter 3, but the following paragraphs describe them briefly and show how they complement each other to
provide an overall system that improves the physical, chemical, and bacteriological qualities of the delivered water simultaneously. Let us consider a particular sample of raw water in its passage through a biological filter and examine the various purifying influences that act upon it successively.

Firstly, the sample enters the water resting above the filter-bed, awaiting its downward passage through the medium. This raw water reservoir is about 1-1.5 m deep, and the average time that the sample will remain here varies from 3 to 12 hours, depending on the filtration velocity. The heavier particles of suspended matter start to settle, and some of the lighter particles coalesce, so becoming more amenable to subsequent removal. During the day, and under the influence of sunlight, algae are growing and are absorbing carbon dioxide, nitrates, phosphates, and other nutrients from the water to form cell material and oxygen. The oxygen dissolves in the water as it is formed and enters into chemical reaction with organic impurities, rendering these, in turn, more assimilable by the algae.

On the surface of the sand there is a thin slimy matting of material, largely organic in origin, known as the *schmutzdecke*, or filter skin, through which the water must pass before reaching the filter medium itself. The *schmutzdecke* consists of threadlike algae and numerous other forms of life, including plankton, diatoms, protozoa, rotifers, and bacteria. It is intensely active, the various micro-organisms entrapping, digesting, and breaking down organic matter contained in the water passing through. Dead algae from the water above and living bacteria in the raw water are alike consumed within this filter skin, and in the process simple inorganic salts are formed. At the same time nitrogenous compounds are broken down and the nitrogen is oxidized. Some colour is removed, and a considerable proportion of inert suspended particles is mechanically strained out.

Having passed through the *schmutzdecke*, the water enters the filter-bed and passes downwards through the interstices between the sand grains - a process that normally takes several hours.

When James Simpson installed his first slow sand filters nearly a century and a half ago, he had no idea of the complex processes of purification he was initiating. He looked upon his sand-bed as a very effective strainer that would retain those particles that were larger than the interstices between the sand grains. This straining action does undoubtedly take place, though in view of the preliminary screening undergone by the water in passing through the *schmutzdecke* it is unlikely that mechanical straining within the bed constitutes more than a small part of the total purification process. Only gradually, as the nature of colloids, bacteria, and viruses became known, did the earlier concept become obviously insufficient to explain the removal of these particles, the dimensions of which are much smaller than the pore sizes of the finest sand used in a filter-bed. Nevertheless the fallacy of regarding filter media solely as straining mechanisms has persisted until comparatively recently, and unwarranted doubts about the efficacy of biological filtration have been raised by falsely equating the results of laboratory tests, in which pathogens and some parasites have been shown to pass unaffected through a column of clean sand, with the conditions that prevail in a working filter through which the same organisms undoubtedly could not pass.

A more significant property of the sand-bed is adsorption, a phenomenon resulting from electrical forces, chemical bonding, and mass attraction interacting in a way that is not yet completely understood. Adsorption takes place at every surface at which water comes in contact with a sand grain. To appreciate the extent of this action it is necessary to visualize the interior of the sand bed as a series of grain surfaces over which the water must pass. The aggregate area of these surfaces is extremely high; in one cubic metre of filter sand there will be some 15 000 m2 - one and a half hectares of surface. Over this the water passes in a laminar flow that is constantly changing direction as it leaves one grain and meets the next. At each change of direction gravity and centrifugal forces act upon every particle carried by the water.
Between the grains are the pores or open spaces, totalling some 40% of the total volume of the bed. Water passing over a grain surface is suddenly slowed down each time it enters one of these pores, and as a result millions of minute sedimentation basins are formed in which the smallest particles settle onto the nearest sand grain before the water continues on its downward path.

Hence during the passage of the water through the bed every particle, bacterium, and virus is brought into contact with the surfaces of the sand grains, to which they become attached by mass attraction or through the operation of electrical forces. The surfaces become coated with a sticky layer, similar in composition to the *schmutzdecke*, but without the larger particles and the algae, which have failed to penetrate. It sustains a teeming mass of micro-organisms, bacteria, bacteriophages, rotifers, and protozoa, all feeding on the adsorbed impurities and on each other. The living coating continues through some 40 cm of the bed, different life forms predominating at different depths, with the greatest activity taking place near the surface, where food is most plentiful.

The food consists essentially of particles of organic origin carried by the water. The sticky coating holds the particles until they are broken down, consumed, and formed into cell material, which in turn is assimilated by other organisms and converted into inorganic matter such as water, carbon dioxide, nitrates, phosphates, and similar salts that are carried downward by the passing water. As the depth from the surface increases the quantity of organic food decreases and the struggle among the various organisms becomes fiercer. Other bacteria then predominate, utilizing the oxygen content of the water and extracting nutrients that would otherwise have passed unchanged in solution through the filter. As a consequence the raw water, which entered the bed laden with a variety of suspended solids, colloids, micro-organisms, and complex salts in solution, has, in its passage through some 40-60 cm, of filter medium, become virtually free of all such matter, containing only some simple (and relatively innocuous) inorganic salts in solution. Not only has practically every harmful organism been removed but also the dissolved nutrients that might encourage the subsequent growth of bacteria or slimes. It may be low in dissolved oxygen and may contain dissolved carbon dioxide but subsequent aeration caused by failing over the discharge weir will go far to remedying both these defects.

In tests on working filters it is not uncommon to find the total bacteria count reduced by a factor of between 1000 and 10 000, and the *Escherichia coli* count by a factor of between 100 and 1000. Starting with an average quality of raw water it is usual to find *E. coli* absent in a 100 ml sample of delivered water, thus satisfying normal drinking-water quality standards.

**Application of slow sand filtration**

Slow sand filtration is an efficient method of removing particulate suspended matter and is therefore applicable to the treatment of groundwater containing solids in suspension. In Surinam and elsewhere it is used to remove ferric and magnetic compounds that have been converted by aeration from soluble ferrous and manganous salts in groundwater.

Its principal use however, is in the removal of organic matter and pathogenic organisms not normally found in groundwater, for which purpose it is a particularly appropriate form of treatment for surface waters of moderate turbidity. Although slow filters are capable of coping with turbidities of 100-200 mg/l for a few days, a figure of 50 mg/l is the maximum that should be permitted for longer periods, and the best purification occurs when the average turbidity is 10 mg/l or less (expressed as SiO₂). When higher turbidities are expected, biological filtration should be preceded by other forms of treatment, such as (in ascending order of efficiency):
(1) plain sedimentation (for turbidities of 20-100 mg/l);
(2) storage with microstraining for algae removal, the detention periods varying from a few weeks to a few months (for turbidities of up to several grams per litre);
(3) natural screening prior to intake (for turbidities of 10-20 mg/l, depending on the degree of clogging of the river bed);
(4) rapid "roughing" filtration (for turbidities of 20-50 mg/l); and
(5) sedimentation preceded by chemical coagulation (if necessary) and followed by rapid "roughing" filtration (for turbidities of 50-200 mg/l).

The turbidity ranges quoted give only a general indication of the limits of each process, and it must be borne in mind that the degree and type of pretreatment may depend as much on the particle size distribution of the suspended matter in the raw water as on the total amount of solids present.

In each case biological filtration will be the last stage of treatment, except when the precautionary measure of chlorination is adopted. It should be particularly noted that biological treatment brings the water to the optimum condition for chlorination, thereby effecting considerable savings in the quantity of chemical required to achieve a given degree of disinfection.

**Limitations of slow sand filters**

Certain conditions may be encountered that may offset the advantages of slow sand filtration and lead to the choice of rapid filters as a more appropriate treatment method. These conditions are described briefly in the following paragraphs.

(1) Where land is restricted or very expensive, the much larger area needed for biological filters may add considerably to the capital cost, or even rule out this form of treatment as a practical proposition. The areas required for treatment plants vary widely and depend on many local considerations, but the following figures, based on actual plants treating turbid river water and having capacities of about 50 million m$^3$ per year, may be useful for purposes of comparison:

- (a) rapid filtration plant, preceded by upward flow settling tanks, chemical dosing, etc. - 3000 m$^2$
- (b) slow sand filtration - 20 000 m$^2$ to which must be added the following areas for pretreatment stages:
  - plain sedimentation - 10 000 m$^2$,
  - raw water storage- up to 1000 000 m$^2$ according to detention period,
  - rapid "roughing" filters - 1 000 m$^2$, and
  - coagulation and sedimentation - 3 000 m$^2$

(2) In countries where construction methods are largely mechanized and where the importation of such materials as steel and cast-iron pipework presents no problems, the reinforced concrete construction and metal fittings of rapid filters may be cheaper to construct than the more extensive (though simpler) non-reinforced construction of slow filters. In the Netherlands, for instance, the initial cost of slow filters is nearly three times that of rapid filters, but this figure includes complete structural covering of the beds, and the installation of mechanical sand-bed cleaning equipment.

(3) Where unskilled labour for cleaning is in short supply it may be easier and cheaper to recruit the skilled staff required to operate and maintain rapid filters (especially when these are fitted with automatic control equipment) than to retain the necessary labour force. However,
recent developments in mechanical cleaning of slow sand filters, which will be described later, make this condition of less consequence than formerly.

(4) In climates where the winters are very cold it may be necessary to install expensive structural precautions against freezing. At the same time the efficiency of purification will be adversely affected by low temperatures. Rapid filters will be equally affected, but because of their smaller area they are cheaper to cover.

(5) Where the water to be treated is liable to severe and sudden changes in quality or where certain types of toxic industrial wastes or heavy concentrations of colloids may be present, the working of biological filters can be upset.

(6) Certain types of algae may interfere with the working of the filters, the usual result being premature choking, which calls for frequent cleaning. In such cases it may be necessary to cover the filter-beds to exclude light - a comparatively expensive addition to capital cost unless it is possible to use locally available materials for the purpose. It is worth noting that this applies only to certain types of algae; other types may actually improve the quality of the treated water and the efficiency of the filters by oxygenating the supernatant water during the hours of daylight.

It is significant that, of the six adverse conditions given above, the first five are particularly applicable to industrialized countries in northern latitudes, and yet, because the advantages of biological filtration so often outweigh the drawbacks, it is in those same industrialized countries that the world's largest installations embodying slow sand filters may be seen.

In countries where these limitations do not apply to such an extent, and for small installations especially, slow sand filtration is undoubtedly the simplest and most efficient method of treatment for many types of surface water.

Advantages of slow sand filters

Quality of treated water
No other single process can effect such an improvement in the physical, chemical, and bacteriological quality of normal surface waters as that accomplished by biological filtration. The delivered water does not support after-growth in the distribution system, and no chemicals are added, thus obviating one cause of taste and odour problems.

Cost and ease of construction
The simple design of slow sand filters makes it easy to use local materials and skills in their construction. The cost of imported materials and equipment may be kept to almost negligible proportions, and it is possible to reduce the use of mechanized plant to the minimum and to economize on skilled supervision. Design is easier, little special pipework or equipment is required, instrumentation can be almost completely eliminated, and a greater latitude in the screening of media and the selection of construction materials can be permitted. Only when a high price has to be paid for land and when expensive superstructures are necessary for protection against low temperatures is the capital cost of slow sand filters likely to equal or exceed that of comparable rapid filters.

Cost and ease of operation
The cost of operation lies almost wholly in the cleaning of the filter-beds, which may be carried out either mechanically or manually. In developing countries and elsewhere where labour is readily
available, the latter method will be used, in which case virtually the whole of the operating cost will be returned to the local economy in the form of wages.

No imported chemicals or other materials are needed for the process, though in many cases chlorination is practised as an additional safeguard. However, chlorination would be equally necessary with any other form of treatment, and, in general, the dosages required to disinfect biologically treated water are less than those needed to disinfect water treated by other methods.

No compressed air, mechanical stirring, or high-pressure water is needed for backwashing, thus there is a saving not only in the provision of plant but also in the cost of fuel or electricity.

The operator of a biological filter requires far less training and skill than does his colleague in charge of a rapid gravity filter, and less supervision and support (e.g., laboratory testing of chemical quality) are called for. Slow sand filters automatically accommodate minor fluctuations in raw water quality, temperature, and climatic conditions and can stand short periods of excessive turbidity or demand without breaking down.

Conservation of water
In water-short areas, biological filters have the additional advantage of not requiring the regular flushing to waste of wash water. In the case of pressure or rapid gravity filters, which need cleaning every few days, this wastage represents some 2 - 3% of the total amount treated. Reclamation may be practical in some places but represents an additional expense.

The water that is passed through a slow sand filter immediately after cleaning and before the biological function has been restored (a process known as "ripening") can either be returned to source or diverted to another filter since it does not carry any impurities additional to those in the raw water.

Disposal of sludge
Sludge storage, dewatering, and disposal are less troublesome with slow sand filters than with mechanical filters, particularly when the latter contain chemical coagulants. Since the sludge from biological filters is handled in a dry state there is virtually no possibility of polluting neighbouring watercourses, and the waste material is usually accepted by farmers as a useful dressing for their land, the mixture of sand and organic matter being especially suitable for conditioning heavy clay soils.