Slow sand filtration

Voordracht uit de 29e vakantiecursus in drinkwatervoorziening 'Nieuwe zuiveringstechnieken', die op 6 en 7 januari 1977 aan de TH Delft werd gehouden.

General Construction

A slow sand filter is basically a hole in the ground containing sand with space above it to hold water to a depth sufficient to provide the pressure necessary for the water to flow through the sand. Underneath the sand some means of collecting and removing the water must be provided. Alternatively, a filter can be built entirely above ground level or partly above and below ground level. There are, therefore, many means of construction that can be adopted, from the very simple, suitable for developing

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countries with limited means and expertise, to the highly sophisticated, incorporating all the most modern mechanical aids.

Methods of Operation

Rates of flow are usually measured linearly as the vertical flow of the top water through the sand and slow sand filters can be operated from rates as low as 0.6 m per day and have been operated up to 12 m per day. The more usual rates, however, are nearer 2 to 5 m per day, depending on individual circumstances. After a period of operation usually lasting several weeks, the accumulation of particulate matter on and in the bed restricts the flow so that filtration rates cannot be maintained with the head available. It is then necessary to remove the top layer of 2-3 cm of sand with the attendant particulate matter and wash it.
This layer of sand can be removed by labourers with shovels and hand barrows or by highly mechanised equipment that is either driven on to the bed surface or is operated from gantries on rails on the walls of the filter. If gantries are used, there is an economic limit to the width of the bed that can be constructed. There is, therefore, a wide range of adaptability to suit local conditions and the nature of the work force available.
The sand that is removed must then be washed and there are a variety of sand washing plants that can be used for this purpose, most of which require pumping of water to achieve the necessary agitation. The main purpose of this washing is to restore to the sand its ability to permit its original flow rate capacity. As the efficient function of a slow sand filter is dependent to a very large extent on the micro-organisms which are attached to the sand grains, there is no special virtue in excessive cleaning which would remove many of these bacteria. Alternatively, in very small filters in areas where adequate quantities of clean sand are readily available, it might be more economic to discard the dirty sand and replace it with new sand.

The depth of sand that is used will depend on local circumstances and is influenced by the quality of the untreated water and the rates of filtration. Generally speaking, the poorer the quality and the greater the filtration rate, the greater the depth of sand should be. But in any case after several layers of sand have been removed for repeated cleanings, the depth of sand left will be less than that required for effective filtration. It then becomes necessary to restore it to its original depth by returning the washed sand. This should not be done simply by placing the clean sand on top of old sand. In this way the bottom sand would never be cleaned, particulate matter would increase over the years, eventually filling the interstices and reducing flow rates. Furthermore, with some hard waters particularly with high bicarbonates, carbonates can crystallise around sand grains binding them together in large, hard lumps which cannot be removed by skimming or broken up by washing. Resanding is, therefore, carried out by digging a trench at one end of the bed, either by hand or with a mechanical trench digger, tipping the clean sand in the trench, then digging another trench alongside, throwing the bottom sand on top of the clean sand and repeating this process across the whole bed.

Basic Principles

Biological Activity

A slow sand filter should not be regarded just as a mechanical sieve which removes particulate matter by physical and mechanical forces. These do play a part in its operation but only a minor part of the overall function. Much has also been written in the past about the importance of the formation of the surface 'zoogleal layer' or 'smutzdecke' which was alleged to be necessary to bring about the physical sieving effect. Most recent work, however, has shown that this surface layer is unnecessary and efficient filtration is achieved without it (Report, 1971-73).
The main quality improvement is brought about by beneficial micro-organisms which live and grow in the filter bed. Many of these organisms are specific filter bed organisms and have found in the filter bed a habitat that is particularly suitable for their activity. Many of these organisms are uncommon in the untreated water and in the filtered water but are abundant in the filter (Report, 1971-73). Their activities may be considered in two groups.

Nutrient Utilisation

Firstly there are those micro-organisms including bacteria, actinomycetes and fungi which utilise for their growth and nutrition the numerous organic compounds present in solution in the water and by metabolising these compounds, break them down or oxidise them into much simpler compounds through a succession of different micro-organisms ultimately to carbon dioxide, water and mineral salts, or at least to intermediate products. As these original organic compounds are usually polluting, their removal is beneficial and results in an improvement in chemical quality. The most abundant of these are the humic compounds which impart a yellow or brown colour to the water and are derived from vegetation and soil drainage and sewage effluents. They can also include, however, many man-made compounds of industrial origin, including detergents, pesticides, oils, phenols, etc. Some of these compounds are very readily utilised by micro-organisms, and some are more resistant and filter bed bacteria can very quickly adapt themselves to utilising some unusual compounds to which they have not been previously exposed. This has been demonstrated with various phenols including phenol, C_6H_5OH; m-cresol, $CH_3C_6H_4OH$; resorcinol, $C_6H_4(OH)_2$; and phloroglucinol, $C_6H_3(OH)_3$, deliberately added to an experimental filter bed. Quantities of 8-10 mg per litre were removed after a few days and micro-organisms could be recovered which were specifically adapted to removing the compounds that were added (Report, 1971-73).

Predation

The growth of micro-organisms which utilise organic nutrients in solution results in the build-up of a large mixed population and wherever large microbial populations occur in the environment, other organisms which can utilise those micro-organisms as sources of food will also become active and multiply. These will include the microbial viruses, bacteriophages, actinophages and mycophages, the very small bacterial predator Bdellovibrio bacteriovorus and the bacterial predators of the genus Myxobacterium, the antibiotic-producing bacteria, actinomycetes and fungi and the predatory unicellular animals, the protozoa, including amoebae, flagellates and ciliates, as well as rotifera and larger animals such as oligochaetes (Report, 1971-73).
The phages, like other viruses, are dependent on living and growing host cells for their growth and reproduction, resulting in the ultimate death and disintegration of the

host cell. Bdellovibrio is a very small bacterium first described by Stolp and Petzold (1962) which is very actively motile and embeds itself into host bacteria by virtue of its speed and grows into the host bacterium and multiplies and disintegrates the host cell. It has been found in sewage effluent, rivers and surface waters and filter beds. It is fairly host specific and utilises gram negative bacteria more readily. In the Metropolitan Water filters in London, myxobacteria are more common. These are capable of killing and lysing a wide range of bacteria and feeding on the lysed cells. Although many antibiotic-producing organisms can be found in filter beds, it is doubtful in such an aquatic environment whether they can produce antibiotics in sufficient quantities to be effective and whether any antibiotics that were produced would be washed away by the flow of water. They may, however, be effective in their immediate micro-environment attached to the sand grains.

It is believed, however, that the protozoa play a major role in predation on other organisms in slow sand filters and have a significant effect on bacterial numbers and activity (Lloyd, 1973). All these organisms will feed predominantly on the saprophytic micro-organisms which are growing in the filter bed but in the process they will also feed on the intestinal bacteria and other organisms of public health significance that may be present in the untreated water and thereby improve the bacterial quality of the water.

The antagonism between the predators and the nutrient utilisers does not in fact reduce the activity of the nutrient utilisers. On the contrary, it is more likely to maintain an ecological equilibrium that effectively maintains the activity of all the organisms in the community (Waksman, 1937).

Effect of temperature

All micro-organisms have their optimum temperature for growth and activity. Mixed communities in an aquatic environment probably have optimum activity at temperatures around 30-35 °C. At higher temperatures the number of different species is more restricted and at lower temperatures rates of metabolism and hence growth and activity are progressively slower. It follows, therefore, that in prolonged cold weather slow sand filters are less effective and this becomes clearly apparent in seasonal differences in chemical and bacterial quality in filtrates in temperate climates. It also implies that they are less effective in countries with prolonged winters with extreme cold conditions apart from the practical problems of cleaning beds under continuing freezing conditions.

One pollutant that responds quickly to temperature is ammonia. This can be utilised as an energy source by some highly specialised bacteria. Nitrosomonas oxidises ammonia to nitrite and Nitrobacter oxidises nitrite to nitrate. Below about 4°C this process rapidly slows down and after short periods of exposure to lower temperatures such as during a cold night when beds are drained for cleaning, their ammonia oxidising capacity takes several weeks to recover. These organisms are also active in rivers and reservoirs and surface waters generally. so that in summer months most of the ammonia has gone before it reaches the slow sand filter, but in winter because of slower activity some ammonia may still be present for the filter to deal with. It has been shown (Report, 1971-73) that an effective way of dealing with this is to encourage an active population of the ammonia oxidising organisms by deliberately dosing the water with ammonia in the autumn and reducing this when the natural ammonia increases, so that this active induced population can continue to oxidise the ammonia.

Characteristics of Raw Water

Unsuitable Waters

The biological nature of slow sand filtration implies that some organic content of the water is required to encourage the necessary bacterial population that brings about purification. The method is therefore unlikely to be satisfactory with waters that contain no organic matter in solution and turbidity due to mineral matter. Neither is it advisable to filter highly turbid waters without some preliminary treatment as these will necessitate frequent cleaning.

Primary Treatment

Undoubtedly the best way to employ slow sand filters is in a dual filtration system with conventional rapid sand filters preceding them. To exploit the most recent results of research into slow sand filtration with maximum rates of filtration, it is important that primary filters should be operated at maximum efficiency. This requires much better cleaning of the sand than is achieved in most conventional filters of this type. It has been shown in the Thames Water Laboratories that particulate matter is liable to increase in the sand and as it increases, filtrate quality decreases. The most effective way of cleaning these filters has been found to be with a combined air scour and water wash sufficient partially to fluidise the bed.

The higher quality water that is obtained from adequately cleaned primary filters extends the interval between cleanings required for secondary slow sand filters and should enable faster rates of filtration to be used without getting significant silt penetration problems.

Algal Growth

Algae can cause filtration problems in two ways. Growth of unicellular algae in storage reservoirs results in an increase in particulate matter which has to be removed either on the primary or secondary filters or both. From the filtration management point of view, this requires more frequent cleaning of filters. Primary filters may require twice or more daily cleaning instead of once daily, and the limit to frequency of cleaning will depend on the hydraulics of the system and its degree of automation. The limit to frequency of cleaning of slow sand filters will depend on the mechanical facilities for sand handling and the available man power.

Filamentous algae

Algae can also grow in the filter beds and in the late summer months in the Thames area filamentous algae grow abundantly. During growth these tend to be semibuoyant and concentrated a few centimetres above the sand. Patches occationally break away and float to the surface. When the bed is drained for cleaning they form a large mass on the surface of the sand which has to be removed largely by hand labour before sand skimming can start. These algae are relatively slow growing dependent on temperature, sunlight and the nutrient quality of the water. Within approximately the first two weeks after cleaning their growth is sufficiently restricted to be able to remove them by normal sand skimming so that if cleaning were carried out during their period of active growth at intervals of not more than two weeks, it would be possible to cope with it by normal sand skimming procedures. These limits, however, are likely to be different under different climatic conditions and with different waters.

There are two slightly different ways in which these large quantities of filamentous algae can be removed. One is to drain the bed down so that the water is just above sand level. The wet mass of growth is then pushed to one side of the bed with wooden pushers and lifted out by crane. The other method is to drain the bed completely and rake the algae into heaps before removing it. If the latter method is adopted, it is essential that the heaps are removed as soon as possible and never left on the bed overnight. This material will very rapidly start to decompose and ferment accompanied by a rapid rise in temperature as in a manure or compost heap, reaching 30-35°C overnight. The cell walls of the algae will decompose and the liquid cell contents will drain out and a dark brown liquid will seep into the sand bed. Under these conditions Escherichia coli have been shown to multiply very rapidly (Report, 1969-70a), reaching numbers from 10 to 20 x 10^6 per 100 ml, in heaps left standing overnight. It is not surprising then that E.coli counts on filtrates from such filter beds are very high when they are first returned to supply.

Bed Shading

Algal growth of all types can be prevented by shading the bed from direct sunlight and in many parts of the world slow sand filters are operated under a roof in a building. This has many operational advantages in addition to the prevention of algal growth. It excludes pollution by birds, either by roosting gulls or by small birds feeding on detritus when the bed is drained down for cleaning, it permits cleaning to proceed during wet weather and it prevents problems from ice during cleaning in very cold weather. Experimental work carried out in the Thames Valley showed, however, that absence of algal growth did not extend the time interval between successive cleanings and that on the very large filter beds used, the cost of the cheapest method of shading was not justified by the saving in labour costs of cleaning (Report, 1969-70b and 1971-73).

Maintenance of Steady State

From all the foregoing it is clear that a slow sand filter is a unique ecological system with the sand acting as a supporting medium for a complex microbial population maintained by nutrients derived from the water constantly flowing through it.
The nature and distribution of that ecological population would inevitably change with any change in the environment, such as a change in filtration rate and more especially a cessation of filtration for cleaning purposes. With very slow filtration rates most of the nutrients would be used in the upper layers where most of the microbial activity would develop. With faster rates, nutrients would penetrate deeper and consequently microbial activity would occur at greater depths. Sudden changes in rates could therefore be expected to cause deterioration in efficiency in a slow sand filter. As the processes are biological, they have an oxygen demand and at very slow rates this demand could be sufficient completely to deoxygenate the water when the whole of the microbial flora would change and the surviving organisms would change the nature of their metabolism, resulting in the production of some very objectionable compounds in the water. It is essential, therefore, if a filter bed has to be stopped for any reason, that it is never left full of water.
When a bed is drained down for cleaning the bacterial micro-environment changes completely. Instead of the interstices of the sand receiving a steady flow of water with its accompanying nutrients, they become filled with air and the nutrient flow ceases. The metabolism of the bacteria changes becoming more oxidative in nature and the bacterial gums and other attachment mechanisms are used as nutrient sources, so that bacteria which were attached to the sand grain surfaces tend to become released so that when filtration recommences, bacteria that were previously attached to the sand become washed out into the filtrate (Report, 1969-70a). The longer the interruption in filtration and the higher the temperature, the greater these effects become. It is important, therefore, that beds are kept out of use for cleaning for as short a period as possible, especially in the summer months and that they are returned to their former filtration rates as rapidly as possible.
There is no advantage to be gained in starting at a low filtration rate and increasing it gradually over several weeks. If beds have been out of use for less than 24 hours, they can be returned to use at their former filtration rates within a further 24 hours.
It has often been stated in the past that filter bed efficiency is lower after cleaning until a new zoogleal layer or 'smutzdecke' is formed, but experimental work at the Thames Water Authority has shown that if cleaning times are short, beds may be returned to use at their maximum filtration rates within 24 hours without any deterioration in efficiency. The deterioration in efficiency that occured when cleaning was carried out by hand labour involving several days out of use was probably due to the metabolic changes described above.
This phenomenon manifests itself to the greatest extent when beds are kept out of supply for several weeks for resanding operations, especially in the summer months. Under these circumstances, some yellow pigmented aerobic sporing bacilli which are common filter bed organisms become detached from the sand and released into the filtrate in very large numbers when filtration is restarted (Report, 1971-73).

Fast filtration rates

When slow sand filters were first introduced for treating river water and with the hand labour methods of sand cleaning available, filtration rates rarely exceeded 2.4 m/day. Houston investigated the effect of primary rapid sand filters on the performance of of slow sand filters over many years (Reports, 1923 to 1933) and ultimately was able to increase rates to 4.8 m/day.
Experimental work at the Thames Water Authority has shown (Report 1971-73) that rates up to 12 m/day can be achieved without any deterioration in filtrate quality.
At these high rates the filter bed microflora extends to a much greater depth so that the whole of the depth of the sand is microbiologically active instead of a concentration of activity at the surface. This is accompanied by a deeper penetration of particulate matter, so that the normal bed cleaning skimmings do not keep pace with the accumulation of silt at lower depths and these rates cannot be continuously maintained. On full scale beds it was possible to operate at these high rates continuously for two years before a major sand cleaning in depth was required.
Two possible way of overcoming this problem which are under investigation are by improving the performance of the primary filters which has already been mentioned or by removing sand to a greater depth at each cleaning operation.
As a result of this work, however, filtration rates up to 7.2 m/day have been approved when the demand is high and on works which are hydraulically adapted to cope with the increased volume and the higher head losses that are involved at these rates. At 12 m/day available head losses of 3 m are necessary for effective operation and to avoid too frequent cleaning.

Management principles

The foregoing discussion has indicated that there are certain management principles which should be followed in operating slow sand filters to get the best results.

1. Start with effective primary filters.

2. Operate at a steady filtration rate which should not be rapidly changed at any time.

3. Never leave idle filter beds full of water.

4. Periods when the beds are left empty for cleaning or other purposes should be as short as possible.

5. Resanding operations which necessitate long periods of exposure should be carried out when temperatures are low rather than when they are high.

6. Beds may be returned to work at their maximum filtration rate if they have been out of supply for less than 24 hours.

7. Facilities for running filter beds to waste at their maximum filtration rate should be available.

8. 'Waste' water from filter beds giving unsatisfactory results can normally be refiltered on neighbouring beds without any problems.

9. Filamentous algae should never be left in heaps on beds overnight.

10. To obtain the maximum advantage from higher filtration rates facilities for adequate head losses should be built into the system.

11. The most economical filtration rates, and depth of sand skimming at each cleaning, and the accumulation of particulate matter in the depth of the sand, will depend on the quality of the water being filtered.

Ozonation and Slow Sand Filtration

When planning a programme of work on higher rates of slow sand filtration, it was assumed that there would be some deterioration in bacteriological quality and in order to overcome this an investigation into prefiltration ozonation was started.
It was soon shown, however, that there was no deterioration in bacteriological quality at higher rates of filtration, but the ozone investigation was started because of other possible benefits (Report 1971-73).
Technical problems with small scale ozone equipment considerably delayed this work but some preliminary observations have been made. Prefiltration chlorination has the disadvantage that chlorine residuals can interfere with the microbial activity in the filter. With ozonation there is no such problem because ozone residuals, if present at all, are very short lived.
The ozone partially oxidises the organic matter in solution and in particular it has a marked effect on colour (Vaillant, 1970).
The partially oxidised organic matter is more readily available as a bacterial nutrient. so that the micro-organisms in the filter bed can utilise this partially oxidised organic matter and break it down to simpler compounds, thus giving a further improvement in the organic quality of the water.
One of the objections to terminal ozone treatment is that this partially oxidised organic matter encourages the multiplication of bacteria in the distribution system.
If the ozone is added before filtration, this phenomenon is exploited by encouraging the baterial growth to occur in the filter so that there is insufficient organic matter left to encourage growth in the distribution system.
Short runs with prefiltration ozonation have shown that a better quality water can be produced but it has not yet been possible to study the effect of continuous ozonation.

References

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Bodemgebruik en aquatische ecosystemen

In projectgroep 5 van MAB heeft van 26 mei-2 juni 1978 een workshop plaatsgevonden voor de regio Europa met als thema: 'Land use impacts on lake and reservoir ecosystems'. De bijeenkomst was georganiseerd door het Poolse Nationale MAB-comité in samenwerking met Unesco. De 33 deelnemers waren afkomstig uit 16 landen.
Doel van de workshop was:
— het verkrijgen van een overzicht van de stand van zaken in dit veld van onderzoek;
— het vaststellen van belangrijke leemten in de kennis;
— het nagaan van de mogelijkheden om de contacten tussen landen onderling op dit gebied te versterken.
Een overzicht van het huidige kennisniveau werd verkregen door inleidingen over de volgende onderwerpen:
De invloed van het bodemgebruik op de excessieve eutrofiëring (Z. Kajak, Polen).
De invloed van de landbouw op de concentraties van stikstof en fosfaat in water (E. Procházková, Tsjecho-Slowakije).
De invloed van de bosbouw op waterbronnen (R. Pierce, USA en H. Keller, Zwitserland).
De invloed van recreatie en tourisme (E. Pieczynska, Polen).
Beheersing van de toevoer van nutriënten afkomstig van diffuse bronnen met behulp van primaire reservoirs (D. Uhlmann en J. Benndorf, DDR).
Paleolimnologische aanwijzingen voor de invloed van de mens (H. Löffler, Oostenrijk).
Ecologische indicatoren voor veranderingen in aquatische ecosystemen (A. Hillbricht-Ilkowska, Polen).
Het herstellen van gedegradeerde ecosystemen in meren (S. Björk, Zweden).
Het proces van de besluitvorming ten aanzien van het bodemgebruik (E. Fernald, USA).
De belangrijkste aanbevelingen voor MAB-5 luiden:
De aktiviteiten in elke regio dienen te worden geconcentreerd op één of enkele goed gedefinieerde problemen.
Voor de samenwerking in de komende paar jaar binnen Europa wordt als belangrijkste punt aanbevolen: de bestudering van de mechanismen via welke het bodemgebruik invloed uitoefent op aquatische ecosystemen.
Bijzondere aandacht moet worden besteed aan interdisciplinaire studies, waarin kwantificering plaats vindt van de toevoer van vaste en opgeloste stoffen uit een afwateringsgebied naar het ontvangende water.
Deze studies zouden de effecten moeten bevatten van de belangrijkste vormen van bodemgebruik, begroeiing, bemesting, afvalwaterlozingen en de toepassing van pesticiden.
Een nauwe samenwerking zou moeten plaatsvinden tussen MAB-5 initiatieven en relevante aktiviteiten van het Internationaal Hydrologisch Programma.
De in vele landen aanwezige kennis op het gebied van de interacties tussen terrestrische en aquatische ecosystemen dient méér te worden aangewend ten behoeve van ontwikkelingslanden. De contacten en de uitwisseling met, en de hulpverlening aan relevante onderzoeks- en opleidingscentra in ontwikkelingslanden moeten worden bevorderd.
Voor het onderzoek naar de invloed van het bodemgebruik op aquatische ecosystemen dient een minimum onderzoeksprogramma te worden opgesteld, waarbij standaardisatie moet plaatsvinden van bemonstering en analyse-technieken. De te verzamelen gegevens zijn onderscheiden in:
a. algemene gegevens van het onderzoeksgebied; b. hydrologische; c. chemische en fysisch-chemische; d. biologische.

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