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SLOW SAND FILTRATION

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I. INTRODUCTION

Slow sand filtration, the first of the modern water treatment processes, was initially developed by John Gibb at Paisley in Scotland in 1804 to obtain pure water for his bleachery. As a sideline to this industrial water treatment process, he would sell off excess filtered water to the local townspeople at so many pence a bucketfull. His design was improved by Robert Thom working at Greenock in 1827[1] and was later employed by James Simpson at the Chelsea Water Company in 1829. Slow sand filters were working at the Gorbals Sanitation and Water Company in 1846, and in 1852,[1,2] following the cholera epidemics which had ravaged London and other cities in Britain in mid-century, it became a legal requirement to slow sand filter all water extracted from the River Thames within 5 mi of St. Paul's. Of interest, both Robert Thom and the Gorbals Sanitation Company employed backwashing for their filters.[2]

From the middle of the eighteenth century, slow sand filtration became nearly universally employed for water treatment until the difficulties associated with high turbidities in surface waters — particularly with some surface waters in the U.S. — led to the development of the rapid gravity sand filter with all its necessary complexities of chemical pretreatment, backwashing, and auxiliary scour systems. However, slow sand filters are still widely used; 20% of the drinking water in the U.K. is still slow sand filtered,[3] as is 80% of all London water.[9] In London (Thames Water Authority), slow sand filtration is the third stage in a four-stage treatment process consisting of long-term storage, rapid sand filtration (or microstraining), slow sand filtration, and disinfection. London's slow sand filters cover a total area of about 72 ha.[4]

Slow sand filtration is of value as, in one simple operation, virtually all turbidity is removed from the water together with much of the organic material originally present and a significant amount of the color. More importantly, in many situations, slow sand filters possess the ability to remove a very high proportion of the coliform bacteria and perhaps virtually all pathogenic bacteria and viruses from the raw water and, distinct from rapid sand filters, they are also capable of removing all the cercariae of schistosomiasis.[5] The disadvantages of the slow sand filtration system include the relatively large area requirements, the high cost of cleaning, and, particularly, the reduced run lengths which result from high turbidities in the raw water. One very noticeable consideration apparent to anyone studying slow sand filtration is the very limited amount of information concerning them which is available in the literature, compared with that published on rapid sand filtration.

A. Filter Design

As with rapid gravity sand filters, slow sand filters consist basically of three sections — underdrainage, gravel, and sand — of which only the sand has any direct role to play in the purification process. Unlike rapid sand filters, the water reservoir above the sand bed in a slow filter can be considered as being actively involved in the improvement of water quality. The appreciable time, of between perhaps 5 and 15 hr, that the water is held above the sand allows for a substantial improvement in water quality as a result of sedimentation, natural flocculation, aerobic biological removal of biodegradable organic material, and die-off of bacteria, before the filtration process commences.

1. Underdrainage

The underdrainage, which has the dual purpose both of supporting the filter medium and of providing free drainage from the system, is traditionally composed of a series of lateral drains leading into a main drain. The lateral drains in such a system may consist of porous or perforated unglazed pipes, glazed pipes laid with open joints, perforated pipes of asbestos cement, or of perforated PVC pipes,[6] of which the latter two are now the most common. The main drains in small filters may also consist of pipes, usually not perforated, in which the cross-sectional area is about equal to the combined cross-sectional areas of the laterals connected to them.[7] In large filters the main drain is usually a concrete channel recessed into the filter floor and covered with tiles or jointed bricks.

Other useful underdrainage devices include[6] concrete slabs set with open joints onto precast concrete ribs or standard concrete tiles set on quarter tiles or a layer of large gravel (40 to 100 mm). Not unusually, in older filters the underdrainage has consisted simply of household bricks set on other bricks arranged to create the necessary channels. This system is still operating adequately in some filters built more than 80 years ago. Recently, there has been a movement to employ porous (no fines) concrete in which case the gravel layer is either dispensed with entirely or reduced to a depth of only about 80 mm.

2. The Gravel

Above the underdrainage the gravel layer again possesses a dual function both of ensuring uniform abstraction of the filtered water and, importantly, of preventing the filter medium (the sand) from entering and blocking the underdrains. The gravel employed should be free from sand, loam, clay, dirt, and organic impurities[6] and should in addition lose no more than 5% by weight after being immersed in concentrated hydrochloric acid for 24 hr. It is built up in a number of layers with the coarsest at the bottom and finest at the top; each layer is composed of carefully graded stones. Usually, the bottom layer should have a diameter of at least twice that of the openings in the underdrainage, and the top layer, in contact with the filter medium, should have a d_{10} not more than four times greater than the d_{15} value of the coarsest sand.[6] The depth of each layer is usually at least three times the diameter of its longest stone.[6] The depth of the gravel plus that of the underdrainage system will be about 0.5 m.

3. The Filter Media

Various materials have been employed for the filter medium in slow sand filters. Crushed coral has been used; volcanic ash has been employed in Ethiopia and the use of burnt rice husks have been investigated in South East Asia,[6] but nearly invariably the medium employed is sand. The sand used is characterized by its Effective Size (ES), a concept introduced by Hazen[9] in 1892, which is the mesh diameter in millimeters of a sieve which retains 90% by weight of the material and permits 10% to pass through, and also by its Uniformity Coefficient (UC) which is the mesh diameter of a sieve which retains 60% by weight of the material under test, divided by its ES. The recommendations for the ES vary between 0.15 and 0.4 mm. Huisman[6] and Than[10] suggest between 0.15 and 0.35 mm. Cox[11] suggests between 0.2 and 0.4 mm and Ridley[12] between 0.25 and 0.35 mm.

The UC should always be less than 3.0 and should preferably be less than 2.0,[12] although it is not necessary to go to extra bother and expense to reduce this to 1.5. Kerkhoven[14] suggested that builders' sand (ES 0.25 mm and UC 2.92) was nearly as good as a filter medium as a normal graded sand of ES 0.21 mm and UC 2.1, although he found that a coarser grade of builders sand with an ES of 0.32 (but with a UC of 2.59) was not really suitable. Joshi[15] reported that a filter-graded sand medium (ES 0.2 mm and UC 2.1) was capable of removing 74% of the applied COD from a particular surface water in India while two builders' grade sands (river sand subjected to minimal screening to remove the too coarse and too fine material), with ES values of 0.25 and 0.32 mm and UC values of 2.9 and 2.6, only removed 64 and 63% of the COD, respectively.

The sand medium employed should preferably be rounded[6] and free from clay, loam, and organic matter. If it is necessary to wash the sand before it is installed in the filter, this will also remove some of the finer grains and lower the UC. The sand to be employed in any particular situation depends largely on what is locally available and — particularly in the developing world — on the cost and transport requirements. It is possible to mix two or more types of sand to achieve a required effective size, but the mixing must be thorough and the resultant mixture will possess a higher UC than that of its components.[6]

Kawata[5] showed that river sand from a local river in North Cameroon required only a minimum of effort to become suitable as slow filter sand. A little washing and the discarding of the grains greater than 0.6 mm in size produced a sand of 0.3 mm ES and 1.72 UC.

It is essential that the ES of the sand selected should not be finer than is essential.[9] Too fine a sand, although improving the quality of the filtrate, will add appreciably to the head loss. The effectiveness of filtration depends not only upon the fineness of the sand, but also on the depth of the sand and on the rate of filtration. If an additional margin of safety is required in any filter it is better to increase the depth of the sand bed rather than to reduce the grain size. On this point it is impossible to overemphasize the importance of pilot plant investigations in the design of a slow filtration unit and in particular in the selection of the filter medium. Simple pilot-plant investigations are the easiest and most effective means of ensuring optimum results for the filtration of particular waters. The ES of the sand selected for the full-scale plant should be just small enough to prevent deep penetration of clogging material while producing a filtrate of the required quality.

The depth of sand required to assure effective filtration is a matter of some debate. The initial depth of sand at commissioning, or following resanding, will frequently be as much as between 1.2 and 1.4 m. This sand layer is then periodically eroded, perhaps 25 or 50 mm at a time, as a result of skimming (cleaning) operations. At some minimum depth, resanding becomes essential. Various minimum depths have been suggested, including 650 mm[16] and 800 mm,[11] although many units operate to considerably lower levels. The Bristol Waterworks Company, England, operate bed depths from a maximum of about 900 to 450 mm. It appears that a minimum depth of as little as 300 mm is adequate for turbidity removal and for the removal of a high percentage of the coliform bacteria from a moderately good quality feed water, but that a 600-mm minimum sand depth is necessary to ensure the removal of all viruses, and perhaps to complete the oxidation of ammonia.[17] Generally speaking, the poorer the quality of the raw water the deeper must be the sandbed.[18]

4. *The Water Reservoir*

Above the sand the depth of new water in the reservoir is commonly between 1.0 and 1.5 m — sufficient head to ensure an appreciable length of filter run. At the slow rate of filtration practiced, this depth of water results in a pronounced nominal retention before the filtration process commences and allows an appreciable degree of purification. The purification achieved stems from settlement of suspended solids, as a result of the coalescing of smaller particles and their subsequent settlement and from the aerobic biological breakdown of biodegradable organic material by heterotrophic bacteria in the presence of a substantial dissolved oxygen content. The lowering of the bacterial content in the 300 mm of water immediately above the sand has also been reported,[19] probably as the result of the migration of bacteria-ingesting protozoa upwards from the schmutzdecke.

B. Treatment Rates

The rate of flow of water through a slow sand filter varies commonly from 2.0 to 5.0 m^3/m^2/day, with perhaps 2.4 m^3/m^2/day (0.1 m/hr) being the "conventional" rate.[12] Naturally, the actual velocity of flow through the filter is appreciably greater than the approach velocity normally recorded by a factor of 1, where 1/p is the effective pore space (which might be about 0.4). Ridley suggested a rate of only 1.2 m^3/m^2/day for slow sand filters on their own, but an increase to 3.6 m^3/m^2/day if the water is pretreated either by rapid sand filtration or by microstraining. Flows as low as 0.6 and as high as 12 m^3/m^2/day have been reported,[18] although the latter rate was following prefiltration using rapid sand filters. Rachwal et al.[3] reported slow filtration rates in the Thames Water Authority of 2.9 m^3/m^2/day following preliminary rapid gravity filtration and 6.0 m^3/m^2/day following rapid upflow sand filters. Certainly, faster rates than the conventional figure of 2.4 m^2/day are possible without unacceptable filtrate quality deterioration if the feed water is not of low quality.

Studies at the National Environmental Engineering Institute at Nagpur in (NEERI), India[20] have adequately demonstrated that with good quality feed water (turbidity less than 10 T.U.), higher filtration rates than normally practiced are possible, but only at the expense of shorter filter runs. Using good-quality feed water a run length of 45 days was achieved at a treatment rate of 2.4 m^3/m^2/day. This corresponded to an annual throughput of 806 m^3/m^2. Doubling the treatment rate reduced the run length to 26 days, but raised the annual throughput to 1520 m^3/m^2/day. On increasing the rate further to 7.2 m^3/m^2/day, the run length came down to only 13 days but the annual throughput rose to 2000 m^3/m^2/day. However, it would be risky to apply these results to any raw water that is to be slow sand filtered. Too high rates with some lower-quality waters would result in silt being carried deeper into the filter, which would necessitate the removal of a considerably thicker-than-normal layer of sand at each skim, or may result in the deep blocking of the filter. Again, pilot-scale investigations are able to reveal the optimum rate of filtration in any particular situation and prevent either filtrate quality problems or problems created by deep blocking of the medium.

1. *Declining Rate Filtration*

With small filters serving small village communities — and, again, particularly in the developing world — it is often considered to be undesirable to continue the operation of the slow filters throughout the 24 hr, principally because it is unlikely that there will be more than one trained operator. In these situations it is normal to close down the filtration process overnight for a period which may be 8 or even 16 hr. Although any variation in the rate of filter operation is to be resisted,[18] the disadvantages of an overnight shutdown can be minimized if only the inlet valve to the filter is closed while the outlet valve is left open.[21] If both inlet and outlet valves are closed for overnight shutdown, the water in the reservoir above the sand becomes stagnant. The lower levels of the water are then in contact, for an appreciable period, with the highly biologically active surface of the sand. This results in the total removal of the dissolved oxygen at this level and the subsequent development of anaerobic activity. Anaerobic activity can create unpleasant tastes and odors in the water but, more importantly, as demonstrated at NEERI,[20] when the band of anaerobic water subsequently passes through the sandbed with the reopening of both valves in the morning the rate of removal of intestinal bacteria is radically reduced. If, however, only the inlet valve is closed and there is a continual, although decreasing, flow through the sand over the night period (declining rate filtration), anoxic conditions do not occur and the unwanted results of anaerobic activity are largely avoided. Paramasivam et al.[20] reported that, following the morning restart of a slow filter which had been closed down overnight, only 43 out of 49 samples taken as the stored water passed through were free from *E. coli* bacteria, as compared with 47 out of 48 for the control filter. They reported a substantial decrease in quality, following the morning startup, that took 8 hr to correct itself. No deterioration in quality was recorded from filters operating with a declining head overnight. The only major disadvantage of this declining rate mode of operation is that, with the water level above the sand being radically reduced towards the morning, there is a danger of large wading birds entering the filter and scavenging from the schmutzdecke. This can be prevented by allowing the height of the outlet weir to be increased to about 200 mm above the sand surface instead of the normal 100 mm.

II. PROCESSES OF FILTRATION AND PURIFICATION

The normal mechanisms of rapid filtration may be split between those mechanisms which operate to bring particles into contact with the sand grains and those which operate, once this is accomplished, to hold the particles in contact with the sand grains.[22-24] The former mechanisms include straining, sedimentation, inertial and centrifugal forces, diffusion, mass attraction, and electrostatic attraction. The latter includes electrostatic attraction, Van der Waals forces, adherence, and chemical bridging. No doubt all these mechanisms operate to some extent in slow sand filtration, but most will operate only to a far lesser extent than with rapid sand filtration. However, with slow sand filtration there is the additional most important purification process of biological activity.

A. Mechanisms of Slow Sand Filtration

Most simply, the purification achieved in a slow sand filter may be considered to be principally the result of straining through the developed filter skin and the top few millimeters of sand, together with biological activity. However, Huisman[7] suggested mechanical straining, sedimentation, adsorption, and chemical and biological activity as the important processes of slow filtration. Straining through the top sand layer of a clean filter will certainly remove much of the larger suspended matter from the water, but it is only when the straining action is enhanced by the formation of a filter skin that this mechanism becomes of major importance. A sandbed made up of 0.15 mm grains will possess pores of about 20 μm diameter and as a result will do little to retain bacteria (up to 15 μm) and certainly not colloidal materials (0.001 to 0.1 μm). Sedimentation, as a mechanism operating within the sandbed, must, during the early stages of the filter run, support considerably the surface straining process and is probably effective with the fraction of suspended material between 4 and 20 μm in size. Huisman[7] sees adsorption as being a most important additional mechanism for the removal of smaller particles. Biological activity, which is concerned principally with the breakdown of trapped organic material as well as with the removal by predation, and other mechanisms, of detached microorganisms is commonly accepted as being most pronounced in the filter-skin layer, but continuing, at a decreasing rate, to a depth of 400 mm or more through the sandbed.

1. The Schmutzdecke

As a slow sand filter is returned to operation at the beginning of a fresh run, there begins immediately, as a result of settlement from the water and straining at the sand surface, the accumulation of a layer of alluvial mud, organic waste, bacterial matter, algae, etc. in intimate contact with the top of the sand bed. This is known either as the filter skin or, more commonly, by the German word Schmutzdecke (dirt layer). The consistency of this layer varies considerably from filter to filter and from one period of the year to another, depending on the material (particularly the algae) of which it is composed. Not only is this schmutzdecke intensely biologically active, with its population of algae, protozoa, bacteria, fungi, actinomycetes, plankton, diatoms, rotifers, bacteriaphages, etc., it is also usually regarded as adding substantially to the effectiveness of the straining process, although at least one author[18] has suggested that the schmutzdecke is not essential and that effective filtration is possible without it.

Of the important mechanisms involved in slow sand filtration, straining is independent of the rate of filtration, which will also have little effect on the processes of adsorption. Sedimentation is dependent on the filtration rate, but the depth of the sandbed is so great, in relation to the low flow rate, and the fraction to be removed is so small that little adverse effect will be noticed from this source if the rate of treatment, within limits, is increased. Biological activity, however, requires time and is favored by slower treatment rates although moderate increases will merely push the activity further down the bed.

2. Biological Activity

Nearly all the suspended matter in the water is trapped at the schmutzdecke level where, if it is organic, it will eventually form the substrate for the mass of heterotrophic bacteria, and other microorganisms derived from the water, which multiply selectively at this level. From the sand surface, dissimilation products from the initial biological activity will be swept down,[7] to act as the substrate for the bacteria active within the upper levels of the sand, until complete breakdown and assimilation is usually achieved. The level of bacterial activity decreases with depth through the sandbed, but normally continues to a depth of perhaps 400 mm. Huisman[7] suggests biological activity is evident down to between 400 and 700 mm, with the depth decreasing as the temperature of the water increases. Nitrogenous organic material will be converted initially into ammonia, which is then oxidized by specific autotrophic bacteria to nitrite and then to the more stable nitrate. An indication of the maturity of a slow sand filter is the absence of ammonia from the filtrate.

3. The Removal of Organic Material

The removal of organics by slow sand filtration is significant, but by no means complete. A removal of 30% of the Permanganate Value by slow sand filters at the Fobney Works of the Thames Water Authority, England, has been reported[25] and Van de Vloed[26] produced a temperature-related empirical relationship of $T+11/9$ mg/l for the removal of Permanganate Value by slow sand filtration. The dependence of organics removal on treatment rate has been demonstrated[6] and it was suggested that the doubling of the rate of filtration would increase the Permanganate Value in the filtrate by 12%.

However, the Permanganate Value can hardly be accepted as more than an imprecise indication of the total content of organic material in the water. Average removals of 50 to 54% COD were reported by Joshi,[15] who also observed that the COD removal from a particular water was better, at the very high value of 74%, with a fine, well-graded sand than the 63 and 64% removals achieved with coarser and less well-graded builders' sand. COD removals of 67 to 73% at a rate of 2.4 m^3/m^2/day from an inflow COD content of between 5 and 10 mg/l have also been reported.[20] More detailed and informative results were produced by Rachwal et al.,[3] who reported that the removal of total organic carbon by slow sand filtration may be as low as 15%. They also reported that the reduction in the absorbance at 254 mm (an indication of aliphatic and aromatic double bonds) might be as little as 12% and that at 400 mm (largely an indication of color) as low as 23%. In addition, the removal of chlorinated organic compounds and of THM precursors by slow filtration is significant, but not remarkable. Burke et al.[27] reported the removal of 29% of the total organic chlorine (TOCl) and 23% of Trihalomethane (THM) precursors from River Thames water by slow filtration as compared with 27 and 53% removal by coagulation and flocculation followed by rapid filtration.

Schmidt[28] suggested that various chlorinated hydrocarbons are nearly eliminated by slow sand filtration although it is not certain whether these are then degraded or merely adsorbed and, either removed during bed skimming or washed out at low concentrations over a prolonged period. Mercury and other heavy metals are also nearly totally removed from the water, principally into the upper levels of the sand, and hence are probably eliminated during skimming, but, if appreciably below the immediate schmutzdecke, it is possible that they too are liable to wash out over a long period.

Sontheimer,[29] reporting on the results of river bank filtration in Germany, stated that there was a constant removal of 3.5 mg/l of dissolved organic chlorine (DOCl) and 10 mg/l of COD, independent of the quality of the river water being filtered. He suggested that the higher the substitution of chlorine in the molecule the lower the observed removal. He also reported appreciable percentage removals of heavy metals such as 33% of the applied mercury, 75% of the cadmium, and 94% of the chromium. Color removal by slow sand filtration is not normally very pronounced. A 30% color removal is often considered to be average. Slade[30] reported a 28% color removal from an original 24 Hazen Units (HU) in River Thames water while Bowles et al.[9] reported from Australia the reduction of the far more easily removable apparent color from 90 to 5 HU. The most abundant organic material in surface is usually humic (colored) material, but the organic content of surface water often also contains synthetic compounds of industrial origin such as detergents, pesticides, oils, and phenols to which the microorganisms of the sandbed quickly adapt, as has been demonstrated[18] with phenol, *m*-cresol, and resorcinol phloroglucinol. However, Rashwal et al.[3] also indicated that removal of biodegradable organic material, as measured by the newly developed ATP test, was as high as 50%.

4. Pre-Ozonation

Rachwal et al.[3] were particularly interested in the effect of pre-ozonation on waters passing through slow sand filtration units. They have reported on extensive pilot-scale and full-scale investigations carried out by the Thames Water Authority in England. The Thames Water Authority is possibly the largest employer of slow sand filters in the world. The actual process of ozonation removes surprisingly little of the organic material, with only about 2% of the total organic carbon being destroyed, but it does bring about major modifications in the type of organic material present, resulting in a decrease of 60% in 254-mm absorbance and of 80% in 400-mm absorbance. The effect of ozonation on the organics in the water is largely to break down larger nonbiodegradable molecules into smaller, biodegradable molecules. The removal of total organic carbon from pre-ozonated water by slow filtration was about 35% as compared with the mere 15% achieved by the reference filter treating non-pre-ozonated water. In addition, there was 75% reduction in biodegradable organic material (ATP test) with slow filtration of ozonated water as compared with the 50% for the filtration of the same source water to which ozone had not been added. There was, in fact, very little difference in the content of biodegradable organic material in the filtrates from the two slow filters (pre-ozonated water and non-pre-ozonated water), although that from the pre-ozonated water was slightly better. There was, however, a considerable difference in the total amount of organic material removed which included up to 70% of the absorbance at 254 mm and 87% of the absorbance at 400 nm by the filter treating ozonated water. Both 1-hr and 7-day THMs and also TOCl were appreciably lower in the slow sand filtered pre-ozonated water than in the filtrate from the reference filter.

5. Aerobic and Anaerobic Activity

While being concerned with biological activity, it is necessary to emphasize the aerobic nature of the biological activity in a slow sand filter. The beneficial biological processes will only continue to operate while there is dissolved oxygen present in the carriage waters. Aerobic biological activity will only continue if the water entering the sandbed contains a minimum of about 3.0 mg/*l* of dissolved oxygen[81] and even at this level of dissolved oxygen the filtrate will probably be anoxic, charged with carbondioxide, and in immediate need of re-aeration. Should the water about to be filtered become anoxic, a number of undesirable results can ensue. Instead of aerobic biological activity in the sandbed there would be anaerobic activity, which nearly invariably produces unwanted end products which create taste and odor. In addition, normal aerobic processes in the reservoir water prior to filtration frequently results in the oxidation and subsequent precipitation of iron or manganese salts, which are then removed at the surface of the filter. Anoxic conditions will lower the oxidation potential and can produce the conditions necessary for the reduction and resolvation of deposited manganese and iron from the surface of the bed, subsequently allowing these salts to pass into the supply system. Perhaps more importantly, as reported above, as a band of anoxic water passes through the slow sand filter the percentage removal of intestinal bacteria will be appreciably lower than under aerobic conditions.

B. The Removal of Bacterial and Other Organisms

1. Mechanisms of Removal

The removal of bacteria from the water passing through slow sand filters is probably due primarily to the action of predators, although the eventually lethal effect of being trapped, as the result of the normal mechanisms of filtration, and held in an unfavorable environment, cannot be discounted. However, investigations by Lloyd[31] have demonstrated the presence of large numbers of bacterial predators of various types both in the interstitial spaces and attached to the sand grains. Many antibiotic-producing microorganisms (bacteria, fungi, actinomycetes, etc.) will also be present in the schmutzdecke, but it is unlikely[18] that antibiotics can be developed in sufficient concentration as those produced are continually being washed away. However, it is possible that produced antibiotics may have some effect on the microenvironment attached to sand grains. Predation will be by a number of species, including bacteriophages, actinophages, mycophages together with bacterial predators of the genus *Myxobacterium*, actinomycetes, and fungi.[18] Larger organisms such as nematodes, oligochaetes, and rotifers may possibly also act as predators at the sand level. However, the major predators are nearly certainly protozoa, which play a very significant role[18] while feeding predominantly on the saprophytic organisms of the sandbed, but also removing the unwanted microorganisms of an intestinal origin. Temperature obviously greatly effects the activity of antagonistic organisms such as protozoa and nematodes, and results from one slow filter in England[32] revealed a drop in the rate of *E. coli* removal from 99% mean for the year to only 41% during a severely cold spell during February 1956. Windle-Taylor[17] considered that antiviral effects were due to the presence of protozoa, but were also due to the presence of molds which produce the substance "statolon" (mycophages which induce the formation of interferon).

2. *Protozoa in Slow Sand Filters*

Evidently, protozoa are of some considerable importance to the purification processes within a slow sand filtration unit. Richards[33] reported heavy concentrations of protozoa within the top 300 mm of a slow sand filter at Walton-on-Thames, England, with small amoeba present at about 3000/cm^3 at the beginning of a run and increasing in numbers to about 21,600/cm^3 at the end. Flagellates were more abundant, reaching 64,000/cm^3 following 6 weeks of operation. Approximately 10% of both the flagellates and small amoeba were found to be in the encysted form. Ciliate numbers ranged from 10 to 150/cm^3 and large and testate amoeba were present in the range of 1 to 1000/cm^3. The numbers of protozoa present — with the exception of *Cyclidium* sp. — declined rapidly with depth, but populations of all groups were found as deep as 200 mm, with small amoeba being present down to 300 mm. *Cyclidium* sp. differed from all the other protozoa present by reaching a maximum concentration at a depth of between 30 and 60 mm. Interestingly, the numbers of *E. coli* were found to vary inversely with the numbers of the flagellates and ciliates, but there was no correlation between the numbers of *E. coli* and the small amoeba. In a slow filter in Australia, Bowles et al.[9] found protozoa together with algae, rotifers, and invertebrates to be abundant in the first 10 mm of sand, but the numbers decreased rapidly over a depth of 80 mm. Of the protozoa, small flagellates were abundant, ciliated species were common, but amoeba were rare.

3. *The Extent of Bacterial Removal*

It is widely accepted that slow sand filtration is a highly effective means of removing bacteria and other microorganisms of intestinal origin from water. High generalizations are sometimes made for the removal of coliform organisms and more specifically for the removal of *E. coli* organisms. It is, however, rather more difficult to discover precise information from the literature.

Huisman[7] suggested that the total bacteria count in water is reduced by a factor of between 1000 and 10,000 and that the factor for the removal of *E. coli* varies between 100 and 1000, with usually none appearing in the filtrate. Van Dijk[21] suggested that between 99 and 99.9% of pathogenic bacteria are removed during slow filtration. Longdon and Fox[34] stated that with their investigations the count of total coliforms in the filtered water rarely exceeded 1 per 100 m*l* from a raw water count which varied between 10 and 10,000 per 100-m*l* sample. Bowles et al.[9] recorded a reduction of coliform numbers from 6000 to 105 per 100 m*l* (98.25% removal) with slow sand filtration during April/May in Victoria, Australia, but with the far less impressive figures of only 122 per 100 m*l* down to 108 per 100 m*l* (11.5% removal) when the water temperature dropped to 6°C in July. Paramasivam et al.[20] recorded the presence of *E. coli* in the filtrate from a slow sand filter in India in only 1 sample out of 48. Joshi et al.[15] recorded the effect that shading had on bacterial removal with 98% of the filtrate samples being free from *E. coli* with a completely shaded filter, but only 68% being free with a filter open to the sky. Joshi also reported on the effect of sand size, with 89% of filtrate samples being free from *E. coli* with sand sizes of 0.21 and 0.25 mm, but only 66% of the samples free with an ES of 0.32 mm. Burman[32] reported a normal reduction of both coliforms and *E. coli* of 99% throughout most of the year in the English climate, but that during persistent cold weather in winter this reduction dropped to 88% for the coliforms and 41% for the *E. coli*. Burman also reported little drop off in the efficiency of bacteria removal immediately following filter cleaning, with the coliform removal being constant before and after at 99%, but with the *E. coli* removal being reduced somewhat from 99 to 94%. In addition, Burman[32] considered the ability of slow sand filters to remove spore-forming bacilli, which he suggested were present in the raw water either as a result of sewage contamination or from the run-off from plowed agricultural land. He pointed out that these organisms are appreciably resistant to chlorination, but that slow filtration had reduced their numbers by a mean of 81% at one works and 88% at another, although immediately after bed skimming this had been lowered from 81 to only 73%.

Poynter and Slade,[4] operating with laboratory-scale filters of 0.092 m^2 surface area and 600 mm depth, recorded a 99.6% removal of coliform organisms and a 99.5% removal of *E. coli* over a period of 18 days at a temperature of 5°C and a treatment rate of 4.8 m^3/m^2/day. Increasing the treatment rate to 9.6 m^3/m^2/day had no significant effect on these removals; 100% removals of coliform organisms were recorded with another laboratory-scale investigation[35] (0.06 m^2 surface area, ES 0.28 mm, 750 mm depth) with inflow concentrations varying from 6000 to 27,000 per 100 mℓ at a treatment rate of around 2.4 m^3/m^2/day. Filtration of a secondary wastewater treatment works effluent, containing up to 2,750,000 presumptive coliform organisms per 100 mℓ, through another laboratory-scale slow sand filter (0.06 m^2 surface area, ES 0.3 mm, 0.9 m depth, 3.5 m^3/m^2/day) at about 14°C resulted in the removal of an average 97% of these organisms.[36]

4. Results from Operational Filters

Results for a 3-year period supplied by the West Hampshire Water Company in England[37] for their slow sand filters indicate a relatively low percentage of bacterial removal during the summer months (June, July, August) with a mean removal of about 92% for *E. coli* with results varying from 64 to 100% removal. The corresponding figures for coliform removal were about 87% in a range from 60 to 100%. During these periods the *E. coli* count in the water supplied to the slow filters was always under 500 per 100 mℓ and commonly less than 50 per 100 mℓ. Inflow water coliform counts were a little higher, but less than 1000 per 100 mℓ and commonly less than 50 per 100 mℓ. Winter removal figures (December, January, and February) were surprisingly better with a mean removal of *E. coli* for those periods being about 95% and for coliforms about 97%. These higher winter removal figures are probably the result of the far higher *E. coli* and coliform counts in the feed water to the slow filter, which were up to 10,000 per 100 mℓ on occasion and averaged about 1000 per 100 mℓ for each organism.

Results of slow sand filtration (2.29 to 3.7 m^3/m^2/day) for a 7-year period from the nearby Bournemouth and District Water Company[38] show a remarkably consistent removal rate for coliform organisms of about 96.5% summer and winter from a mean count of approximately 3600 per 100 mℓ during the winter months, but only about 500 per 100 mℓ during the summer months. For the Chigwell Treatment Works of the Essex Water Company (2.4 to 3.5 m^3/m^2/d, ES 0.25 mm) over a 5-year period[39] only 8 samples from 35 for the months of July (water temperature 16 to 19°C) show the presence of *E. coli* in the filtrate from the slow sand filters and then only one or two organisms per 100-mℓ sample, but the inflow count was always below 20 per 100 mℓ. The only January results (1984) which indicated any appreciable number of *E. coli* in the feed water to the slow sand filters give an average of less than 3 per 100 mℓ in the filtrate from an inflow count of more than 100 per mℓ (water temperature 4 to 6°C).

Presumptive coliform removals at this works were similar to those for *E. coli.* Langham Treatment Works of the Essex Water Company[39] operates at the same rate and with the same size sand as at Chigwell. During the months of January (water temperature 2 to 7°C) 35% of the filtrate samples, for those days on which positive results were obtained from the inflow water, showed no coliform organisms from a mean inflow count of approximately 420 per 100 m*ℓ*. For the same period more than 81% of the filtrate samples showed no *E. coli* organisms from a mean inflow count of more than 170 per 100 m*ℓ*. The results for July (mean water temperature 19°C) indicated that 66% of the filtrate samples were free from presumptive coliforms and 86% of the filtrate samples were free from *E. coli* from inflow counts which ranged from 4 to 240 per 100 m*ℓ* for the coliforms and from 4 to 43 per 100 m*ℓ* for the *E. coli.*

Results from the slow sand filters at the treatment works of the Newcastle and Gateshead Water Company[40] show a mean reduction of presumptive coliform organisms (inflow 45 to 5000 per 100 m*ℓ*), over a 5-year period, to be 94.1% during the months of January, February, amd March (mean temperature 2°C) and only 90.5% for the warmer months of June, July, and August (mean temperature 15°C). For both the winter and summer periods the removal of *E. coli* organisms averaged 88.8%.

5. The Extent of Virus Removal

Virus removal by slow sand filtration was demonstrated as being highly effective by both Windle-Taylor[17] and Poynter and Slade,[4] although Windle-Taylor reported that viruses were not removed by clean "sterile" sand.[4] Filtering water containing about 100 plaque-forming units (PFU) per milliliter of attenuated poliovirus 1 through a 600-mm depth of sand at a rate of 4.8 m^3/m^2/day a virus removal rate of 99.9% or greater was achieved[17] at various temperatures below 20°C. With a sand bed of only 300-mm depth it was found that four viruses passed through for every one passing through the 600-mm sand bed, but this still represented a 99.6% or greater removal by the shallower filter. Increasing the rates of treatment to 7.2 m^3/m^2/day drastically reduced the efficiency of removal. Windle-Taylor also reported on the marked reduction in virus numbers on storage in the reservoir. This amounted to a reduction of between 60 and 75% per day at temperatures of only 4 to 5°C, while at 20°C nearly complete removal was possible in 24 hr. These results must indicate the importance of the appreciable retention time available for the water in the slow filter above the sandbed.

Poynter and Slade,[4] employing a 0.09-m^2 surface area laboratory-scale slow filter, investigated the slow filtration of water containing between 400 and 600 PFU/m*ℓ* of the LSc 2ab strain of poliovirus 1. They concluded that slow sand filters are extremely effective at removing enteroviruses although the efficiency of removal is affected by temperature. At a treatment rate of 4.8 m^3/m^2/day through a 600-mm depth of sand a 99.999% removal was achieved at a temperature of 11 to 12°C, but this removal efficiency dropped to 99.8% at 6°C. In warm weather (water temperature up to 18°C) they considered that only one virus in a million passed through the slow filter. Faster treatment rates, as appreciated by Windle-Taylor, markedly reduced the removal of viruses. At 4.8 m^3/m^2/day and 5°C, 99.93% of the viruses were removed (also 99.6% coliform and 99.5% *E. coli*), but this was reduced to 99.78%, (99.4% coliform, 99.6% *E. coli*) at a treatment rate of 9.6 m^3/m^2/day. A further increase in treatment rate to 12.6 m^3/m^2/day resulted in only a 98.05% removal of the viruses together with 93.2% of the coliforms and 97.0% of the *E. coli.*

Later work[30] on virus removal using full-sized filters (0.337 ha), at the Coppermills works of the Metropolitan Division of the Thames Water Authority, operating at rates which varied from 1.12 to 4.15 m^3/m^2/day at temperatures between 6 and 11°C revealed virus reductions of between 97.1 and 99.6% with an average of 98.7%. That these percentage removals were lower than previously reported by Poynter and Slade[4] was probably due to the sandbeds employed being only 0.45 and 0.3 m deep as compared with the 0.6 m for the earlier work. Although filter cleaning had some effect on the removal of bacteria, it had none on the reduction of viruses. This work by Slade revealed that no one type of virus was removed preferentially and that a greater variety of viruses was present before as compared with after filtration. Cocksackie viruses Bl and B5 were the most common in the prefiltered water with the occasional appearance of cocksackie B3, B4, and polio 2. Poliovirus 1 was isolated from the prefiltered water on one occasion. Cocksackie viruses B1 and B2 were discovered in the filtered water together with the occasional polio B2. It was concluded that coxsackie group B and poliovirus behave similarly in a slow sand filter and that therefore the results of earlier experiments using attenuated poliovirus type 1 are applicable to a much wider range of viruses.

Poynton and Slade,[4] operating with small laboratory-scale filters, found that *E. coli* reductions were slightly less than those for poliovirus, although the removal rates were parallel. Consequently, they concluded that the removal of *E. coli* organisms represented a good parameter by which to judge the removal of viruses through a slow sand filter. As a result of the work with full-scale filter and with far larger volumes of water, Slade[30] found the removal percentages of *E. coli* organisms to be slightly less than for viruses and again concluded that *E. coli* removal can be used as a guide to virus reduction by slow sand filters. However, he pointed out that the absence of *E. coli* in some slow sand-filtered samples which did contain viruses illustrated the limitation of *E. coli* removal as an absolute indication of viral pollution. The weaknesses of the present tests he suggested is the limited volume (100 m*l*) of water on which the *E. coli* test is based as compared with the 15 to 200 *l* employed for viral examinations.

6. *The Removal of Schistome Cercariae*

Schistosomiasis (Bilharzia) is one of the major plagues of the modern world with perhaps more than 300 million people suffering from the disease at the present time. This number is increasing, particularly with the spread of irrigation.[41] The vector for this disease is an aquatic snail. The disease is caused principally by one of four species of trematode worms — *Schistosoma japonicum, S. mansoni, S. haematobium,* and *S. intercalatum* — which between them exist in nearly every country in Africa, through much of South America, the Middle East, and in several countries of the Far East.[42]

The infective organisms for man are the cercariae produced from the infected intermediate host, the snail. Although these cercariae cannot exist for extended periods in water, in that they die off completely within 72 hr and probably within 24 hr, they are moderately resistant to chlorination, are not removed by coagulation and flocculation, and pass through rapid sand filters. Small grain size sand filters and, also, diatomaceous earth filters will effectively remove the cercariae. Several workers[43-46,48] investigated the capabilities of various types of sand filters for removing the cercariae from water, but only recently have reliable results[47] been produced from adequately controlled experiments. Leiper,[43,44] working in Cairo, had no success with a 102-mm depth of desert sand, nor did he have any success when he precoagulated the water. Also using precoagulated water, Witerberg and Yofe[45] found that the cercariae passed through a 750-mm depth of sand, although neither sand size nor treatment rates were recorded. Using 0.91-m column of 0.1 to 0.4 mm sand at a rate of 2.7 m^3/m^2/day, Unrau and Richards[47] were able to remove all the cercariae from the raw water. During a later investigation, Unrau[46,47] reported that it was possible to remove all cercariae, dosed at a concentration of 10,000 per 200 m*l* of water, using a sand with an ES of 0.22 mm and a UC of 1.73 and with a treatment rate of as high as 72.2 m^3/m^2/day. Laboratory-scale horizontal sand filters investigated by Benarde and Johnson[48] and filled with a 952-mm length of 0.35 mm sand removed all cercariae from the inflo water even at rates of up to 24 m^3/m^2/day. Similar results with horizontal-flow sand filters of 1.5 m length and 0.37 mm ES operated by Unrau[46] also proved effective at removing all cercariae.

Kawata[47] carried out a series of controlled laboratory experiments employing 152-mm diameter PVC tubes filled with sand of either 0.2, or 0.3, or 0.4 mm ES. The treatment rates were 9.6 or 2.9 or 0.96 m^3/m^2/day, with a constant 2.4 m head of water above the sand. Some 2000 cercariae (1 to 2 hr old) were placed at the top of each column at the beginning of each monitored run; 15.1% of the applied cercariae was recovered from the filtrate of the 0.4 mm ES, 600-mm deep sand column operating at 9.6 m^3/m^2/day within a 6-hr period while only 0.1% was recovered from the 0.2 mm ES, 600-mm deep column operating at 2.9 m^3/m^2/day within a 10-hr period. Using a deeper bed of 1.2 m sand, no cercariae were recovered from any of the filters at any of the treatment rates. Kawata concluded from his work that in order to be certain of removing all cercariae, a slow sand filter should have an initial sand depth of 1.2 m and a minimum depth of 0.6 m, that the sand should be of an ES of 0.3 mm or less, and should be operated at no more than 2.9 m^3/m^2/day.

7. *Removal of Aquatic Animals*

During investigations carried out by the Water Research Center in the U.K. into the penetration of various water treatment processes by aquatic animals,[25] it was discovered that slow sand filters gave better results than either rapid gravity sand filters or pressure filters, and certainly better results than those obtained with coagulation, flocculation, and sedimentation, which, on occasion, resulted in increases in the animal counts.

At the Castle Carrock works the slow sand filters reduced the animal count from about 8900 to only 3.6 animals per cubic meter in the filtrate. By comparison the pressure filters, working in parallel, only removed 75% of the animals immediately after backwashing and immediately prior to backwashing allowed 20% more animals through than were passing on to them. The Staines slow sand filters accomplished a similar reduction with the animal count, being reduced from about 240 to only 0.6 animals per cubic meter. Slow sand filters were thus responsible for a very high quality of finished water from the point of view of the animal populations. Those animals which did penetrate through to the filter effluent were normally benthic species which could have been expected to colonize the filters. Planktonic species were effectively removed by the filters.

Results obtained at the Fobney Water Treatment Works were not as good as those from Castle Carrock or Staines. This was considered to be a result of the vulnerability of the site to flooding and many of the animals in the filtrate were probably due to colonization of the filter beds and underdrains. Several species which were not conspicuous in the raw water, but which are characteristic of aquatic substrate or waterlogged solid media were found in the filtrate. These included numbers of the *Gastrotricha*, various species of oligochaete worms, and two species of harpacticoid. Filter cores from the Fobney slow filters revealed that, in general, animal numbers were appreciably higher in the upper levels of the sand, with the prominent exception of nematodes which were present in large numbers in the lower levels. This suggested their colonization of those regions. The Fobney filters were also effective at reducing algal counts by about 90% to a mean of about 24 clumps per milliliter.

III. FILTER OPERATION

A. Commissioning a New Filter

Since an effective slow sand filter is a highly biologically active unit, it is not possible to consider operating a filter freshly filled with a clean medium with the expectancy of achieving a highly purified potable water immediately. Initially it is necessary to fill the filter with water and this is always done by filling from the bottom upwards. The upward movement of the water drives the air before it and prevents large and potentially very disruptive bubbles from being trapped in the sand. Usually, this filling from the bottom is continued until the water has appeared above the medium and there is a protective depth of between 100 and 200 mm above the sand, so that when the bottom valve is closed and filling from the top commences, in the normal manner, there will be no scouring of the sand surface by the inrush of water.

Once the water level in the reservoir above the sand has reached the normal operating head (1.0 to 1.5 m), filtration can be started at about one quarter[26] the design flow rate. Then, over the next few weeks, the rate of treatment is slowly increased to the design flow while the filter medium gradually "matures". During this period the filtrate from the new filter is run either to waste or is recycled through another mature filter.

With the slow filtration of raw water the schmutzdecke will develop within a few days on even hours, but the maturing process is concerned not so much with the largely organic filter skin developing on the surface, but with the changes occurring within the top 400 mm or more of the sandbed. To some extent, the process of maturation will involve the development of the correct balance of electrostatic charges on the individual grains of sand, particularly if the sand is derived from newly crushed rock, but most importantly maturation is associated with the slow development of the required balance of bacteria and other microorganisms in the zoogloeal layer developing on the sand grains. The developing biological activity will have the triple role of entrapping and destroying unacceptable microorganisms, of facilitating the breakdown of organic material from the water, and also of autotrophically oxidizing the ammonia, resulting from the breakdown of nitrogenous organic matter, to nitrate. The period of maturation may require a time of up to 40 days, or even more. Schmidt[28] has demonstrated more than 40 days is required before a new filter is capable of eliminating 100% of synthetic detergent present in the inflow water. With the increasing temperature the period required for maturation will decrease appreciably. Towards the end of the expected period of maturation tests should be made on the filtered water to ensure that the required physical, chemical, and, particularly, the bacteriological purification is being achieved before it is put into supply. In situations in which there is only a limited capacity for testing water quality, and perhaps, none for carrying out bacteriological checks, ammonia determinations can be very helpful. There should be no ammonia in the filtrate from a mature filter.

B. Filter Cleaning

The length of the run between one filter cleaning and the next will depend upon a number of factors: on the rate of filtration, the size and uniformity of the sandbed, the quality of the water being filtered, and particularly on climatic conditions which greatly influence the development of algal blooms. A "normal" run will vary from situation to situation and might be anything from 30 to 60 to 100 days or more. Immediately after cleaning, the outlet control valve will only need to be slightly open to achieve the required filtration rate. Then daily it will be opened little by little, more and more, to ensure that the correct flow through the filter is maintained as the head loss develops until the valve is fully open. Bed cleaning is necessary when, with the maximum water head above the sand and the outlet valve fully open, it is no longer possible to achieve the design flow rate.

For filter cleaning the sequence of operation is normally as follows:[12,49]

1. Close the inlet valve and allow the water level to drop by continuing filtration, preferably overnight.
2. Open the drain valve situated just above the sand surface to run off any remaining supernatant water.
3. Allow the water to drain down to within about 200 mm below the sand surface.
4. Skim off about 25 mm thickness of the accumulated schmutzdecke and associated sand.
5. Return the filter to operation.

Should the situation require it, Step 1 can be dispensed with and the operation commenced with Step 2. Step 4 should be carried out as quickly as is feasible, preferably in 1 day. Most authorities on slow filters[12,49] would accept only the necessity to drain down to about 200 mm below the sand surface, but some[18] would like to have the filter completely emptied in order to prevent the development of anaerobic conditions in the flooded but static bed. Certainly the longer the cleaning process takes or the more elevated the temperature the greater necessity there is to drain the sand completely.

1. Manual Cleansing

Traditionally, skimming is carried out manually although mechanized skimming processes are now incorporated at most larger modern works in the developed world. Labor-intensive practices are still more acceptable in most of the Third World. Manual skimming is usually carried out by gangs of men using broad-bladed shovels and wheelbarrows, although scraping by hoe and sand transportation by baskets balanced on the head is more normal in some parts of the world. The practice is to scrape the schmutzdecke and sand into a number of low, parallel windrows from which it can be easily shoveled up and barrowed away. If wheelbarrows are being used it is important to prevent penetration by the wheels into the sandbed either by running on planks or by employing barrows with broad tires. Semimechanized removal will involve manual skimming, but removal of the sand by conveyor belt or by water jet-operated sand pump. If the schmutzdecke is formed largely of filamentous algae it will be easily curled back and removed so long as it is not too dry and brittle. However, should the schmutzdecke be composed of diatoms or other nonfilamentous microorganisms, cleaning is less easy and closer supervision of the work force is necessary. On occasions, if it is essential to return a filter to operation quickly and if the work force is limited, it is possible merely to rake the schmutzdecke into ridges without removing it and then to refill the filter for a further run. A thorough clean can then be carried out on the next occasion.

It is of importance that the cleaning process is carried out as quickly as possible not only to ensure that the slow filter unit is back in operation and producing treated water as soon as possible and with as little overload on the other parallel units as can be managed, but also to avoid the drying out of the filter bed and to prevent pollution of the exposed sand surface. A 24-hr period for a slow sand filter to be out of operation for cleaning, which includes draining down, skimming, smoothing, and refilling, should be the optimum period. The four men, for 4 days using vehicular scrapers at least one English works must be considered to be excessive. Excessive drying of the filter sand will result in the death of much of the microorganism population and in a major reduction of biological activity once the filter is returned to operation. Allowing the bed to stand empty, or with at least the top section drained of water, will result in highly aerobic conditions for the microorganisms adhering to the sand grains. No normal substrate will be available for the microorganisms during this period which will, as a result, turn to the bacterial gums and other attachment mechanisms as a source of substrate.[18] The ingestion of the attachment gums will leave many bacteria free to be washed through when the filter is next operated, thus reducing the effectiveness of the treatment and adding many additional bacteria to the filtrate. The longer the interruption and the higher the temperature the more pronounced will be the effect. This phenomenon is most marked when the filter has been out of operation for some time, probably for resanding, when it is not uncommon for yellow-pigmented sporing bacilli (normal bed microorganisms) to become detached and to impart a pronounced yellowish color to the filtrate on restart.[18]

Sandbed surface contamination can occur from a number of sources, but principally from birds (avian pollution), from the men working in the filter, and from the vehicles which are frequently used for skimming and sand transport. In many parts of the world avian pollution can be very troublesome, and at times potentially dangerous, because of the depth into the sand to which this pollution may seep — the bigger the birds the greater the problem. In some areas it may be necessary to employ young boys to act as bird-scarers to ensure that the birds do not alight in unattended sections of the drained filter.

Bed pollution by the work force can be avoided by taking a few elementary precautions. Regular health checks of the workers are essential, no matter where in the world the filters may be operated, to ensure that no carriers of enteric diseases are working in an exposed sandbed. A cholera carrier may excrete 10^6 cholera vibrios per day[50] and yet feel perfectly well. It is necessary that every time a worker enters or reenters the sandbed he must be forced to walk through a shallow bath of disinfectant — preferably followed by a bath of clean water — to ensure that no contamination is carried in on his feet. In addition, it is necessary to control the sanitary habits of the workers while in the filter. Some authorities[66] suggest supplying the work force with protective clothing — overalls and rubber boots — not to protect them, but to act as a further safeguard for the exposed sand. Should protective clothing be issued it is of importance that it is only worn during filter cleaning operations. There was a situation which developed in East Africa where, following each filter cleaning, it was noticed that the coliform count in the filtrate shot up to alarming levels, and then it was realized that the workman who cleaned the small filter was wearing the same boots that he also wore to clean out septic tanks!

During the filter cleaning process it is also necessary to swab down the walls of the filter box to remove adhering algae and other growths. As each skimming lowers the level of the sandbed, it is periodically necessary to adjust the heights of the supernatant drain and of the outlet weir. Filters are returned to operation by filling from the bottom until there is a sufficient, scouring-preventing depth of water above the sand and then reverting to normal filling. Operation is often commenced at about one quarter the initial flow rate and increased to full rate over about 12 hr.[18] The filtrate is again wasted (or recycled) for between 24 and 48 hr to allow an effective schmutzdecke to become established. The filtrate is returned to supply when testing has demonstrated it has attained an acceptable quality. Should it not be possible to test the filtrate, or if the water is not chlorinated before going into supply, it is advisable to allow 48 hr before the filtered water is sent to the consumer.

Although the cleaning of slow sand filters is now usually associated with a draining and surface skimming technique, this is not an invariable practice, as will be seen during the discussion of mechanized cleaning techniques. Nor was it invariably the practice in the early days of slow sand filtration when both Robert Tham at Greenock (1827) and the Gorbals Sanitation and Water Company (1846) employed a form of backwashing to clean their slow filters.[1] At the University of Surrey[1] in England a small slow sand filter was developed which incorporated backwashing. Vigorous backwashing was discovered to quickly and efficiently reduce the silt content in the sand from an original 17% down to about 1%. This resulted in some stratification of the sandbed, but also in a substantially increased uniformity in the crucial top 50 mm.[1] Rigorous sand backwashing was not, however, discovered to be essential. Instead, a gentle backflush was used to render the blocked filter permeable again. A filter run of 46 days was achieved by backwashing as the head loss reached 500 mm (about twice weekly). During this time the silt content at the sand surface increased from 0 to 10 to 20 to 27 and, finally, 43% until it was skimmed off by a conventional cleaning process. As the silt content of the surface sand rose appreciably during the backflushings, the head loss development, which did not increase correspondingly, could not be attributed principally to the content of silt at the surface. More probably, high silt contents only contribute largely to the blocking process when the silt particles are packed down evermore closely by successive filter runs. This continued packing of the silt is prevented by the frequent backflushing. This technique is probably not applicable to large slow sand filters, but might be applicable to small household or village filters.

2. *Mechanized Cleaning*

Mechanized slow sand filter cleaning can involve either skimming (as is normal) or washing the sand *in situ* or a one-operation system of sequential skimming, sand washing, and resanding. Mechanized skimming is carried out either using specially designed or suitably modified vehicles or with a gantry skimming device that spans the whole bed. Both the *in situ* washing and the sequential skimming, sand washing, and resanding processes require a gantry-mounted system.

Mechanized sandbed skimming can be operated using either tracked or wheeled vehicles. If wheeled vehicles are employed it is essential that broad tires are fitted to prevent overdisruption of the sand surface. It is also essential to avoid overheavy tracked vehicles as their use can result in heavily compacted undersand and in damage to the underdrainage system. Simple scrapers have been employed in the cleaning process, but these are only able to skim and not to lift the removed material.

Currently the vehicle skimmer is most commonly fitted with a horizontal twin auger-screw device which both skims off the schmutzdecke/sand mixture and pushes it towards the center line of the vehicle from where it is picked up by a wide scraper flight and transported rearwards by a rubber belt conveyor to fall into a dumper truck, which then carries it out of the bed for subsequent washing. This type of mobile sand skimmer operates at approximately 12.5 m/min, cutting a 2.5-m swathe through the schmutzdecke and removing the sand/schmutzdecke mixture at a rate of about 46 m^3/hr. In order to sense any undulations in the sand, a pressure plate is provided in front of, and attached to, the skimmer head. Final leveling can either be carried out by the skimming vehicle or by a tractor-mounted leveling device. Portable ramps are essential to permit vehicles to enter and leave the filter and whenever vehicles are employed in a filter it is essential they be fitted with an effective drip tray to prevent any possibility of oil falling on the sand.

Similar twin-auger skimming devices can be fitted to a traveling gantry which spans the whole bed. As the gantry slowly progresses along the length of the filter the skimmer travels repeatedly and continually to and fro across the bed, skimming and removing the schmutzdecke. Such a system can also be employed for resanding operations. The gantry, in order to be at all economic, must be capable of being employed on all the filters at one works but, even so, it will only be suitable for the larger filter works. It is one-man operated and is capable of skimming a large filter (3700 m^2) in one shift.[101]

Washing *in situ* has also been associated with the "Sivade-system": a gantry-mounted cleaning process, not requiring the filter to be drained, in which a number of bottomless boxes were lowered across the bed onto and a little way into the sand.

High-pressure water injected through lances washed upwards, cleaning the sand within the boxes, and then the whole contraption was lifted and moved onwards along the filter, cleaning the surface strip by strip. With this process there was no sand loss and one man was able to clean a large filter during one shift. There are, however, some appreciable disadvantages with this system.[49] Experimental work concerned with this *in situ* cleaning process was carried out at the Ashford Common Works of the Metropolitan Water Board (as it was then) in London.[19] It was found that, when blocking of the sand bed was primarily due to biological factors, an *in situ* cleaned pilot-plant filter developed a higher rate of head loss than a manually skimmed reference filter, with the runs rarely exceeding 2-weeks duration. The more rapid buildup of head loss was suggested as being the result of the inability of the *in situ* backwash system to remove all the algae from the sand. Conversely, following prolonged operation (19 months and 17 cleanings) of the two filters, it was found that there was only 2% of silt throughout the depth of the *in situ*, backwash-cleaned filter compared with 7% for the manually cleaned reference filter, which by then had had 300 mm of sand removed and was ready for resanding.

After cleaning these two filters it was noticed that with the manually skimmed filter there was still a quick fall-off in bacterial numbers near to the surface of the sand while in the *in situ*-washed filter there was a much slower fall-off in numbers which continued through the depths of the sandbed. At this time the filtrate from the manually-skimmed filter was marginally better in quality than that from the *in situ*-cleaned filter.

Other gantry cleaning systems are in use including the one developed by Hawker Siddeley for the Barmby slow sand filtration works of the Yorkshire Water Authority which both skims off the dirty sand layer, washes the sand, and returns it immediately back into position in one pass of the gantry along the sandbed.

3. *Sand Washing*

The washing of the sand removed during a filter-skimming operation is commonly carried out immediately in order to prevent troubles developing associated with putrefaction and with bird scavenging and rodent feeding. However, at the Bristol Waterworks Company in England the removed material is allowed to stand for 2 months to allow the schmutzdecke to rot away; otherwise, blocking difficulties are encountered in the sand washer.

Sand washing appears to be carried out by a variety of machines which appear to be nearly as varied in their designs as there are slow sand filtration plants. The simplest system is to use a sand washing platform consisting of a low brick wall enclosing the heap of sand to be washed with the only opening blocked by a plank of perhaps 80-mm depth. The operator merely plays a high-pressure hose on the sand mass to wash off the organic matter and to suspend it in a shallow depth of water which overspills to waste over the plank weir and into a washwater gutter. More complex washes usually makes use of high-pressure water jets in a simple hydraulic countercurrent cleaning process to wash the dirty medium and to remove the cleaned sand while the suspension of organic debris rises with a moderately gentle upward flow of water and overspills to waste. Washing and reclassification is sometimes carried out by passing the dirty sand through a series of revolving sieves onto which water is played.

C. Resanding

Resanding of a slow sand filter bed is carried out when, after a number of skimmings over perhaps a period of several years, the bed depth has declined to an accepted minimum. This resanding can be carried out simply by adding clean sand on top of the existing bed, but, by so doing, the beneficial effect of the established biological system under the existing sand surface will be lost and an extended period of maturation will be necessary once the bed is recommissioned.

A more acceptable practice for bed resanding[6] is the technique known as "throwing over". For this, the initial step is to remove the top biologically active layer of the sand down to a depth of about 400 mm and to store it at one side while new or cleaned sand, to a depth corresponding to that removed by all the skimmings, is added to the exposed surface. Finally, the initial top (thrown-over) sand is replaced as the top layer and much of the original biological activity is retained. As a result, the required maturation period for the newly resanded bed is much reduced. In addition, the throw-over technique is useful for the prevention of cumulative fouling at lower levels in the bed which can result in either a deterioration of effluent quality or in blockages at a deep level. Also, by periodically lifting out and replacing this sand layer, the tendency for it to become increasingly compacted over extended periods is prevented.

Burman[18] has pointed out that not only should resanding be carried out as quickly as possible, but that it should only be attempted during the coldest season of the year. He argued that while the bed is empty of water the microorganisms attached to the sand grains are denied essential nutrients and as a result they become more oxidative in nature and begin to use the bacterial gums, by which they are attached to the sand, as substrate with the results already suggested in Section III.B.1.

The total removal of the sand from a slow filter bed should not be necessary under normal conditions of design and operation. Deep cleaning should only be required if there has been deep penetration of silt or other clogging material as the result of either a too coarse sand in the bed and/or of a too fast rate of treatment. Another reason for the removal, cleaning, and replacement of all the sand in the bed can be excessive compaction of the sand as a result of employing over-heavy vehicles for the skimming process. It may also become necessary as a result of a high bicarbonate and carbonate content[51] of the water from which crystalline carbonates may be deposited around the sand grain, binding them together in hard impermeable lumps.

D. Principles of Management and Operation

The objective of running a slow sand filter is, as Huisman and Brown[49] suggest, the production of high-quality water over 24 hr a day and 365 days a year — or, with some smaller units, over the required number of hours each day. A slow sand filter is, however, not a machine whose properties can be precisely calculated and forecast. It is an ecosystem of living organisms and the characteristics of any particular filter depends upon such factors as the possible variations in the quality of the raw water, changes in climatic conditions, the dynamics of the microorganism population both at the filter surface and within the sandbed, and also on the care taken in the design and construction of the unit.

In particular, the filter operation will only be as good as the designer, the builder, and especially the operator, allow it to be. Operator training and supervision, as discussed below, is of paramount importance, especially for slow sand filtration units operating for smaller communities in the developing world. The designer influences the results of filter operation in terms of length of filter run and effluent quality by four important design factors.[95] These are the grain size distribution of the filter medium, the depth of the filter medium, the depth of the supernatant water above the medium, and the selected rate of filtration. Accurate information concerning these factors can often only be obtained through the operation of a pilot-scale filtration unit.

Burman[18] suggests that there are eleven principles of good management for a slow sand filter unit. These include the use of effective primary treatment to remove excess turbidity, a steady state of operation, never leaving idle beds full of water, cleaning as quickly as possible, and resanding only during the coldest months of the year. He emphasized the importance of maintaining a steady treatment rate at all times as sudden changes in the rate result in specific nutrients in the water not reaching, or passing through, those layers of the sandbed at which microbial forms capable of dealing with them have been developed. He also emphasized that the most economic filtration rates, and also the depth of skimming during the cleaning process, depend upon the quality of the water being filtered. An additional important principle of slow sand filter operation is to never have more than one bed out of operation at any one time. To do so imposes additional unnecessary strain on the operating filters and must detract from the quality of the filtrate produced. Being in a position of having to clean more than one filter at a time also means that the best use is not being made of the labor force — usually the most expensive factor in water treatment. It is normally better to clean filters before it is essential rather than concentrate the activity of the cleaning gang into a short period.

IV. ALGAE AND SLOW SAND FILTERS

Algae accumulate in surface waters as a result of the presence of certain nutrients (particularly nitrates and phosphates) and under the influence of sunlight. Algal blooms can develop wherever there is standing or slow-flowing water. Algal blooms can create pronounced difficulties in slow sand filtration even in the spring and summer of the moderate British climate. The intensity of the blooms and the associated difficulties can be considerably more pronounced in warmer and sunnier climates. The algae grow either in the river, or lake, from which the water to be treated is abstracted, or in the storage reservoir or in the water above the sand in the slow filter.

Algae, particularly if they exist on the surface of the sand as an intrinsic constituent of the schmutzdecke, are usually regarded as being beneficial to the treatment process and an essential part of the balanced filter operation. They can, however, result in the early blocking of filters and runs have been reported as being reduced to as little as one sixth of the normal period by blooms of algae.[52]

A. Zones of Algae Activity

Algae can exist in three sections of a slow sand filter.[51] There may be planktonic forms in the supernatant water in which a bloom may consist of as few as 500 forms per milliliter or as many as 35,000 or even 45,000 forms per milliliter. They are usually green algae and may belong to mobile species such as *Chlamydomonas* or *Casteria* onto nonmobile varieties such as *Scenedesmus* or *Ankistrodesmus*. Algae also are abundant either immediately over the surface of the sand or intimately associated with the schmutzdecke and associated sand. These algae may be of many varieties such as the filamentous *Melosira, Spirogyra,* and *Cladophera* or nonfilamentous varieties, principally diatoms and green algae. The numbers greatly increase during an English summer when the dominant species are principally nonfilamentous diatoms and green algae. *Nitzschia* has been reported[51] as averaging 10^8 cells per square meter of sand surface in late spring and as providing 300 mg oxygen per square meter per hour during active photosynthesis. Although *Melosira* is often condemned as being a filter-blocker,[3] filamentous forms attached at the sand surface are frequently buoyed up by oxygen bubbles and play no part in blocking the filter.

At the Christchurch works of the West Hampshire Water Company[37] in England, blooms of *Cladophera* are accepted as being beneficial. For much of the summer period their development in the filters partially shades the sand surface and prevents the development of filter-blocking varieties. It is only before the development of the *Cla-*

dophera blooms, or after they have died back or following the cleaning of a filter, that trouble is caused by algae reducing the length of a filter run — often following the rapid development of *Diatomo* sp., *Navicula* sp., and *Nitzschia* sp., which multiply very quickly as soon as the conditions are suitable (bright sunshine, clear water, but only moderate temperatures appear to be optimum). In the Thames Water Authority, *Melosira* var. is frequently the dominant variety of algae in the spring with *Cladophera* in the summer.[9] The growth of some buoyant filamentous algae in slow filters in the Thames Valley, particularly in the late summer months, does not especially add to blockage problems as they are concentrated a few centimeters above the sandbed.[18] However, large masses of filamentous algae can create considerable problems at the time of filter cleaning. Often it is necessary, initially, to drain down the water to just above the sandbed and manually direct the wet mass with wooden pushers to one side from where it can be lifted out by bucket and crane. Alternatively, the bed can be drained down completely and raked into heaps for immediate removal. If these heaps are not immediately removed the algae quickly begins to decompose, the temperature rises, and there is a leakage of a dark brown liquid into the sandbed.[18] *E. coli* are also reported as developing rapidly in these heaps.

Melosira is frequently the cause of filter blocking as are the planktonic forms of *Asterionella*, *Fragilaria*, *Cyclotella*, and *Stephenodiscus*. The blue-green algae *Gloeotrichia* have been known to block a filter so effectively that it has not been possible to drain it down.[52]

Some algae, either as a result of their size or because of their shape or because of their motility, are able to penetrate into the sand bed and, not infrequently, through it. Small needle-shaped algae such as *Nitzschia acicularis* and *Synedra* are able to penetrate with some ease[51] as can *Scenedesmus*, *Microcystis*, *Phytoconis*, *Pleurococcus*, *Chlamydomonas*, and even *Euglena*. Bowles et al.[9] reported that during the Australian winter the diatoms *Nitzschia acicularis* and *Navicula* sp. were predominant in the schmutzdecke together with the filamentous species *Melosira granulatu*, while in warmer weather with more intense solar radiation the green filamentous algae *Zygnema* sp. predominated with masses of long streamers and even formed dense patches on the water surface. On cleaning, this particular algae compacted as a partially dried algal skin to a thickness of about 2 mm and was easily rolled up and removed.

The small algae, such as *Nitzschia*, which are able to penetrate slow sand filters in small numbers, represent no health hazard,[52] but may possibly create taste problems and may also, after death, provide substrate for after-growth of organisms in the distribution system. The degree of penetration depends on the size of the sand grains, the size and shape of the algae, the rate of filtration, and the length of operation of the bed.

B. The Effects of Algae on Filter Operation and Efficiency

The effects of algae on the operation and efficiency of a slow sand filter are various. These effects may be listed as:

1. Over-early blocking of the filter
2. Production of taste and odor in the water
3. Increase in the concentration of soluble and biodegradable organics in the water
4. Increased difficulties associated with filter cleaning
5. Difficulties (and benefits) associated with the precipitation of calcium carbonate
6. The development of anoxic conditions
7. Light attenuation

The effect of algae in blocking filters and, not infrequently, greatly reducing the run lengths, has already been discussed in some detail. This must be the most serious consequence of algal blooms in the water and on the sandbed and as a result, considerable efforts are often made to prevent blooms developing and to remove algae prior to the slow sand filtration stage. The *Standard Methods for the Examination of Water and Wastewater*[56] lists the following as filter-clogging algae: *Dinobryon, Anacystis, Chlorella, Gymbella, Closterium, Synedra, Rivularia, Cyclotella, Navicula, Tabellaria, Asterionella, Palmella, Spirogyra, Oscillatoria, Trachelomonas, Fragilaria,* and *Anabaena.*

1. Taste and Odor Problems

Taste and odor production must also be one of the most important disadvantages associated with algal blooms in water. The taste- and odor-producing components are produced either by the death and subsequently the lysing of the cells or as a result of the metabolites produced by the living cell. Postchlorination is often responsible for intensifying the initial taste and odor effects. *Mallomonas, Anabaena, Asterionella,* and *Synura* are all well known for producing unwelcome taste and odor in water. In addition, the *Standard Methods*[56] lists *Uroglenopsis, Hydrodictyon, Anacystis, Synedra, Peridinium, Geratium, Aphanizomenon, Staurastrum, Dinobryon, Nitella, Tabellaria, Gomphosphaeria, Volvox,* and *Pandorina* as taste- and odor-producing algae.

Should it not be possible to prevent the production of taste- and odor-creating compounds in the water by preventing the development of the responsible algae, then it will probably be necessary to destroy or remove the odoriferous compounds themselves. This can readily be achieved by the addition of chlorine dioxide, which is particularly efficacious at destroying the taste produced by the algal species *Mallomonas, Anabaena, Asterionella,* and *Synura* as well as from various *Vorticella* and *Actinomycetes.*[53] More simply, but perhaps more expensively, powdered activated carbon can be added to the water to be filtered. Powdered activated carbon[54,55,57] is a fine powder of normally less than 100 μm size which is dosed into the water as a 5 to 10% slurry at between 5 and 25 mg/*l*, although lower continuous doses of about 2.0 mg/*l* have been used. Although it is not recoverable once dosed to a slow sand filter, there will be a residual effect over a long period, possibly until the accumulated activated carbon is removed along with the schmutzdecke when the filter is skimmed. It is possible, if continuing taste and odor problems are expected, to begin, after cleaning, with a high dose of up to 50 mg/*l* in order to form an active adsorbing layer at the sand surface and to continue with a much reduced dose of perhaps only 2.0 mg/*l* for as long as required. Should it not be practicable to employ chlorine dioxide or activated carbon further, accentuation of the problem can be prevented by the employment of the ammonia/chlorine technique instead of straightforward chlorination.

2. Additional Oxygen Demand

It is reported[51] that up to 30% of the organic compounds produced by algae leak into the water. Appreciable amounts of glycolic acid, polypeptides, and carbohydrates are produced and the concentration of such compounds as sucrose, ribose, and maltose have been detected in the water above the filter in concentrations as great as 10 mg/*l*. This represents a massive addition of soluble organics, most of which are readily biodegradable, but which must add very appreciably to the respiratory demands of the filter and require considerable dissolved oxygen to satisfy. Some nonbiodegradable compounds can pass into the water supply where they can create further problems of after growth and taste and odor production especially if they are partially broken down and rendered immediately biodegradable by the addition of oxidizing disinfectants.[3]

The increased difficulties of filter cleaning associated with massive growths of filamentous algae have already been mentioned, but if a filter is emptied for cleaning at the time of a heavy bloom of various algae and then the surface is allowed to dry, a hardening, even cementing, can occur to make the process of skimming very difficult and costly.

3. High pH

During the photosynthetic activity of algae, inorganic carbon sources in the water, such as dissolved carbon dioxide, bicarbonate, and carbonate, are used for anabolic processes. This both reduces the natural buffering capacity and produces hydroxyl ions with the result that the pH of the water rises considerably up to, on occasions, pH 10, 11, or even higher. As a consequence, magnesium hydroxide and calcium hydroxide are precipitated onto the sand grains.[82] This can have the effect of either helping to block the filter or, by being deposited on the grains themselves, of increasing the effective size of the sand or of altering the shape of the sand grain. The former effect increases the difficulties of operation while the two latter may materially alter the efficiency of the filtration process. An unusual effect of photosynthetic activity was recorded[82] in Brisbane, Australia. High pH values caused a pronounced deposition of calcium carbonate onto the filter sand. Then, during periods of high turbidity of the raw water, alum was added to a presedimentation basin. The resultant water from this chemical pretreatment had a pH of as low as 5.0, but on coming into contact with the deposited calcium carbonate the pH was automatically corrected to between 7.0 and 7.5 until all the calcium carbonate had been used up. It was also noticeable that corrosion of the walls of the filter box ceased at the level of the sand. Unfortunately, if the applied water had a pH of less than 5.5 in the presence of excess aluminum ions, then the Al^{+++} reacted with magnesium hydroxide on the sand to form aluminum hydroxide, which would completely block the filter. Surface skimming was of no help in reducing this blockage, which persisted until an alkaline water supply was applied to convert the aluminum in the hydroxide into aluminate ions.

4. Oxygen Depletion

While there is adequate solar radiation, algae are able to respond photosynthetically and to produce oxygen in relatively large quantities, but this production ceases as the sun goes down. However, although the algae have ceased producing oxygen they have a continuing requirement for dissolved oxygen for respiration purposes. The rate at which algae use up oxygen from the water may only be between 10 and 15% of the rate at which they may be able to produce it at the height of their photosynthetic activity. But, because of the limited storage capacity that water has for oxygen, the presence of an intense bloom of algae may cause it to become anoxic overnight. Anaerobic activity may then ensue. The results of anoxic conditions and anaerobic biological activity, as discussed above, can be the production of tastes and odors, the resolution of deposited iron and manganese salts, and the passage through the filter of appreciable numbers of coliform and other potentially more dangerous microorganisms.

A further unwanted effect of large numbers of algae in the slow filter is that of light attenuation and the reduction of photosynthetic activity together with a decrease in the amount of oxygen produced both at and above the sand surface. This must have an effect on the beneficial aerobic biological activity while doing nothing to reduce the anoxic conditions during the night. Light attenuation can result either from the turbidity produced by a mass of floating and swimming planktonic algae or from the shading effect of a mass of attached and floating filamentous algae. Temperature can also produce adverse effects from a concentrated bloom of algae. A sudden drop in temperature can kill off the algae present, producing an immediate heavy concentration of biodegradable organic matter and consequently a very high oxygen demand. Normally, in these circumstances, the filter would have to be cleaned at once.

C. The Control of Algae

The prevention of algal blooms can be brought about by using one or more of a number of possible techniques. Both chemical and physical methods may be employed and in at least one example there is a biological approach to the problem.

1. Control of Pollution

Blooms of algae occur in waters that contain certain minimum concentrations of essential nutrient salts, particularly nitrates and phosphates. In some situations the critical concentration level of these nutrients results from the discharge of polluting material to the surface water system from which the potable water supply is taken. Should it be possible to prevent the discharge of these effluents the tendency of the water to develop algae will be much reduced. It is not the fact that the water discharged is polluted, in that it possesses a high oxygen demand, that is important, but merely that the natural or accelerated satisfaction of this demand will result in an appreciable nitrate and phosphate content. It is not sufficient to ensure that the effluent is well purified prior to discharge. Either it must pass through a form of tertiary treatment to remove phosphates and nitrates or its discharge into the source stream must be prevented, if this is at all possible.

2. Filter Covers

Covering slow sand filters to shade the waters from direct sunlight would appear to be an obvious answer to the problem of algae development. Slow sand filters, even of a substantial area, have been covered over in Holland[6] by substantial roofs, but this has principally been a safeguard against difficulties encountered during very cold weather. Small, village-scale slow filters are sometimes covered in Thailand with what appear to be excellent results, but the only record of this is a substantial increase in filter run following filter roofing due to the reduction in numbers of a nonalgal aquatic organism — the midge larvae *Ablabesmyia chironomidae.*[58] Burman[16] suggests that the advantages of covering slow filters include the exclusion of birds and hence the prevention of avian pollution, the prevention of ice problems during very cold weather, and the ease of cleaning during wet weather. However, he reported no extension of the interval between successive filter cleanings in the Thames valley when a slow sand filter was covered. Despite Burman's report from England, it would still appear that this technique has much to recommend it as a method of reducing algal problems in tropical countries and it is unfortunate that there is not more information available.

3. Chemical Treatment

Chemical treatment to prevent algal blooms using various additives has been suggested and tried. Chlorination of the supernatant water has been attempted, usually employing low chlorine concentrations of between 0.2 and 1.0 mg/*l*, but even up to 8.8 mg/*l*[22] has been used and it has been claimed that this prolonged the filter run without harmfully effecting the treatment process. It can be visualized how a low dosage of chlorine could prevent an incipient algal bloom, but an instinctive caution would cause most water engineers to be very careful of this technique without definite beneficial results having been first achieved over an appreciable period with a pilot-scale plant.

Unless there is a pronounced chlorine demand the chlorine will come into contact with the schmutzdecke and, if in any appreciable concentration, must have some damaging effect. One report[59] indicates the production of a gelatinous impermeable slime on the sand surface by the addition of chlorine. In addition, with prechlorination there is the potential danger of THM production.

The use of ozone prior to slow sand filtration, as already discussed,[3] has been extensively researched by the Thames Water Authority in England. The addition of ozone to water which had been initially prefiltered through rapid sand filters, but prior to slow sand filtration, effectively doubled the run length at one works (2 to 5 mg/*l* ozone) and increased it by 50% to 90 days (2.0 mg/*l* ozone) at another, but was only effective during periods of high algal growth. Ozone had no effect on run lengths when turbidity, and not algae, was the cause of filter blocking. That ozone was effective against the algae on or above the sand was indicated by the lower diurnal dissolved oxygen levels as compared with the reference filters.

Importantly, ozone had no effect against weed blankets if these were already established before it was added. It was essential, in order to be effective, that ozone was added continually from the commencement of a run. Any algae, such as *Stephanodiscus,* which managed to penetrate the primary, rapid filters were bleached, rendered nonviable, and to some extent flocculated by the ozone, but still could, if present in sufficient numbers, result in an increased rate of head loss. In the case of the reference filter (no ozone added) these small algae created a slower increase in head loss, but the algae penetrated deeper into the slow filter.

Certainly the addition of ozone prior to the slow sand filters altered the relative proportions of algal species. Without the addition of ozone the reference filter contained principally the filamentous *Cladophera* and filter blockers such as *Melosira.* In the filter to which ozone was added the algal population was made up mainly of filter-penetrating species such as *Scenedesmus* and *Synedra.* However, with a bloom of *Microcystis,* algal penetration was reduced, in comparison with the reference slow filter, with the pre- and post-filtration water turbidities for the reference filter being 11 FTU and 2.5 FTU and for the ozonated filter 11 FTU and 0.3 FTU. As a result of its short half-life and of the appreciable water retention time, ozone, when added to the water entering the slow filter, never reaches the schmutzdecke.

Copper sulfate has been widely employed for the control of algal blooms in reservoirs and can be useful in the same manner for preventing trouble in slow sand filters. The copper sulfate is best added to a presedimentation tank although it could be added directly to the water of a filter. Only small dosages are necessary and these vary with the temperature, and alkalinity of the water and possibly also with the type of algae to be controlled. Low temperatures reduce the effectiveness of the chemical and high alkalinity values result in early precipitation;[60] *0.15 mg/l is quoted as being suitable* for low-alkalinity waters (less than 40 mg/*l*) of storage reservoirs and possibly 0.3 mg/*l* for higher alkalinities; these figures are probably suitable for slow filters. Holden[16] lists concentrations of copper sulfate required to eradicate various species of algae.

Burman[32] has reported that with an addition of 0.74 mg/*l* of copper sulfate to a raw water reservoir in the London area, only 0.17 mg/*l* reached the slow filters, but this resulted in an increase in coliform organisms (but not of *E. coli*) passing through the filter. He suggested that this was because these coliforms were probably saprophytic in origin and of low temperature preferences. Also, the copper ions reaching the filter might have killed off some algae which would have provided nutrients for bacterial growth and the copper had probably also reduced the number of antagonistic protozoa which keep down the bacterial numbers. Dosing directly into a slow filter must always be an activity associated with some risk, subsequent on accidental overdosing, both to life on the schmutzdecke and, even in the extreme, to that of the consumers. If attempted, it should always be under the direction of a competent chemist. Copper sulfate dosing should preferably be limited to prefilter situations.

4. *Biological Methods*

The use of fish for the control of algae in slow sand filters has been advocated[49] and may on occasions be of some appreciable value, but it must be emphasized that if fish are used they must be top feeders such as tilapia and that on no account should bottom feeders like carp be employed because of the danger they represent to the schmutzdecke. Although not presently advocated, there may be some positive potential in the development of the use of predator organisms to remove algal blooms. Results from the West Hampshire Water Company[37] in England indicate that the sudden development of algae predators such as chironomids, rotifers, and small crustacea such as *Daphnia* can reverse the development of head loss part-way through a filter run. While studying algae from a different point of view, i.e., that of growing and harvesting them rather than of preventing their blooms, the researchers at the Pig and Poultry Research and Training Institute, Primary Production Department, in Singapore[61] noticed that algal blooms could be very quickly destroyed by the presence of large numbers of the rotifers *Brachionus* and of the cladoceran *Diaphanosoma*, but particularly by the predator *Moina*. Possibly some investigation into the cultivation and application of algae predators to slow sand filters might be profitable.

5. *Physical Removal*

Both rapid gravity sand filters and rapid upflow sand filters are used by the Thames Water Authority in England as primary filters prior to slow sand filters where they are both appreciably effective at removing algae from the raw water although needle-shaped algae and motile flagellates pass through[52] as do *Stephanodiscus*.[3] Diatomaceous earth filters are also extremely effective for algae removal, particularly if the turbidity is low, and algae at concentrations of 10,000 organisms per milliliter have been reported as being removed.[52] Microstrainers employing 25 and 35 μm meshes are successfully used for the pretreatment of waters prior to slow sand filtration to remove the algae, but are of little use with coagulated waters as the formed flocs tend to be fluid in nature and easily flow through the apertures.[62] At the Bristol Waterworks Company in England the employment of microstrainers led to improved filter operation with the production of a less dense schmutzdecke.[51] Over a long period, 70% of the applied algae was moved by the microstrainers, including 97% of the *Asterionella* and 90% of the *Synedra*. The chain-forming *Fragilaria* were easily removed while the small, disc-shaped diatom *Cyclotella* passed through. The chrysophycean *Dinobryon* broke its structure and passed through and there was only limited removal of *Anabaena* (24%) and *Tribonema* (14%). Other techniques for the removal of algae prior to slow sand filtration might be adapted from the wastewater industry in which horizontal flow rock filters, microstrainers with polyester fabrics, and a vacuum filter with a finely divided precoat of paper material have all been experimented with. Swanson and Williamson[3] reported good results from a long retention horizontal filter employing 76 to 152 mm rock. A microscreen employing synthetic (polyester) fabrics with aperture as small as 10, 5, or even only 1.0 μm has proved to be very effective at straining out algae from water.[63] Vacuum filtration in which a paper precoat is continually used, removed, washed, separated, and reformed and yet provides a medium of high trapping efficiency combined with a good throughput was developed at the University of California[64] and has been operated in both America and Australia.

6. *Algae in the Storage Reservoir*

Should the trouble with algae emanate from a storage reservoir, there are a number of techniques that can be employed, most of them widely used in the water industry.

Copper sulfate addition has been widely accepted, as already discussed, but results are variable.[66] Strangely, the employment of copper sulfate has not been cleared for use as an algicide in water by the Ministry of Agriculture, Food, and Fisheries in the U.K., but its use is recognized by the Department of the Environment as a compound which is commonly used in water treatment and is considered unobjectionable on public health grounds.[67] Water circulation by inflow jetting has proved to be successful at the Queen Elizabeth II reservoir in London to control the growth of algae, but destratification techniques employed in other parts of the country have been disappointing.[68] In at least one situation the cropping of blue-green algae has been successful,[67] but this technique is unlikely to be useful with other algae. The diversion of nutrient-rich streams is a useful and often practical solution.[69] The addition of chemicals to coagulate and flocculate nutrient-rich waters either to the input water to a prereservoir or to the whole reservoir[70,71] has been frequently attempted. Of the important nutrients it is the phosphate which is removed. Aluminum salts (Al^{+++}) and iron salts (Fe^{+++}) have been used. Lime has also been employed.

Dosing with ferric chloride ($FeCl_3$) to the inlet flow into a reservoir has been successfully employed by the Anglian Water Authority in England. This reduced the soluble phosphate to less than $10\ \mu g/l$ and also reduced the algae content by 60%.[67] Some trouble with algae blooms is still encountered for a limited part of the year possibly as the result of phosphorous release from the sediment induced by anoxic conditions. However, the sediment deposited in a limited shallow area of the reservoir is amenable to removal by dragline.

For the direct flocculation and removal of the algae rather than that of the nutrients, chemical addition in the form of alum plus lime has been employed,[74-77] although magnesium salts plus lime[72,73] have perhaps produced better effects. In addition, the natural coagulant chitosan — a polyglucosamine derived from the chitineous material in squilla (a marine arthropod often caught with prawns) — has proved to be extremely effective at flocculating and removing algae.[61,78,79] Water hyacinths have been employed in the wastewater industry for removing algae from stabilization ponds and might possibly be applicable in the potable water industry in some parts of the world.[81]

V. SLOW SAND FILTRATION IN THE DEVELOPING WORLD

In the technologically advanced countries of the world, slow sand filtration offers advantages in many situations, even in competition with the highly developed rapid sand filtration processes. For smaller communities replying on low turbidity waters for their supplies, slow sand filtration provides a simplicity of operation, a consistently high-quality treated water, together with a high safety factor which cannot be matched by rapid filtration. In addition, there is little water wastage and only a low production of waste sludge. In larger communities the same advantages are available, but perhaps in these situations slow sand filters are often more advantageously employed as one in a series of processes to produce, at all times, a treated water of a reliable quality from sources of only low or medium quality. The disadvantage of a periodically high-turbidity raw water supply can be overcome either by extended-period storage or by prefiltration employing rapid sand filters, or by both. The relatively high costs of skimming in areas of high labor charges can be considerably reduced by selective mechanization. The large area requirements remain, but the reliance of Greater London on slow sand filtration suggests that this is not an insurmountable problem, particularly if the demand for area is reduced by a substantial increase in the rate of treatment following initial rapid filtration. It is, however, in those countries operating at present with only low technologies — the so-called developing world — that slow sand filtration has the most to offer. Certainly for large-scale water treatment installations supplying the large cities of the tropical world slow sand filtration must be considered, because of its simplicity and reliability, as being preferable to the complexities and to the often major operational inefficiencies of the now nearly ubiquitous rapid sand filter. But, it is for the treatment of surface waters as small town and village levels that slow sand filtration can be recognized as the only adequate answer to the search for a reliable and effective water treatment technique.

A. Slow Filters for Larger Installations

For large treatment works in the developing world the low technology requirements of slow filtration make few demands on the limited resources represented by highly trained technicians. With minimal requirements for pumps, compressors, chemical mixers and dosers, sludge thickeners, pH controllers, and laboratory supervision, not only is there little demand for highly skilled technicians, but there is also little call for mechanical and electrical spare parts, and it is the difficulty of acquiring spare parts for machinery that inhibits the effective treatment of potable waters in so many places. In addition, there is little continuing demand for chemical pretreatment additives and no requirement for frequent laboratory testing to ascertain the optimum dosages. In many areas of the world, the limited water losses resulting from slow filtration as compared with those from rapid sand treatment makes the former again an attractive proposition. And, unlike the situation which exists in most countries of the developed world, the need for a large labor force for filter cleaning is not necessarily a disadvantage. In many Third World situations, it is a decided advantage. In most of these countries there is a large reserve of lowly paid unskilled labor which it is socially desirable to employ.

1. Some Disadvantages

Having emphasized the advantages of slow sand filtration in these situations it is necessary to stress the disadvantages. Most importantly, it is necessary to emphasize the prerequisite of a suitable water supply. It is essential to have a raw water supply which is not subject to prolonged periods of high turbidity as, apart from chemical pretreatment or rapid filtration, it is debatable whether the design parameters of the other available turbidity-reducing techniques have, as yet, been adequately determined for large-scale treatment, and if chemical treatment or rapid sand prefiltration is to be employed so much of the value of slow sand filtration for the developing world is removed. Intense algal blooms are also to be avoided if possible as they can lead to pronounced problems on the larger scale although they might be avoidable on a smaller scale. High color in the raw water is a further disadvantage. Apparent color is readily removable,[9] but slow sand filtration can only be relied upon normally to remove about 30% of dissolved or colloidally present colored material.[30]

B. Slow Filters for Smaller Installations

On a smaller scale, at the medium or small town level, and even more so for the large village, the advantages of slow sand filtration for the developing world become much more pronounced and the disadvantages assume much smaller proportions. At this level slow sand filtration of surface waters for community supply is nearly unavoidable as a result of its simplicity, its low operational costs, and, overwhelmingly, the high quality, particularly in respect of the low bacterial content, of the treated water.

The relative simplicity of the design of smaller-scale slow sand filtration units is an immediate advantage for smaller populations. There is not even the necessity to employ reinforced concrete for the filter box. Sloping walls and local masonry are frequently quite suitable. Locally obtained materials are also often adequate for the under drainage system. Suitable gravel is usually locally available and suitable sand requiring little or no screening is usually readily obtainable. As a result, there is little demand made on the, usually strictly limited, available foreign exchange. In addition the relatively simply technology of slow filtration means that operators with only simple skills can be employed. It is not even essential that they be literate. Operators from the locality are readily discovered and easily trained.

1. Operators and Supervisors

The adequate training of locally recruited, and hitherto unskilled, operators is, however, of very considerable importance. Some of the frequent operational faults recorded[14] in these situations include not skimming the filter bed surface frequently enough, not allowing sufficient time for the adequate maturing of the filter, digging up the whole of the sandbed during cleaning operations, and not initially refilling the cleaned filter from the bottom. These faults, and others, are the result either of poor operator training and/or poor supervision. It is essential that however small the treatment unit, the operator is adequately trained in day-to-day operation as well as in the correct procedure for filter cleaning. The need to maintain the design head of water above the sandbed, the ability to regulate the outlet valve each day to maintain the correct treatment rate, the necessity not to interfere with the schmutzdecke, the ability to recognize when skimming is required, the necessity to carry through the skimming operations properly and speedily, and the ability to maintain simple records are essential parts of a village operator's training. The operator must be adequately trained, but this alone is insufficient. If there is an installed water treatment unit there must be periodic supervision of the operator(s). Supervision should preferably be the responsibility of a regional or national authority with the supervisor traveling, perhaps over a large area, to oversee the operation of a number of small treatment works. There are two considerations which are the essence of supervision and these are perhaps of even greater importance in the developing world than in the developed world. Supervision must be as frequent as possible and it must be irregular in its timing.

2. Prefiltration Reduction of Turbidity

At a village or small town level the necessity to pretreat the raw water to reduce its initial turbidity is by no means an insurmountable difficulty. Various of the simple techniques discussed above are readily and easily applicable on a smaller scale. Of these, the horizontal-flow gravel filter is probably the best researched and the most suitable. Further investigation of this process is still necessary to allow for precise design under all circumstances. However, sufficient results have been achieved with laboratory-scale, pilot-scale, and village-scale units to enable perfectly adequate horizontal-flow filters to be designed and built at the smaller treatment works level.

Algae can still constitute a difficulty with this size of works, but there are techniques available and already discussed for minimizing the problem of which probably the best for the smallest filters is the shading of the filter surface. For this, only a simply constructed roof is required and frequently of no great size. It is remarkable, considering that area requirements are so often cited as being one of the major drawbacks of the slow sand filtration process, how small a filter needs to be. For the limited individual water demand in many developing countries a population of 2000 people can be served by a total slow filter area of only about 80 m^2 to 90 m^2 — less than 10 by 10 m.

3. Quality of Filtered Water

Of the various advantages suggested for the employment of slow sand filtration in medium- and small-sized towns and in villages, in most of the developing world, it is the bacterial quality of the filtered water which is of paramount importance. It is a quality which can never be matched by a rapid filter. With smaller-sized treatment works in the developing world it is always the disinfection stage that is most a risk, as a result of either faulty design, inadequate operation, or of unreliable supplies of the disinfectant. At many small water treatment plants a disinfection stage is not included because of the technology involved, because of the cost, and because of the nearly total unreliability of disinfection systems under the prevailing conditions. In these circumstances, with many treatment units without a disinfection stage and others at which it is not operating satisfactorily, slow sand filtration with its pronounced ability to remove pathogenic organisms is the only water treatment technique which can be considered.

C. Some Aspects of Design

Several publications are concerned with the specific design requirements of slow sand filtration units in the developing world.[6,12,82,83,95,100] These design requirements differ from those for the developed world only in emphasis and not in principle. The emphasis being particularly concerned with simplicity of construction and operation, the use of locally available material and the peculiar requirements of small treatment units.

Although reinforced-concrete, vertical-wall filter boxes are now invariably employed in most parts of the world, sloping wall filter boxes constructed of locally available masonry or rip-rap or even mass concrete may be more appropriate in some areas. Sloping-wall filters can be constructed for lower costs than vertical walls and by employing lower skills. However, with any material other than reinforced concrete the filter must be sunk into the ground and this raises the question of water tightness. Not only may there be substantial loss of water from the filter, but with high ground water levels, possibly during the rainy season, and with the filter level lowered for cleaning there is the danger of pollution seeping inwards. This is always potentially serious, but especially if the surrounding land is polluted, as it will be so often, by cattle droppings. With a low-level filter it is also essential to extend the walls of the filter box up above ground level for about 1 m both to prevent the entry of small children, animals, and snakes, etc., but also to prevent the entry of polluted surface water during periods of torrential rain.

The need to construct at least two filters in parallel is an apparently obvious design feature which is frequently forgotten with small units as is the necessity to install a drain-down pipe to allow the supernatant water to be removed quickly prior to cleaning. An equally common fault is to fail to install a valve to allow the empty filter to be refilled from the bottom. The use of a too coarse filter medium is also not unknown as is the employment of an over shallow depth of medium.

Inlet and outlet arrangements are of some major importance with the principal requirement being that of simplicity. Inlets systems in all slow sand filters need to be designed to ensure equal distribution of water, to prevent turbulence in the reservoir, and to adjust or maintain the depth of water. Important with small treatment units in the developing world is the necessity for the inlet to be designed to prevent damage to the schmutzdecke and for the outlet to be easily adjusted to cope with the reducing level of the sandbed. Floating final weirs have been advocated[2] for use in these situations, but would appear to be an unnecessary refinement — simplicity and durability must be the essence of the design.

In all designs for slow sand filters for use in the developing world, and particularly for the smaller units, it is the operator who must be borne in mind. Nonessential complexities must be avoided and durability of any features must be encouraged. It is possible to train even unskilled operators to run a simple treatment unit, but it can be extremely difficult to raise funds or engage the expertise necessary to provide spares for broken or unusable equipment.

D. Advantages and Disadvantages

Overall, for the developed high-technology countries of the world and also for the developing world, the full advantages of slow sand filtration may be listed as:

1. Relative simplicity of design and construction
2. Relative simplicity of equipment and operation[11,12]
3. Only limited supervision required[11,12]
4. Usually no necessity for chemical pretreatment[11]
5. Suitable sand is usually readily found[11] and it requires only minimum of screening
6. Filtrate water is less corrosive and more uniform in quality than that from a chemically treated water[11]
7. Operational costs are relatively low
8. There is only a small wastage of water[12] — particularly if the water filtered during the maturation period, and following filter cleaning, can be recycled
9. Only a minimum of sludge is produced[12]
10. There is no ammonia in the filtered water
11. There is excellent removal of pathogenic organisms[11]
12. The limited power requirements[12]

The disadvantages include:

1. Relatively large area requirements with correspondingly large structures, large volumes of sand, and consequently high initial costs[11]
2. Little flexibility of operation[11]
3. Only low efficacy for color removal[11]
4. Poor results if the water to be filtered has a high algal content[11]
5. Short runs and consequently high costs if feed water has a pronounced turbidity[11]

However, it is the example quoted in Holden[16,99] which has perhaps the greatest impact — emotionally if not entirely rationally — on those considering the installation of slow sand filters, particularly in the developing world. This examples cites the situation in two towns in Germany in the 1890s. These two towns, Hamburg and Altona, both drew their water supplies from the River Elbe. At Altona the water was slow sand filtered, but at Hamburg it was only settled. During 1892 there was a cholera epidemic in the region and of the 580,000 inhabitants of Hamburg, 19,890 became infected and 7582 died, while in Altona, of the 143,000 inhabitants there were only 328 deaths and these were considered to have drunk water in Hamburg.

E. High-Turbidity Waters

The principal disadvantage of slow sand filtration must be the severe limitations imposed upon run lengths should the turbidity of the raw water rise appreciably for more than a short period. Maximum turbidities for prolonged periods of between 10 and 50 turbidity units[11,81,82,83] have been quoted, although it is normally accepted that higher turbidities, perhaps 50 to 120 TU, can be tolerated for 1 or 2 days without major increases in the head loss.[81] It is believed that high turbidity in surface waters was the original reason that slow sand filtration had to be rejected in many parts of the U.S. and led to the development of rapid filtration techniques. Throughout much of the tropical world surface waters have high turbidities during at least part of the year which corresponds with the rainy or monsoon season. This again is a major reason that slow sand filters have not been more widely adopted in regions where, apart from the difficulties of high turbidities, they could most advantageously be employed.

The principal reasons for high turbidities in surface waters in tropical areas are[96] uneven but high annual rainfall distribution, high temperature fluctuations, specific water quality characteristics such as hardness, and the presence of humic materials, deforestation, together with land cultivation techniques which often encourage soil erosion. Very high turbidities are met with during the rainy (monsoon) season and this is the season when the risk of water-borne epidemics is greatest as a result of the wash-off of fecal matter which has been disposed of inadequately. It is therefore of high importance that slow sand filters with their proven ability to remove bacteria and other potentially dangerous organisms should be able to operate through periods of high surface water turbidity.

Some people, with reason, question the effectiveness of the turbidity parameter for assessing the acceptability of waters for slow sand filtration, and it has been argued[84,85] that water turbidity reflects such properties as colloid concentrations, color, dissolved material and suspended solids, and that only the suspended solids content, which directly influences the head loss development in a slow filter, should be used.

1. Available Technique

A number of techniques can be employed for reducing high turbidities in the source water down to a level acceptable to slow sand filtration. Some are of proven efficiency, some of lesser effect, and at least one is still to be adequately defined. These techniques can be listed as:

- Infiltration wells and galleries
- Storage
- Plain sedimentation
- Rapid roughing filters (vertical flow)
- Horizontal-flow gravel filters
- Chemical pretreatment
- Rapid sand filters (gravity, upflow, pressure)
- Coarse filtration at the river bed.

Infiltration wells and galleries are employed widely in the Indian subcontinent and occasionally in other parts of the world. They can be extremely effective either for the partial treatment of high-turbidity waters or for the total treatment of less turbid waters. Large diameter shallow wells situated on the river bank may be employed so that the water abstracted from the river must percolate through the silt of the river bottom and the gravel of the river bed to reach the well, from which it may then be pumped directly to the slow sand filters. More sophisticated arrangements have infiltration galleries running into the river-side well. They may be laid either in the bank parallel to the flow or under the river.

Chemical pretreatment for the coagulation and flocculation of finely divided suspended material, followed by sedimentation, can be employed prior to slow sand filtration in exactly the same manner as for rapid gravity sand filtration. This is effective but limits, for much of the world, the major advantages of slow sand filtration of simplicity and low operational costs. However, it is widely employed in the African state of Lesotho and occasionally in other parts of the world where the increased cost and operational complexity does not detract greatly from the perceived advantages of slow sand filtration.

Plain sedimentation prior to slow sand filters has been attempted, but it is only of appreciable efficacy if the suspended solids to be removed from the feed water are of sufficient size to settle readily within a few hours. This is rarely the case and the technique is rendered less attractive by the need to construct a well-designed settlement tank which can involve a major, and perhaps limiting, expense for village supplies in many parts of the developing world. Interesting results of plain sedimentation have been reported[86] from India when the River Ganges might be carrying between 5000 and 10,000 mg/ℓ of fine suspended material during the monsoon period. Much of this material was of an appreciable size and quite good results were reported with sedimentation. A 30-min retention period tank was reported as reducing the suspended solids by 60% (removal of solids down to 0.05 mm size) and a retention period of 3 hr achieved a 70% removal. This still left a high concentration of suspended material in the water and the corresponding reductions in turbidity were only 10% after 30 min and 30% after 3 hr.

Long-period storage of low-quality raw water is practical in many places and particularly London. Over a long period in a reservoir readily settleable suspended material is removed. There is some coalescing and settlement of finer suspended material. There is also a continuing reduction of biodegradable organic material as a result of aerobic bacterial action and, most importantly, there is a very substantial die-off of potentially harmful bacteria and viruses. Long-term storage prior to slow sand filtration can be very effective at reducing raw water turbidity to acceptable levels and the practice is employed at village level in Thailand[87] and elsewhere. However, there is always the danger of exchanging one difficulty in the form of mineral turbidity for a bloom of algae produced during the retention period. Multiple level off-take points can be a simple and effective method for avoiding surface blooms of algae, but difficulties can be encountered if water is withdrawn from the lower anoxic levels.

Coarse-media gravity filters have been suggested[10,85,88] as pretreatment techniques for slow filtration. The medium employed would normally be rock or pebbles although coconut fiber has been tried and found to be quite effective. The shredded fiber, however, was found to be not as good at producing a consistent effluent quality as the mineral media and also to have a much shorter serviceable life.[10] Coarse filtration in the river bed at the point of abstraction has also been used. This filter may be in the form of a basket of pebbles through which the water must be sucked. For a shallow stream a more reliable method is to lay the perforated abstraction pipe on the river bed, across the flow, and just on the upstream side of a low weir. The pipe is then covered with gravel and the stream itself deposits a layer of silt. The abstracted water must then be pulled through both a layer of silt and a depth of gravel which will effectively reduce the initial turbidity. The gravel/silt prefilter is held in position by the weir and the flow of the stream is continually washing off the top layer of silt and replacing it with fresh material.

For larger, more sophisticated situations, where there is a turbidity problem with the raw water, conventional rapid sand filtration is best employed.[18] The rapid sand filters can be either conventional gravity filters or upflow sand filters or pressure-filters and are normally operated without chemical pretreatment. All these techniques are widely employed in the U.K. where rapid gravity filters are installed prior to slow sand filters at, among many other sites, the Barmby Treatment Works (Yorkshire Water Authority) and the Walton Treatment Works (Thames Water Authority). Upflow rapid sand filtration is employed at the Fobney Treatment Works (Thames Water Authority) and pressure filtration at the Alderney Waterworks of the Bournemouth and District Water Company. The employment of rapid sand filtration normally ensures the treatment rate of the subsequent slow sand filtration units can be considerably higher than the "conventional" 2.4 m^3/m^2/day and might rise to 6.0 or even 12.0 m^3/m^2/day.[18]

Research has been carried out at the University of Dar Es Salaam[84,89] into four different techniques for reducing raw-water turbidity prior to slow sand filters. The use of plain sedimentation on its own, and then with the aid of inclined lamella plates, was investigated. It was concluded that as the quality of the water following sedimentation processes did not meet the required raw water standards for slow sand filtration, it is only useful if the feed-water is without appreciable amounts of fine material (silt, clay, colloids), or in conjunction with chemical flocculation. Vertical roughing filters were found to be quite successful and to give very similar results to those obtained with horizontal-flow roughing filters but because of their limited silt storage capacity, which resulted in limited run lengths, and because of the extra pumping required the investigation into their use was abandoned in favor of that of the horizontal-flow filters.

2. Horizontal-Flow Gravel Filtration

Horizontal-flow gravel filters have been employed for the prefiltration of turbid raw water prior to slow sand filtration in England, at the old Fobney Treatment Works,[25] in Germany in the Ruhr Valley, and in Switzerland at Aesch, Aarbey, and Aure.[90]

In continental Europe it is mainly river waters of limited turbidity which are passed through horizontal-flow prefilters[96,97] prior to slow sand filters. Extraction is normally suspended during periods of spate. As a result of the low suspended solids loading of these prefilters, homogeneous filter beds can be operated at appreciable treatment rates. In the German example,[91] Ruhr water is slow sand filtered into the subsoil to recharge the groundwater and horizontal flow gravel filters were provided to ensure more secure operations by protecting the slow sand filter from shock loads. These prefilters are quite sizeable, being between 50 and 70 m long, and filled with 0.4-m depth of 5 to 12 mm gravel on top of a layer of 30 to 70 mm gravel. The flow is longitudinal and the floor of the unit slopes slightly upwards. The flow rate is 10 to 20 m/hr.[85,91] The suspended solids content of the river water rises to 270 mg/*l* in spate conditions and can be reduced through the horizontal filter by 75%, but to achieve this the treatment rate has to be dropped to 8 m/hr. Of considerable interest is the fact that the percentage of volatile matter in the suspensions varies with season and weather conditions from 10 to 50%. The lower the volatile matter content of the suspended solids the more readily they are removed by the horizontal-flow filters, e.g., 58% of the suspended solids are removed with a volatile solids content of 45% and 90% when the volatile matter is reduced to 17%.[91] Initially, much of the suspended solids removed is trapped in the first 4-m length and most within the first 20 m, but this entrapment zone is expected to move along the filter as the storage capacity at the inlet end becomes full. A complete run is expected to take between 5 and 6 years because of the very high storage capacity for removed silt. Certainly at Aesch (Switzerland), where the horizontal flow gravel filter[91] of 15-m length operates at an average rate of 5 m/hr(8 m/hr maximum), it had not been cleaned for 4 years and the following slow sand filter had not been cleaned for 3 years. When cleaning becomes essential with this type of prefilter it was, until recently, assumed to be necessary to remove all the gravel media, wash them, and replace them. However, recent work[97] carried out by the International Reference Center for Waste Disposal (IRCWD)[97] at the laboratories of the Swiss Federal Institute for Water Resources and Water Pollution Control (EAWAG) has indicated that periodic draining of the gravel filter can go a long way towards restoring full filter efficiency.

3. Investigational Work in Thailand

Much work has been carried out in Thailand at the Asian Institute of Technology into the operation of horizontal-flow gravel filters. Initially the work was carried out on a laboratory scale and then on a pilot scale. There are now several of these horizontal-flow filters operating on a village scale in Thailand. The laboratory-scale model was 1.2 m long with four consecutive 300-mm compartments containing 9.1, 6.4, 2.8, and 9.1 mm crushed stone.[58] The rate of treatment was 14.4 m/day and the raw water employed for both laboratory- and pilot-scale investigations varied normally between

24 to 50 JTU, although this increased to as high as 114 JTU during rainy periods. On average, the turbidity was reduced by between 60 to 64% and, interestingly, this was accompanied by a 70 to 75% removal of coliform bacteria for an inlet water count which varied between 1100 and 2400 per 100 m*l*. In addition, a 55% drop in the dissolved oxygen content through the prefilter indicated some substantial biological activity, although some of the oxygen will have been utilized for the oxidation of iron salts, the concentration of which fell from 0.5 mg/*l* at the inlet to 0.1 mg/*l* at the outlet.

Following the laboratory-scale work at the AIT, a pilot-scale horizontal-filter 6 m long by 1.5 m wide by 1.0 m deep was constructed[58] filled with vertical layers of 15.7, 6.8, 4.5, 3.5, 3.4, 4.5, and 15.7 mm crushed stones, which was again operated at 14.4 m/day. The removal of turbidity was 63% following an early maturation period of 20 days. It was perhaps strange that a maturation period was necessary for a process in which, it would be expected, most of the turbidity removal was brought about by sedimentation. This may again point to the unsuitability of turbidity as a parameter with which to judge the quality of water reaching a slow sand filter. In this case some of the turbidity removal may have been associated with colloidal material in the water which probably would not have a pronounced effect on the increase in head loss in the following slow filter. The authors suggested that the maturation period was necessary to allow overlarge pore spaces between the crushed rock particles to become blocked. Kuntschik[91] also reports the necessity for a short period of maturation as did Symons and Pardoe,[92] who reported an increase in the removal of turbidity from 15 to 75% over a 7- to 10-day period. In East Africa during the early stage of operation of an installed horizontal-flow prefilter[84] it was discovered that the turbidity of the feed water was scarcely reduced. This was thought to be due to dusty, mechanically broken gravel or to excessive electrostatic repulsive forces which were reduced as the filtration continued.

Other investigations[63,93] using horizontal-flow coarse media filters to attempt to remove algae from water found that no maturation period was necessary.

4. *Research in Tanzania*

The extensive investigations carried out into prefiltration at the University of Dar es Salaam[84,89] revealed that there was little difference in results of operation between coarse-media vertical filters and coarse-media horizontal filters, but, largely because of their extremely large silt storage capacities and their appreciable lengths, it was decided that the horizontal-flow filters had the greater potential as pretreatment units prior to slow sand filters. In the early small-scale experiments[89] the superiority of small aggregates over large aggregates was demonstrated, although the turbidity removal declined markedly with flow of greater than 2 m/hr for all the aggregates investigated. From these early investigations it was concluded that future designs must include coarse pebbles at the head of the filter with this section being perhaps broader and accepting higher flowrates (up to 2 m/hr) than a narrower, smaller-media, downstream section. Also, it was concluded that the Reynolds Number in the second half of the horizontal-flow filter should be less than 5 with a flow rate of between 1.0 and 2 m/hr. The length of the filter would vary with the quality of the water, but should be at least 15 m.

Later work by the University of Dar es Salaam[84] was carried out at village sites. One of the prefilters, 9 m long, consisted of three compartments in series containing, initially, 16 to 32 mm gravel, then 8 to 16 mm gravel, and finally 4 to 8 mm gravel. Using this prefilter, the turbidity was reduced from 115 to 30 NTU at a flow rate of 0.5 m/hr, from 48 to 10 NTU at 0.75 m/hr, and from 38 to 17 NTU at 1.5 m/hr. All the gravel sections contributed to turbidity removal but the removal of suspended solids was accomplished principally in the first 3.0-m long section with the most pronounced reduction being in the first 1.5-m length. Along the whole 9-m length the suspended solids content was decreased from 130 to 16 mg/ℓ at a flow rate of 0.75 m/hr and from 96 to 29 mg/ℓ and 78 to 8 mg/ℓ at a flow rate of 1.0 m/hr. The reference slow sand filter (ES, 0.24 mm) for this stage of the investigation, receiving water which had not been prefiltered, blocked after 3 days of operation at a rate of 0.2 m/hr while the slow sand filter receiving prefiltered water and operating at the very appreciable rate of 0.4 m/hr continued for 7 days. A longer prefilter containing four 4-m compartments in series, with 16 to 32 mm gravelin the first, 8 to 16 mm in the second, 4 to 8 mm in the third, and 2 to 4 mm in the fourth, was able to reduce the inlet water turbidity from 92 to 39 NTU at a flow rate of 0.5 m/hr and from 69 to 34 NTU at a flow rate of 1.0 m/hr.

5. Research in the U.K. and Peru

Investigations into the operation of horizontal-flow prefilters at the University of Surrey[93] involved three filters 2.5 m long by 0.3 m by 0.3 m, of which one contained 10 mm graded gravel, another 20 mm graded gravel, and the third, 40 mm graded gravel. The raw water fed to these filters was variable in quality with a turbidity range from 2.0 to 100 NTU and the fecal coliform content varying from 1000 to 10,000 per 100 mℓ. When operating the filters in parallel at flow rates of between 0.5 and 2.0 m/hr, it was found that performance was consistently inversely proportional to gravel size, with the 10-mm gravel filter removing up to 90% of the fecal coliforms and up to 75% of the turbidity. Collaborative work by the Panamericano de Ingeneria y Ciencias de Ambiente (CEPIS-PAH of WHO) demonstrated that larger gravel is more useful for reducing gross suspended solids when influent turbidities were in the range of 200 to 2000 NTU. With these filters-in-parallel investigations at Surrey, it was noticeable that it was the first 1-m length of each filter which was the most effective. With increasing flow rates the length of this effective section increased — implying that it is retention time that is the most important factor.

Further investigations by the Surrey team with the three filters in series in the order 40 mm gravel then 20 mm and then 10 mm, with influent water turbidities of only between 2 and 20 NTU, achieved a removal of fecal coliforms of up to 96% and a turbidity removal of between 60 and 75%. Long-term improvements in filter operation were observed during these investigations, indicating the need for a pronounced maturation period before full efficiency is achieved and suggesting the importance of biological activity.

An investigation into the filtration of secondary sewage treatment works effluent through a horizontal-flow gravel filter carried out at the University of Loughborough[36] is of some interest to the potable water industry. Using a horizontal prefilter divided into sequential compartments of 150 mm length of 14 to 20 mm gravel, 1500 mm of 5 to 6.3 mm gravel, 100 mm of 6.3 to 10 mm gravel, 100 mm of 10 to 14 mm gravel, and 150 mm of 14 to 20 mm gravel, very appreciable reductions in both suspended solids and coliform organisms were achieved.

At flow rates of 2 m/hr, suspended solids reductions of from 63 to 62% were achieved and at the increased rate of 4 m/hr these reductions dropped only to 60%. The percentage reduction in coliform organisms amounted to 86% at a rate of 4.0 m/hr and 99.5% at a rate of 1.2 m/hr.

Certainly very encouraging results have been achieved using horizontal-flow gravel prefilters, but there is such a pronounced disparity between results so far obtained in different circumstances that one must agree with the authors of the third report from Dar es Salaam[84] that at this stage "adequate guidelines for the design of horizontal-flow prefilters are not yet available". More precise information is required, particularly concerning the removal of suspended solids, in relation to different combinations of gravel sizes, flow rates, and especially the sizes and types of particles in the water which are to be removed.

6. Recent Work in Switzerland

Recently published work[96,98] of the investigations carried out by Dr. Boller at the EAWAG laboratories in Switzerland has gone some considerable way towards providing the additionally required information. Filtration tests were carried out using suspensions of Kaolin in water with particles sizes smaller than 20 μm, and averaging about 1.75 μm, so as to suitably represent suspension in presettled river waters. Various filter media were examined including glass spheres, quartz, pumice, and charcoal, which all possess very different surface characteristics but which all exhibited similar efficiencies within the horizontal-flow filters. This latter is an important observation in that it indicates that a variety of locally available filter media, such as broken bricks, could be employed without detracting from the efficiency of the prefilter.

During this research a number of parameters were investigated, including size and type of filter media, filter length, filtration rates, filter loading, filter efficiencies, and head losses. The variation of filter efficiency (per unit filter length) with particle size of the suspended Kaolin, filter grain size, and filtration rate (meters per hour) was demonstrated. A semiempirical filtration model was developed for horizontal-flow filters in which the effluent quality and final filter resistance are the two main criteria. The actual reduction of suspended solids in the water passing through the filter is described in terms of filter efficiency as a function of rate of filtration, type of suspension, filter loading, and sizes of the filter media. This filtration model[97] can be employed to simulate horizontal-filter operations and will reduce the number of filtration tests required while attempting to optimize filter design.

This investigation also revealed that as the solids are removed by gravity settling they form loose agglomerates of several millimeters height on top of the media grains. The height and shape of these agglomerates depends upon their slope stability and, once this is exceeded, the deposited material moves downwards within coarse media, but the movement is prevented if the medium is smaller than 4 mm. This gradual downward movement restores the retention capacity of the upper regions of the filter medium and helps maintain the filtration efficiency long into the run. It also leads, obviously, to the collection of the removed solids at the filter bottom and enhances the effect of filter drainage in restoring removal capacity.

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