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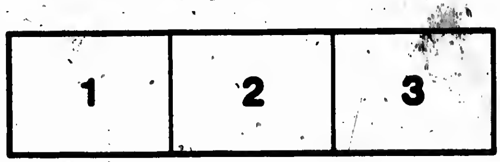

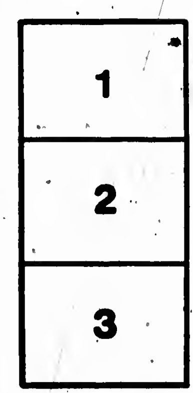

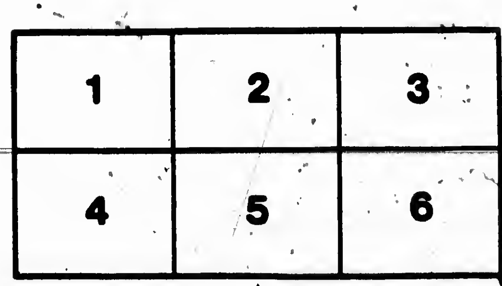

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Canadian Society of Civil Engineers.

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SAND FILTRATION OF PUBLIC WATER SUPPLIES.

BY R. S. LEA, ASSOC. M. CAN. SOC. C. E.

(*To be read Thursday, Jan. 19th*, 1899.)

The present century, particularly the latter half of it, is especially noted for the wonderful progress which has been made in scientific knowledge. None of the results are of more practical importance than the developments which have taken place in the facilities for transportation, and for the transmission of power over long distances.

The direct outcome has been a continually growing tendency towards centralization in most industrial operations; which, in turn, has resulted in an increase in the number of people living in towns quite out of proportion to the total growth of the population. For instance, in the year 1790 there were but three towns in the United States with populations of 8,000 and over; and these comprised less than 4 per cent. of the whole number of inhabitants. In 1880 there were 286 such towns; ten years later the number had increased to 448, and these included about 30 per cent. of the total population. Again, in 1840, there were only three cities with populations as great as 100,000; in 1890 there were 30; while at the present time almost half the people in the country live in places with populations of at least 1,000.

These are figures which apply to the country at large. In certain districts, however, the percentages are much higher. For example in the State of New Jersey, 52 per cent. of the people live in places of 8,000 or over, in Connecticut 54 per cent., in New York 60 per cent. and in Massachusetts 70 per cent. The last State, with a total population of about 2½ millions, has 40 cities of 10,000 and over, and 20 of

25,000 and over. In the countries of Europe the same conditions and tendencies obtain to even a greater degree.

These figures, derived from census reports, etc., are given in order to call attention to the magnitude and direction of this movement, which has taken place to any considerable extent only during the last few decades; but which has, nevertheless, practically created an important branch of engineering.

From this crowding together of people in restricted areas, in close proximity to industrial establishments, have arisen many new and complicated problems; among the most important of which are those connected with the maintenance of sanitary conditions of existence. Besides this, not only are these problems rapidly increasing in number and difficulty, but there is a growing appreciation of the danger of unsanitary surroundings, and consequently, of the necessity of having such matters properly dealt with.

In thickly populated districts and in the neighhbourhood of cities and towns the wastes of human life and human industry are a continual menace to the health of the inhabitants. Nature's method of preserving the balance between growth and decay, by utilising animal waste as plant food, is no longer effectual. The lakes and streams begin to serve the double purpose of sources of water supply and receptacles for sewage. Hence it is evident that among the most urgent of the questions with which the municipal * engineer may have to deal are those connected with the securing and maintaining of the degree of purity necessary in water intended for domestic use.

The proper methods to be employed in the accomplishment of this object depend as much upon biological as upon mechanical principles, so that a certain degree of familiarity with these principles and with the methods of the chemist and biologist will be necessary to the engineer engaged in such work, in order that he may be able to avail himself intelligently of their assistance.

European cities, having earlier felt the necessity, have devoted much more attention to these matters, and are consequently further advanced in their methods of dealing with them than is the case with the cities in America. Nevertheless, by far the most important series of investigations into the subject of the purification of water and sewage are those known as the "Lawrence" experiments, carried on under the direction of the Board of Health of the State of Massachusetts.

* The name "sanitary engineer" having been appropriated by those engaged in the occupations of plumbing and gas fitting, is no longer a suitable designation in this connection.

This Board, from its foundation in 1869, always devoted a great deal of attention to the condition of the water supplies of the State. In 1886, the time being particularly appropriate, it appointed a body of experts to the exclusive duty of conducting a series of observations and experiments, with the object of finding the best methods for purifying both water and sewage. These experiments are still in progress, and the annual reports of the department, giving the results of their investigations, are exceedingly valuable to engineers and others interested in such questions.

In Berlin and in a few other large European cities having water works departments provided with the necessary scientific equipment and management, many careful experiments have been made on the working of the large water-filter beds of the systems. The results of such experiments as these have an especial value from the fact that they are conducted on a large scale, and under conditions which exist in actual practice. On the other hand, these same circumstances render them less reliable as a means of determining the true principles upon which the process of filtration depends.

The object of this paper is to describe, as fully as reasonable limits will permit, first, the circumstances under which water supplies become polluted, and the nature of this pollution; and second, the process of purifying it again in large quantities by sand filtration.

Of course pure water is preferable to purified water; or, as has been said, with water "innocence is better than repentance." Unfortunately, however, water whose natural state is above suspicion is often exceedingly difficult to procure, except at a cost which is practically prohibitive. Consequently, many cities and towns, especially the larger ones, are forced to use such waters as may be practically available, and to make the best of them. But this best is by no means to be held lightly. By the methods to be described later it is possible to so change the nature and characteristics of polluted water as to convert it to the appearance, taste, and probably absolute wholesomeness of the most innocent of mountain torrents.

Water has the unfortunate capacity of readily dissolving many of the substances with which it may come in contact; so that outside of the laboratory, chemically pure water is practically unknown. Some of these foreign elements may not only be quite harmless, but may actually improve the quality of the water. It is, however, with the others, which make the water containing them unsightly in appearance, disagreeable to taste or smell, or dangerous to health, — in other words, with the substances which constitute pollution,—that we are especially concerned.

If we divide all waters according to their source, into *ground* waters and *surface* waters, the general statement may be made, that it is only in the latter class that are found what may be properly termed polluted supplies. The former are subjected to such a rigorous process of natural purification as to place them beyond the need of any artificial treatment.

Surface waters, or the waters of lakes, ponds, rivers, streams, etc., are liable to receive more or less serious pollution from the following sources:—

1. They may be colored by the drainage of swamps.

2. The waters of many streams become turbid with clay and other suspended matters after heavy rains.

3. The waters of lakes, ponds, and storage reservoirs are liable, at certain seasons of the year, to contain large growths of algae and other minute water plants which float about barely visible to the eye, but which are capable of imparting to the water disagreeable tastes and odours.

4. Any of these classes of surface waters may have discharged into them a greater or less quantity of human sewage; leading, under certain circumstances, to very grave consequences.

In determining the quality of a given water supply, the proper method of procedure is as follows:—

1. To make a local examination of the water shed, in order that all probable sources of pollution may be discovered.

2. Then, if necessary, to have chemical analyses made of samples of the water, by which the nature of the contamination, and to a certain extent its amount and origin, may be ascertained.

3. To make a biological examination giving the number and species of the living organisms that may be present. This will be of assistance in interpreting the chemical analysis; and also in detecting the possible presence of organisms, which in themselves might constitute an element of danger.

Before discussing the results of these analyses, it may be stated in advance, that it is in connection with the *organic* matter in water, dissolved or suspended, visible or invisible, that serious pollution from a sanitary standpoint is to be apprehended. And it is in the information which they furnish on this point that the chief value of the analyses consists. But in order to interpret them properly it will be necessary to allude briefly to the constitution of organic matter and to the changes it is liable to undergo.

To begin with, it includes all those combinations of the chemical elements whose formation depends upon the processes of life; and which, therefore, occur either in plants or animals. Its history is cyclical, consisting of a *constructive* phase or period of growth, and a *destructive* phase or period of decay; the death of the plant or animal forming the dividing line between the two phases. The cycle begins by the appropriation of inert, purely mineral substances from the earth by the green plants, which derive the necessary energy from the sunlight; and ends with the complete disintegration of the more or less complex structures which constituted its organic character, and the return of the elements to the earth.

With regard to the nature of the changes it may have undergone, it is only with those in the second or destructive phase that we are concerned. At the beginning of this phase, at the death of the plant or animal, we find that all organic matter is composed mainly of carbon, oxygen, hydrogen, and nitrogen. The more nitrogen it contains, the more objectionable it is from a sanitary point of view. This destructive process is essentially one of oxidation. The first step is the oxidation of the carbon by the oxygen of the body itself, or by that from without forming carbonic acid gas, and leaving the nitrogen and hydrogen to unite to form ammonia. As decomposition proceeds, the ammonia is itself oxidized—the hydrogen to form water, and the nitrogen to form nitrous acid. The last step is the reduction of the nitrous acid to nitric acid. The nitrous and nitric acids do not remain free but combine with some base present, as soda or potash, to form nitrites and nitrates, the latter being purely mineral substances; so that the final results of the decomposition process are carbonic acid, water, and nitrates. Thus the dead inorganic materials needed for the formation of organic structures are only borrowed; and ultimately are returned to the earth again as inert as when they were taken from it.

Returning now to the chemical analysis, we find the results given in some such form as the following, which is the one used by the Massachusetts State Board of Health:—*

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* The figures in this table indicate parts per 100,000.
There are also columns for the date of collection and examination, and for noting the colour, turbidity, etc.

Sample.	Residue on Evaporation.		Ammonia.			Chlorine.	Nitrogen as		Hardness.	
				Albuminoid.						
	Total.	Loss on Ignition.	Free.	Dissolved.	Suspended.		Nitrites.	Nitrates.		
A	3.85	1.00	.0002	.0048	.0012	.49	.0050	.0000	1.6	Average surface water.
B	40.25	—	.097	.0316	.0222	6.32	.3500	.0300	5.3	Private well.
C	10.50	2.40	.027	.0156	.0120	2.78	.1400	.013	3.6	Mystic Lake.

Now it has been found that a very accurate, and at the same time comparatively easy method of determining the organic matter in water by a chemical analysis is to determine the amount and condition of the nitrogen present. Thus, under the head of Albuminoid Ammonia, are entered amounts which are proportional to that part of the nitrogen which is derived from fresh organic matter, *i. e.*, from organic matter which has not yet begun to decompose. These columns, therefore, represent the possibilities of putrefaction still existing in the water. The amounts under Free Ammonia represent decay begun; under Nitrous Acids (or Nitrites) decay still further advanced; while under Nitrates the amounts entered represent the nitrogen derived from that portion of the original organic matter which has passed through all the stages of decay, and which has been converted into purely mineral matter again.

The importance of the determination of the chlorine is, that an excessive amount points to contamination by sewage which always contains a considerable proportion of common salt.

The actual amounts of the different substances as they occur in water supplies are exceedingly minute, as will be seen by referring to the above table of analysis, one of which samples (B) is a highly polluted one. Hence, in themselves these substances are of very little importance. It is in the history of the water which their presence indicates that their significance lies. Thus the chemical analysis can tell us not only what is in the water, but also a great deal about what is going on in it. It is only within recent years, however, that the methods of organic analysis have been capable of producing such results; when the first attempts at water purification were made, very little was known of the organic matter in solution, and the object aimed at was simply the *clarification* of the water, or the removal of suspended matter visible to the eye.

This was the condition of things when James Simpson, in 1839, constructed a sand filtration plant for one of the London water companies. Each of the beds of this system consisted of a broad shallow basin or reservoir with water-tight bottom and sides. The depth was about 12 feet, and it was filled to about half this depth with the filtering material, which consisted of uniform layers of small stones, gravel and sand, the stones on the bottom and the finest sand on the top. Through the bottom layer of stones and gravel extended a number of branch drains leading into a larger central drain which was connected to the outlet (Fig. 2). The inlet to the filter bed opened above the surface of the sand, and both it and the outlet were provided with gates. The process of filtering consisted in flooding this bed of sand and gravel, and drawing off the water from beneath by means of the system of underdrains, which were built with open joints. The rate could be regulated by the gates or other apparatus on the inlet and outlet pipes.

As filtration progressed the surface of the sand became gradually choked up by the formation upon it of a layer composed of material removed from the water. When this layer became so impervious as to prevent the water passing in sufficient quantities, the filter was stopped, the water level drawn down below the surface of the bed, and the deposit layer removed, together with from ½ to 1 inch of sand. When the surface was smoothed and levelled, the bed was ready to be put in action again.

The frequency of the scrapings depended upon the condition of the water and the rate at which it was filtered; and when the sand layer had become reduced in thickness to what was considered a proper minimum, the whole amount removed was replaced at one time, either by new sand, or by the scrapings after they had been thoroughly washed.

The results from the use of these filters were so satisfactory according to the ideas of purified water then in vogue, that in the following years several others were built in England, and a little later on the continent, especially in Germany. Some of the most important of the continental filters built during this period were designed by the English engineers Gill and Lindley. They were all built on the same general lines as the Simpson filter described above, the details varying somewhat with the individual notions of the designers.

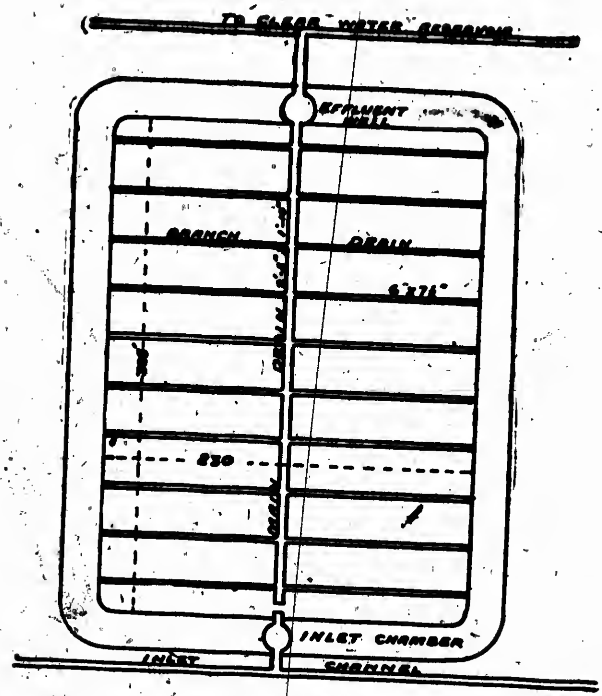


FIG. 2.
Plan of underdrains of Hamburg filters.

In America practically no attention was paid to the matter. The late Jas. P. Kirkwood was employed by the city of St. Louis to report upon the condition of its water supply. His report included the result of his personal observations of the working of several European filters, and was translated and widely read on the continent of Europe. But his recommendations to St. Louis, so far as filter-beds were concerned, were not adopted. And between that time and 1892, only two plants were built in America, one at Poughkeepsie, N. Y., in 1872, the other in 1874 at Hudson, N. Y., both being after designs by Kirkwood.

A little earlier, in 1870, the English chemists Wanklyn and Frankland invented new and improved methods of organic analysis which led to more attention being paid to the organic matter in solution in water. A new importance was also attributed to it at this time by reason of the ideas which were then held concerning the processes of fermentation and decomposition. It was supposed that decay could be communicated to sound organic matter by contact with other organic matter already in process of decomposition; this being the theory advanced by the chemist Liebig, who held that ordinary alcoholic fermentations were produced by the dead and decaying yeast cells, instead of by the action of the living and growing cells as we know now. And so it was considered that the presence of decomposing vegetable or animal matter in water would tend to set up injurious putrefactive changes in the digestive organs and thus produce disease. Hence when analyses of the effluents from the sand filters showed only a moderate reduction of the organic matter—seldom as much as 50 per cent—the result was considered very disappointing, and as indicating that this method of filtration, while capable of improving the appearance and taste of the water, was of slight hygienic value.

Not many years later, however, these ideas and theories were broken down by the researches of Pasteur, who demonstrated that the processes of fermentation and putrefaction were dependent upon the presence of living organisms; and that some of these organisms were capable of causing disease. A new view was now taken of organic matter in water, the presence of which was to be not necessarily dangerous in itself, except as indicating the probable presence of germs. Yet, while chemical purity was now deemed of much less importance than biological purity, the former remained the standard, owing to lack of satisfactory methods of prosecuting the study of these organisms.

Then, in 1881, came the famous discovery by Dr. Robert Koch of his "plate culture" method. Hitherto, owing to the extreme minuteness of these creatures, and the enormous rate at which they increased in number under circumstances favorable to their growth, it was almost impossible, with the methods then available, to make much progress in the knowledge of the subject. But with the advent of Koch's invention these difficulties were to a great extent removed. It now became possible to determine the number of germs, to study their habits of life, functions, etc., and to classify them into species, in a manner which, considering the kind of creature dealt with, seems quite marvellous.

Besides placing the germ theory of disease on a firm basis, this discovery of Koch's marks the beginning of the period during which it has been possible to deal with the subjects of the purification of water and sewage in a rational and scientific way. Numerous investigators at once began the study of these questions under the new and vastly improved circumstances. Inasmuch as the results of many of these experiments have a direct bearing upon the subject under consideration, a brief description of the nature and some of the characteristics of the bacteria will be given before proceeding further.

BACTERIA.

They belong to the lowest and smallest forms of life. Structurally they are composed of a single cell with a wall, possibly of cellulose, and contents consisting of apparently structureless protoplasm and a nucleus; and are thus comparable to the bone, blood, nerve cells, etc., which represent the ultimate structural composition of the animal body.

They are of such extreme minuteness as to be visible only to high powers of the microscope. In their greatest dimensions they vary from $\frac{1}{10}$ to 2 micro millimetres (from $\frac{1}{250000}$ to $\frac{1}{12500}$ of an inch). A sphere $\frac{1}{25}$ of an inch in diameter could contain more than 500 millions of the larger ones, and it would take a thousand of them placed in a row to reach across the diameter; so that it is little wonder that their presence was, until a few years ago, scarcely suspected. They are generally transparent, but may be stained for purposes of study by some of the aniline dyes.

It was at first doubtful whether they should be classified as plants or animals; but it is now definitely decided that they are plants. Some of them have the power of motion, which appears to be by means of little hair-like appendages or cilia. They reproduce by fission,—a simple process by which a single bacterium divides itself in the middle, thus producing two. Under favorable conditions this multiplication can go on with incredible rapidity. They comprise a great number of species with definite characteristics and requirements for growth, etc. All these species are included in the general term *bacterium*, or *microbe*, or *germ*.

They may be classified in various ways depending upon their form, the nature of their environment, the products of their action, etc.

According to its form a germ may belong to :—

1. The *micrococci*, or ball shaped.

2. The *bacilli*, or rod shaped.

3. The *spirilla*, or spiral shaped.

They occur usually as separate individuals, but may also occur in pairs, tetrads, or in a row like a chain. Besides these forms they are often found under certain circumstances in irregular groups or masses, held together by a transparent glutinous material which they secrete through their cell walls. These sticky, jelly-like masses are termed zöoglœa. Unlike the algae and other green plants they cannot exist upon purely inorganic matter, but require for their nourishment matter already organized in s[illegible] form. Moisture is also a necessity to their proper growth; and thus according to their habitat or preferred environment they are classified as:

1. *Saprophytes*, living on dead animal or vegetable matter, or on water containing these in solution.

2. *Parasites*, subsisting on a living host, in the body of which they grow and multiply, in some cases without any injurious effect, but in others causing disease and death. It is not known whether these results are produced by their action in obtaining their food or by the products which are thus set free. These injurious members of the parasitic class are the so-called pathogenic or disease-producing bacteria; such as the well-known germs of typhoid and cholera. Some species of bacteria are able to exist either as saprophytes or parasites, and are called *facultative*.

Another classification depends upon their ability to live in the presence or absence of oxygen, *e. g.:*

1. *Aerobic* requiring the presence of oxygen.

2. *Anärobic*, unable to exist in the presence of this gas.

Facultative anärobics can live either with or without oxygen.

There are various other ways of classifying them which are of no special interest in this connection. The most important classification, from our point of view, is that which divides them into parasites and saprophytes. The great majority of bacteria belong to the latter class, and depend for their nourishment entirely upon lifeless animal or vegetable material. Their energies are thus devoted to the task of attacking dead and decaying organic matter, tearing it apart (in the chemical sense), breaking up its complex combinations, and ultimately reducing it to unobjectionable inorganic compounds. This is accomplished in many different ways, depending upon the attendant circumstances and the species of the dominating germ. But the final result is the same. All these destructive processes in the history of organic matter, which have been previously referred to, were formerly considered to be purely chemical; but it is now known that if the bacteria are absent or in any way rendered inactive, no decomposition of any kind can take place even in air. Hence, it is evident that the rôle they play in nature is, for the most part, a beneficent one. They are the universal scavengers, and but for them all organic growth would in time be overwhelmed by its own waste.

There are, however, also the pathogenic members of the parasitic class, which, though few in number when compared with the others, are yet possessed of the same capacity for multiplication when the conditions are favorable. But while the absence of such conditions will arrest their growth and development, it does not necessarily cause their death. For instance, the temperature most suitable to the typhoid germ is that of the human body, which is its natural habitat; yet, it can exist for months in the middle of a block of ice, and then continue its normal career with undiminished energy and virulence. Hence, of the different kinds of water pollution, human sewage is the most to be feared, since it is at any time liable to contain such germs; and the method which can best ensure their removal is evidently the one best suited for domestic purification.

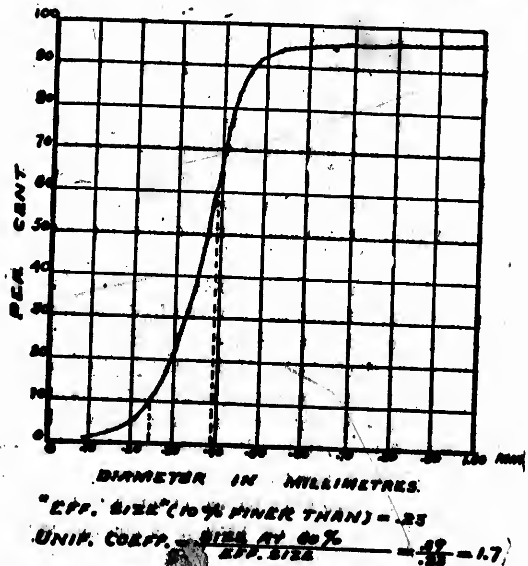
With the adoption of bacterial purity as a standard for water purification, it is no wonder that it was anticipated that the sand filter would prove even of less hygienic value than it did from the chemical point of view. Thus in a paper read before the Institute of Civil Engineers about this time the following statement occurs: "Filtration is another remedy put forward as infallible by those who have not grasped the subject. How can filtration affect substances dissolved in water? And as for the minute organisms found in putrescent bodies, they could pass a hundred or a thousand abreast through the interstitial spaces of ordinary sand as used for this purpose." Nevertheless, as experiments and tests multiplied, it soon became evident that these same clumsy contrivances were actually removing from 97 to 98 per cent. of all the germs contained in the water. Not only this, but continued study and experiment since then have resulted in such changes in the methods of building and operating these filters, that they can now be depended upon to remove from 99 to 100 per cent. of the bacteria, and although numerous other devices for filtering have been invented and tried, so far none have been shown to be equal in efficiency to the sand filter. Thus did these earlier engineers build better than they knew, and produce results whose excellence they did not even suspect.

Investigation into the manner in which it was possible for a comparatively porous material like the sand bed to hold back such infinitesimal bodies as the bacteria revealed a paradoxical condition of affairs, viz., that these germs, while constituting the most dangerous element in the pollution of drinking water, were at the same time the chief agents in its purification. It was found that the purifying action was partly mechanical and partly biological, the circumstances attending the latter not being very well understood. The manner in which it takes place and the means by which it may be enhanced, will be referred to while describing the construction and operation of a modern filtration plant.

In describing the materials of the bed and the best method of disposing them, we shall begin with the sand.

SAND.

It is in the sand layer that the actual purification takes place; and it is observed that the efficiency and economy of the process are dependent to a considerable extent upon the size of the sand grains



Graphical representation of a mechanical analysis of a sample of sand.

and the thickness of the bed. It is the smaller grains which determine the "effective size" of a sample of sand; since, by filling up the spaces between the larger ones they fix the diameter and length of the channels through which the water must pass.

At Lawrence, as the result of experimenting on the rate at which water flows through various sizes of sand, the "effective size" is taken as that of the grain which has 10 per cent. by weight of the sample smaller than itself, and 90 per cent. larger. This size is obtained by a process of mechanical analysis described in the Report for 1892, which also gives what is termed the "uniformity co-efficient," the latter being the ratio of the size of the grain which has 60 per cent. smaller than itself to the "effective size." (See Fig.) If we look more closely into the purifying action of the sand, in order to be able to understand just how it is affected by difference in the "effective size," "uniformity co-efficient," thickness of the bed, etc., we shall see that what takes place is as follows:—

When water is first let in to the filter, it rises to a depth of 3 or 4 feet above the surface of the bed; and it is either held there for some hours, or filtration is allowed to proceed at once, the first part of the effluent being wasted. In either case, the sand grains at the surface soon become enveloped in a membranous film composed partly of the zöoglœa form of the bacteria, and partly of the more or less finely divided organic matter which the water holds in suspension. This sticky jelly-like substance, extending around and between the sand grains, entangles and holds back the smallest particles in the water, even the bacteria themselves. The latter are not only prevented from moving further, but are detained under such adverse circumstances as to not only arrest their growth and multiplication, but also to cause their death.

Naturally the larger suspended particles, water animalculæ, fragments of plants, etc., are stopped at the very surface of the sand, and a continuous mantle called by the Germans the *Schmutzdecke* is soon formed and covers the whole bed. Under certain circumstances, as for example when the water contains a large algæ growth, this layer forms a dark greenish carpet of a texture like felt, which when dry can be peeled off in flakes. Ordinarily, however, since it contains a certain quantity of silty matter, it penetrates the sand for a depth of half an inch or so. But even when formed in this way there is often almost a distinct plane of cleavage between it and the sand below, which makes it very easy to remove with broad square-cornered shovels.

This operation becomes necessary when the gradual thickening of the surface layer prevents the required quantity of water from passing.

It will thus be seen that the surface film forms by itself an exceedingly effective filtering material, but with a very delicate structure; and as such, should be carefully guarded against any influence which might cause its fracture. Several European engineers have concluded that it alone constitutes the actual filtering medium; and that the remainder of the sand bed serves merely for its support, and for steadying the flow of the water through the bed. But experiments made at the Lawrence Station do not by any means verify this view. Indeed they have shown that if great care is taken not to disturb the underlying sand, almost the whole of the surface layer may be removed without at all affecting the bacterial character of the effluent. It is also shown that a new filter does not arrive at what is called its "full bacterial efficiency" until it has been in use for a considerable time; even though in the meantime surface layers may have been formed of sufficient thickness as to completely clog the filters.

By examining the sand, it has been found that this sub-surface purification only occurs when the sand grains for a considerable depth below the surface have become coated with a film of the gelatinous organic material referred to above. It has also been shown that if, during scraping, the bed is subjected to any considerable mechanical disturbances, as by spading, by which these envelopes are broken and detached, the result is a decided inferiority in the quality of the effluent. It is a well known fact, that the longer sand is in use the greater is its efficiency for filtering purposes.

All these considerations go to show that while undoubtedly most of the purification takes place in the surface layer, it is not absolutely essential. The facts stated are chiefly of importance in so far as they indicate the true principles upon which the process of filtration depends. They should by no means tend to lessen the care which ought always to be exercised to preserve the surface layer intact. The purifying power of the main body of the sand should be considered as a factor of safety, and as an additional guarantee of good results.

As to the influence of the size of the sand, it may be stated generally that the "uniformity co-efficient" should be as low as possible. Also that the smaller the "effective size" the more efficient is the filtration, the less liability is there to disturbing effects, and the sooner does the sand arrive at its full bacterial efficiency. At the same time it must be operated at a lower rate, becomes clogged more easily, and thus requires more frequent scraping. The latter performance, together with the periodic renewal of the sand, will form the principal part of the expense of operation. There is thus a minimum limit beyond which it would be uneconomical as well as unnecessary to go. The best size, taking everything into consideration, will evidently depend to a considerable extent on the quality of the water and other local circumstances.

The "effective size" of the sand used in the principal European filters varies, according to Mr. Allen Hazen, from .20 to .44 millimetres; and the "uniformity coefficient" from 1.5 to about 3.7.

As to the proper depth of the sand layer, there is even now considerable difference of opinion among engineers. The great variations in the depths of the sand in the older filters, shown by Fig. 1, are not surprising, considering the fact that when the most of them were built nothing was known of their biological action. If we adopt the view, that it is only the surface film which filters, the determination of the best thickness becomes merely a matter of comparing the extra operating expense due to the more frequent renewals of a thin bed, with the corresponding saving in first cost. In most of the European filters the renewal does not take place till the thickness of the bed has been reduced to from 12 to 24 inches. The former is the limit imposed by the Imperial Board of Health of Germany. It would seem to be better practice to require a minimum depth of from 2 to 3 feet, in order to have at all times the benefit of the steadying effect produced by depth of bed. Besides this there is the additional advantage of having a deep permanent layer, which is never disturbed, and which, therefore, causes the filter to increase instead of decrease in efficiency as it grows older.

GRAVEL.

The layer of gravel serves to support the sand and to conduct the water horizontally to the under-drains. The excessive thickness used in some of the old filter beds (see Fig. 1) is not at all necessary, 12 or 15 inches being quite sufficient. It should consist of 3 or 4 layers of graduated sizes, the top one being fine enough to support the sand without any liability of the layers getting mixed. Around the openings into the underdrains the separate stones should be carefully placed so as to avoid any possibility of movement when the water begins to flow. If necessary the gravel must be thoroughly washed before being put in place.

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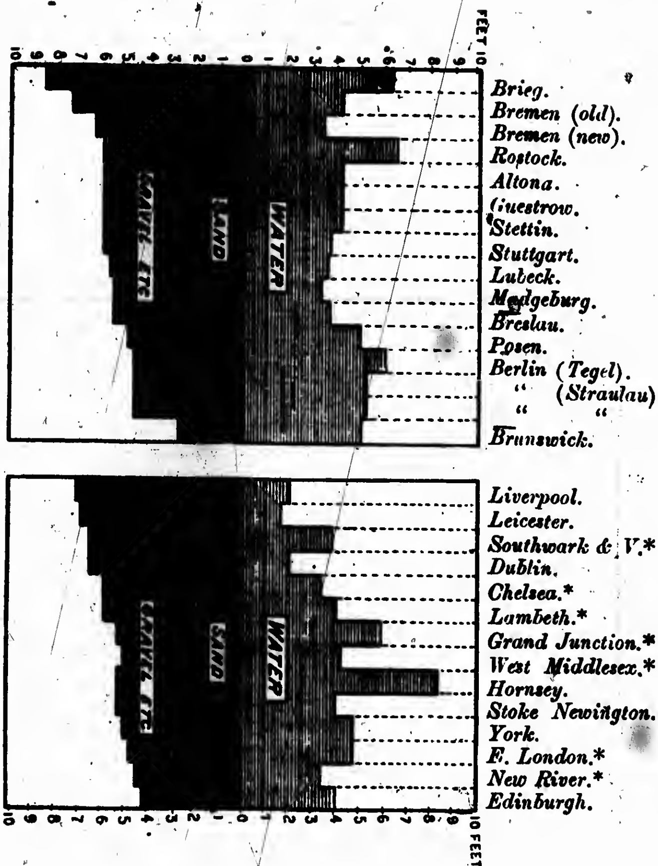

Fig. 1.—Diagram showing Depth of Materials in several European Filter Beds.

* London Water Companies.

UNDERDRAINS.

In arranging the underdrainage system of a filter, which includes the gravel bed, the object to be aimed at is to cause the water to sink vertically through the sand, and as nearly as possible at a uniform rate in all parts of the bed. In order to effect this it is evident that

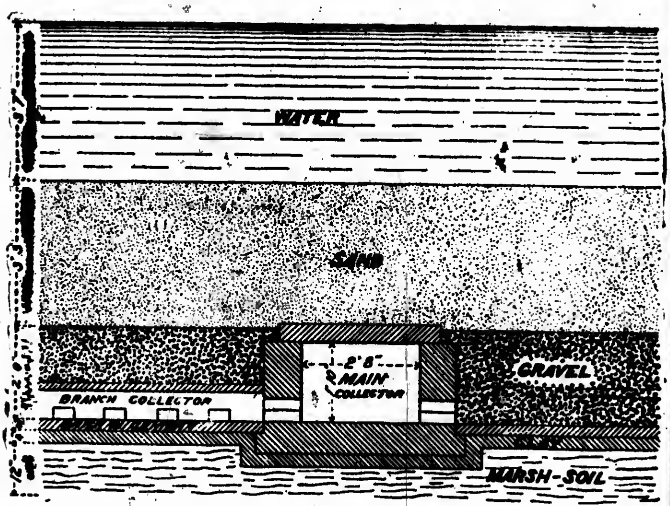

FIG. 3.--Section of Hamburg filter bed.

the resistance to horizontal motion in the underdraining system must be everywhere nearly the same. Attempts have been made to calculate the proper size of the underdrains, using formulæ for the flow of water through gravel and sand of various sizes. A discussion of the matter will be found in the Report of the Mass. State Board of Health for 1892, and also in Allen Hazen's book on the "Filtration of Public Water Supplies," p. 32-41. With round tile drains, and a daily filtration rate of 2.57 million gallons per acre, Mr. Hazen suggests the following limits to the area which pipes of the different sizes should be allowed to drain :

Diam. of drain.	To drain an area not exceeding	Corresponding velocity of water in drain.
4 inches.	290 square feet.	0.30 ft. per sec.
6 "	750 "	0.35 "
8 "	1530 "	0.40 "
10 "	2780 "	0.46 "
12 "	4400 "	0.51 "

and a cross-sectional area for the larger and main drains of at least $\frac{1}{5000}$ of the area drained. With the rate mentioned this would give a maximum velocity in the drain of 0.55 ft. per second.

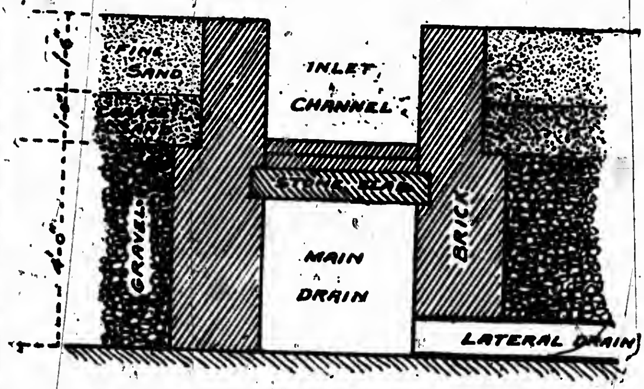

FIG. 4.—Section of filter bed proposed in 1866 by Kirkwood for St. Louis, Mo.

These underdrains are variously constructed of open jointed channels of stone or brickwork, or of tile pipes with perforations or open joints. (See Figs. 3, 4, 5, 6.) There is no advantage in spacing the laterals more than about 16 feet apart, as the extra quantity of coarse gravel necessary would cost more than the saving in the pipe. In some filters the underdraining has been accomplished by means of a double bottom of open brickwork supported on arches or other arrangements of the same material.

The lateral drains usually rest upon the bottom of the basin, but the main drain is often placed lower. (See Figs. 5 and 6.) If the top of the drain is higher than the coarsest layer of gravel, that part should be closed to prevent the entrance of the fine gravel.

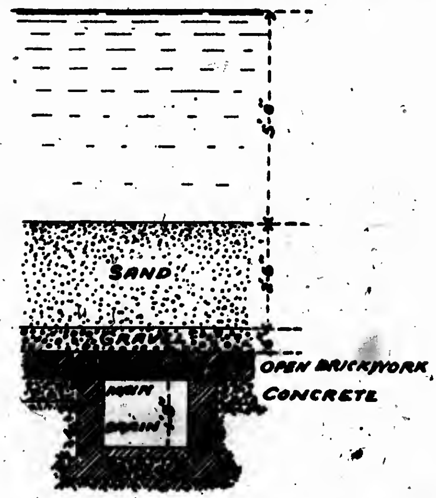

FIG. 6.—Section of filter bed New River Water Company (London).

In several of the old filters vertical ventilating pipes extend from the underdrains above the surface of the water on the bed. These are for the purpose of allowing the escape of air from below, so as not to cause disturbance by passing through the sand. They are not used in the latest filters, as it was found that they were of no advantage, but rather a source of trouble, through the formation of channels between them and the sand, which allowed water to pass without filtration.

BASIN.

The basin which encloses the filtering materials must of course be water-tight; and in that respect the same care must be exercised in its design and construction as would be necessary in the case of any reservoir for holding water. Its depth will depend upon the thickness of the bed and the height to which the water is to be allowed to rise, but does not usually exceed 10 or 12 feet. The bottom is usually level, or perhaps with slight depression for the lateral drains. The walls

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Fig. 8.—COVERED FILTER BED AT ASHLAND, WIS.

may be either vertical or sloping, depending upon the material used. Taking into account the necessity of uniformity in the filtration rate at different points of the bed, vertical sides are probably preferable to sloping. Local circumstances will as a rule determine the best method of construction and the material to be used. The latter may include stone masonry, brick, concrete, earth embankments, puddle, etc.

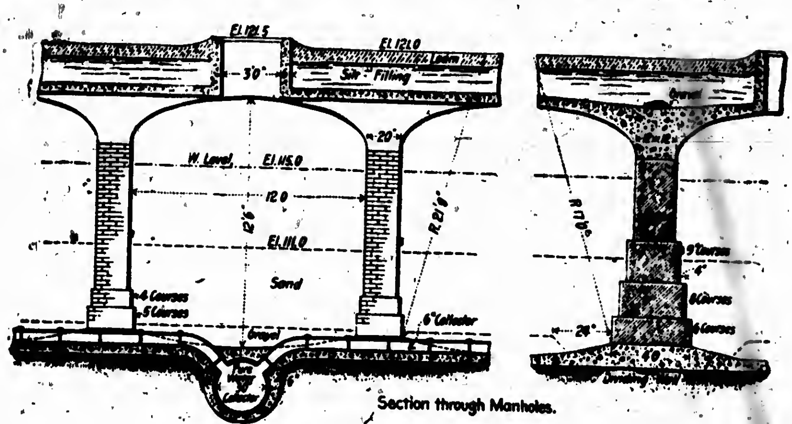
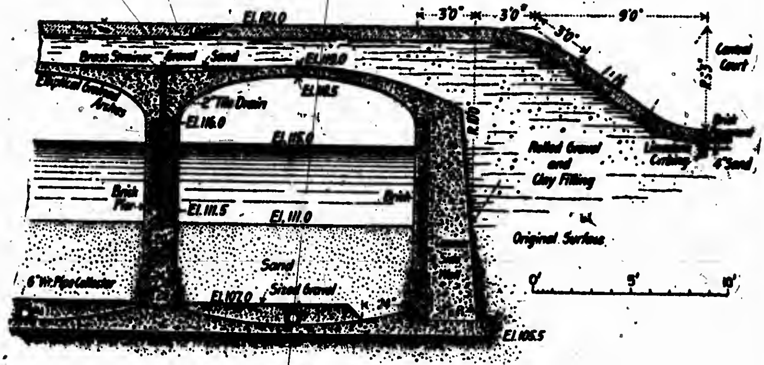


FIG. 6.—Section of filter bed for Albany, N.Y.

Concrete is a very satisfactory, and in most cases an economical material to use for any part of the structure.

If a roof is required it should consist of groined arches, supported on pillars, preferably of brick. (See Figs. 8, 9 and 10.) Care is necessary to obtain a solid foundation for the latter, as the form of roof will not admit of much unequal settlement. A good plan is to form the bottom of flat inverted arches which will give a firm and even support for all the pillars; and the lateral underdrains will then lie along the hollows midway between the rows of piers. (See Figs. 6 and 7.) With a roof of this kind vertical side walls will be more economical than sloping ones. But the plane surface between the wall and the bed must be broken by projections, in order to prevent the liability of unfiltered water passing along the junction; which remark also applies to the piers. It is to prevent this same contingency that the gravel layer is only carried to within 2 or 3 feet of the walls, its place being filled by the sand which here composes the whole depth of the bed.

(See Figs. 6 and 7.) Around the inlet and outlet chambers there should be no gravel within 5 or 6 feet of the walls.



Section through Piers.

FIG. 7.—Section of filter bed for Albany, N.Y.

Manholes must be constructed in the roof for the admission of light and air. Also a "run" for entering and removing the sand scrapings, etc. With piers spaced 14 or 16 feet on centres a light and strong roof can be built of concrete at a very moderate cost. When the roof is finished it is covered to a depth of two or three feet with earth surmounted by a layer of loam, which may be seeded down or laid out in flower beds, etc.

For open filters the sides may be of earth embankments, made water tight by a layer of puddle or concrete. If of the former, a paving of brick is necessary, which must be of sufficient strength to withstand the action of the ice where it is exposed.

OPERATION.

Before proceeding with the methods of operating a filtration plant, reference will be made to Fig. 11 which shows diagrammatically a filter bed with inlet, outlet, underdrains, etc. With a given flow of water through the bed, the vertical distance H represents the head required to force this quantity through the surface film, the sand, gravel and underdrains. It is variously termed "loss of head," "head on the filter," "filtering head."

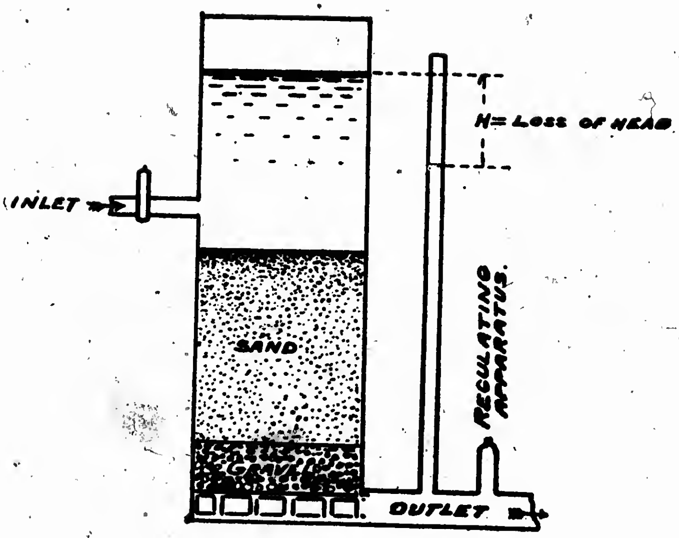


FIG. 11.—Diagram showing various parts of a filter bed.

The depth of water in the majority of European filter beds is usually from 3 to 4 feet, with the full depth of sand. In some of these filters, it was allowed to rise and fall according to fluctuations in the removal of the effluent. Such variations in depth, however, are found to have an injurious effect upon the surface layer, and on the efficiency of the filtering process; in the newer plants, therefore, they are provided against by an apparatus on the mouth of the inlet pipe by which the water when it reaches a certain height automatically closes the inlet. These consist usually of some form of balanced valve worked by a float. In connection with an open filter such an arrangement must be protected from frost.

The inlet opens into a small chamber at the side of the bed from which it is separated by a wall. The water flows over the wall on to the bed, and is prevented from disturbing the surface of the sand by paving it for a short distance from the chamber. Sometimes the water enters by overflowing an open masonry channel extending across the surface of the bed. (See Fig. 4.)

The loss of head, corresponding to a given rate of flow of water through the filter, will depend upon the extent to which the surface film has formed, and the friction in the sand, gravel and underdrains; but under any given conditions it varies (within practical limits) directly as the rate.

In some of the old filters, the outlet was connected directly to a clear water basin, or pump well; and the difference in level between the surface of the water in the filter and of that in the well was, of course, equal to the loss of head. Fluctuations in the draft upon the well produced corresponding fluctuations in the filtering head, and therefore in the rate which was thus automatically adjusted to the demand. In others, however, some sort of apparatus was placed between the filter and the clear water basin by which the rate could be kept constant. This is now considered to be of the greatest importance for the reason that bacterial tests of the effluents have shown that marked deterioration invariably follows fluctuation in the rates. This is probably caused by the mechanical disturbances produced in the sand bed and surface film. For details of such tests, see Report Mass. State Board of Health for 1894.

In the newest plants, therefore, some kind of an arrangement is always provided for the regulation of the flow, examples of which are shown in Figs. 12, 13 and 14. Since the rate varies directly as the loss of head, it is immaterial which is regulated. Some of these devices, therefore, regulate the flow directly, while others accomplish the same result by the indirect method of regulating the loss of head. In order that the former may be kept the same from one day to another, the latter must be gradually increased as the period of service of the bed extends, so as to correspond with the increasing resistance of the surface layer. This is effected automatically in the device shown in Fig. 12, which was designed by Lindley for the filters at Warsaw. The apparatus is contained in a water-tight chamber, connected on one side with the filter, and on the other with the clear water basin. The rate at which the water can pass from one to the other depends upon the depth to which the slits in the sliding pipe extend beneath the surface of the water. This is adjusted by weights at the other end of the chain which passes over a pulley. Thus the rate can be kept constant; and as the resistance of the bed increases the level of the water in the chamber will automatically adjust itself to produce the necessary differences in level or loss of head.

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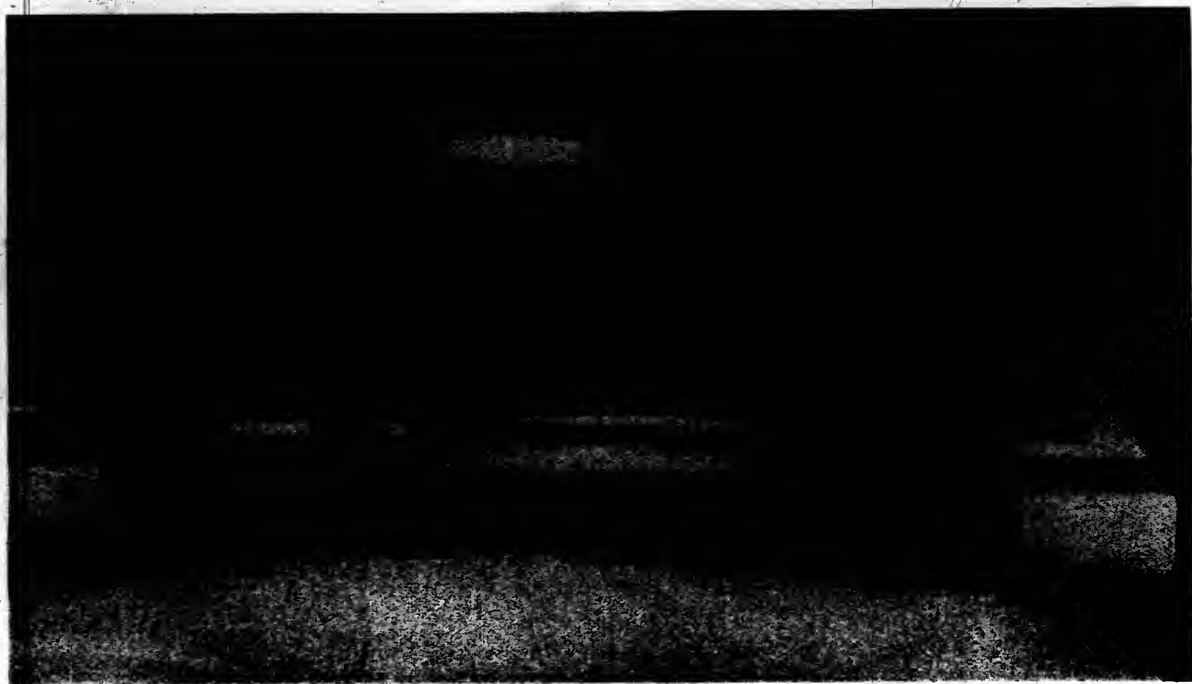

Fig. 9.—COVERED FILTER BED AT ASHLAND, WIS., SAND IN PLACE.

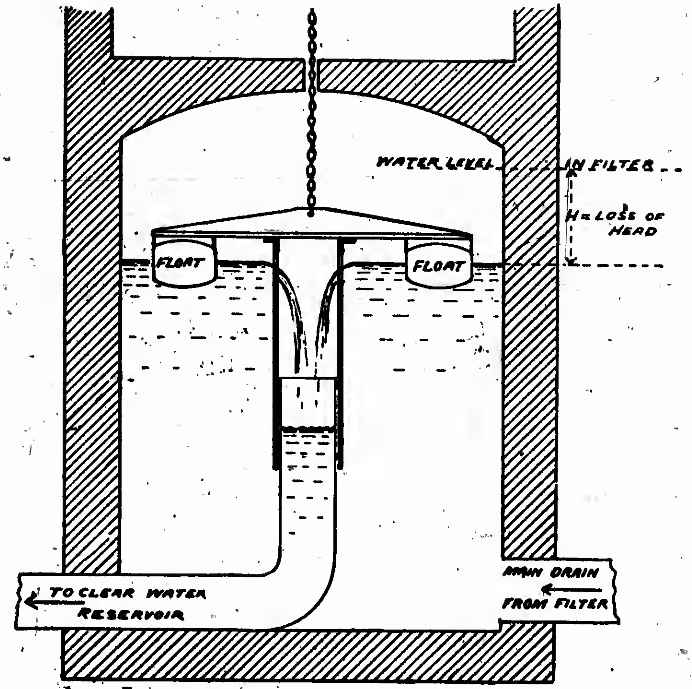

FIG. 12.—Regulator designed by Lindley for the Warsaw filters.

Fig. 13 shows the method of regulation devised by Gill for the Tege Works of the Berlin Water supply. The outlet from the middle chamber is through a weir; and the depth of water on its crest, and, therefore, the discharge, is indicated by the height of the float read on the scale *a*. This is kept constant by means of the gate. The corresponding loss of head is shown by the difference of the readings on scale *b*. Keeping the water in the filter always at the same level, a constant rate can only be maintained by the gradual falling of the level in the right hand chamber and a consequent wider opening of the gate.

Fig. 14 shows the principle used in the new Hamburg filters. A similar method was recommended by Kirkwood for St. Louis. The

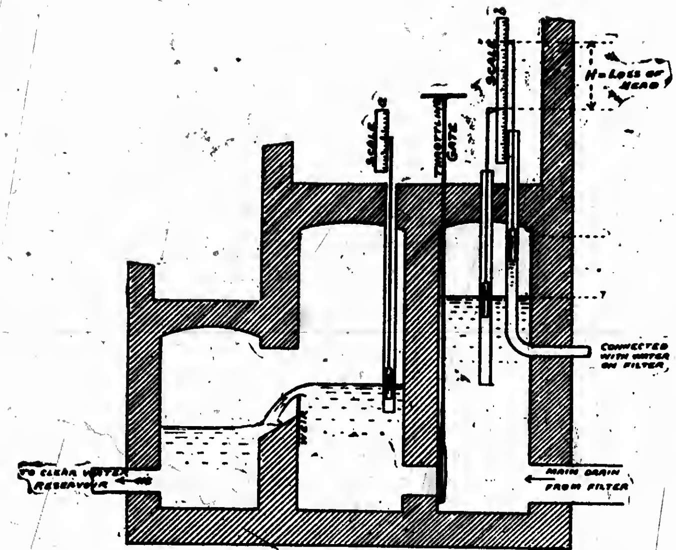

FIG. 13.—Regulator used in the Berlin (Tegel) works.

scale on the right reads downwards, and its zero corresponds to the level of the surface of the water on the filter, which must of course be kept constant. In the first chamber is a float with a pointer attached. The reading of this pointer on the right scale evidently gives the loss of head. The reading of the same pointer on the other scale gives the corresponding rate. This is accomplished in the following way: The outlet of the first chamber is through the weir, which is movable in a vertical direction. The smaller scale is fixed to this weir as shown in Fig. 14, so that the distance between the crest of the weir and the zero of the scale is the same as that between the pointer and the water line of the float. Both loss of head and the rate may therefore be regulated by lowering or raising the weir.

As to the limit beyond which the loss of head should not be allowed to go, the general opinion seems to be that it should not be greater than the depth of water on the bed, though the Lawrence experiments have not shown any bad effects from exceeding this limit.

As a general thing it may be stated that, everything else being equal,

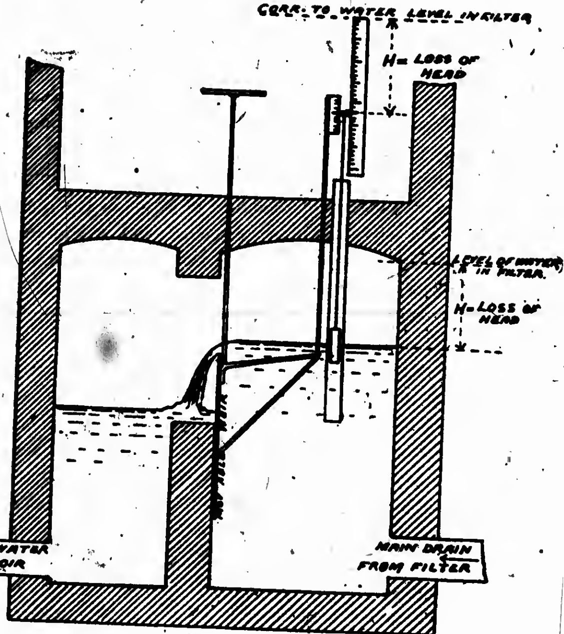

Fig. 14.—Regulating apparatus used in the new Hamburg filters.

the higher the rate the poorer the quality of the filtrate. But with fairly low rates this deterioration is slight, so that entirely satisfactory results can be obtained with rates up to 3 or 3½ million gallons per acre per day. Probably higher rates could be safely employed if very great care were exercised in the operation of the filter. The relative effects of high and low rates from a financial point of view are discussed further on.

SCRAPING THE FILTER.

When the clogging of the filter bed has become such as to require a loss of head greater than the prescribed limit, the inlet is closed and the water allowed to drain away until it has sunk some distance below the surface of the sand. When this has become sufficiently firm, workmen enter the bed with planks, wheelbarrows and broad flat shovels. With these they carefully remove the surface layer and pile it up in little heaps, which they afterwards remove with the barrows. The depth removed varies from ½ to 1 inch, and averages about $\frac{5}{16}$ of an inch. The surface of the sand is then raked to loosen up the packing caused by the boots of the workmen, and after smoothing down any irregularities the planks are removed and the filter is ready for another period of service.

The refilling begins from below by admitting through the underdrains filtered water from another bed in action. The object of this is to drive out the air from the pores of the sand, where its presence in the form of bubbles would cause considerable unnecessary friction. When the water has risen a few inches above the surface of the sand, the lower connection is shut off and the refilling is completed by means of the surface inlet.

Before filtration proper begins the water should be allowed to stand on the bed for several hours; or the first million gallons or so should be wasted. The amount wasted can be reduced by beginning the filtration at a low rate, and gradually increasing it to the maximum.

When the scrapings have reduced the sand-bed to the minimum allowable thickness, the total amount removed, which has in the meantime been thoroughly washed, is replaced at one time. Before doing so the surface of the permanent layer which is never removed, should be loosened up by being spaded over to a depth of six inches or so. If this is not done, there is a liability of sub-surface clogging at its junction with the clean sand.

When the filter is started again, it is, except for the permanent layer, in the condition of a new filter, and so requires extra care in operating it, and the filtrate should be wasted for a much longer time than is required after the scrapings. Piefké of the Berlin Water Works places this period at six days.

Considering the labor necessary and the time the bed is out of use, this replacing of the sand is an expensive operation, and should not occur oftener than can be avoided. In most plants the usual period is about once a year.

SAND WASHING.

Sometimes it is possible to obtain new clean sand at less cost than is necessary to wash the old. But this is rarely the case; hence an important part of the equipment of a fair-sized filtration plant is the apparatus for the washing of the sand. The simplest of the methods employed for this purpose consists of a broad shallow box, which is set in an inclined position. The dirty sand is thrown into this box, and a jet of water played upon it from a hose. The water overflows from the lower end of the box and carries the dirt with it. This is continued until the water runs off clean.

The more elaborate methods employ mechanical means to force the water through the sand. Drum-washers, operated by horse or steam power, are largely used in Germany. They are set in an inclined position, and the sand, with streams of water playing upon it, is forced from the lower to the upper end by means of revolving spira blades. Various other methods more or less on the same principle are employed. Fig. 15 shows the sand-washer used at Hudson, N. Y.

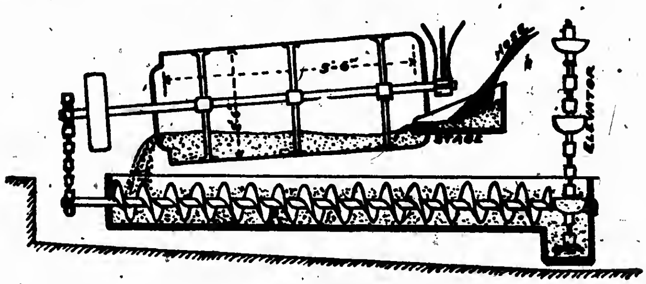

FIG. 15.—Sand washing apparatus used at Hudson, N.Y.

The dimensions are shown on the figure. The dirty sand is shovelled on to the stage, from which it is washed by a hose jet into the revolving cylinder. From the lower end of the latter it falls into a wooden trough 1 foot square in section and closed at both ends. The screw forces the sand into a pit at one end, from which it is elevated by buckets to the floor of the sand storehouse above. The water overflowing the box carries the dirt with it.

The "Ejector" washer is probably the most efficient of all the methods employed. It consists of a series of conical hoppers arranged in a row. At the bottom of each hopper is an ejector through which a stream of water passes under a pressure of 15 or 20 lbs. The dirty sand is thrown into the first and largest hopper. From this it is ejected through a vertical pipe into a trough, from which it falls into the next hopper. Here the same thing occurs; and the process is repeated until the water, which is continually overflowing from the hoppers, comes off clear. The whole arrangement must be enclosed in a masonry pit, from which the dirty water is conducted by drains. Six or eight hoppers are required for each machine, which will have a capacity of from 5 to 6 cubic yards per hour. Sand washers of this type are used in the new filters at Hamburg (Fig. 16); and are to be used in the plant now under construction at Albany, N. Y. Details of the latter are given in *Engineering News*, Feb. 10, 1898.

The volume of water required in sand-washing varies, according to the method used, from 12 to 20 times that of the sand; the ejector machines apparently requiring the most. The question of cost will be referred to under maintenance.

INTERMITTENT FILTRATION.

The operations which have been described in the foregoing pages are those connected with the carrying on of what is known as *continuous* sand filtration; and in determining what methods produce the best results, our only test has been the degree of bacterial purification effected. The reason of this is, as we have already seen, that in waters at all likely to be used as public supplies, the actual amount of organic matter is relatively so small as to be of little sanitary significance. Nevertheless, there is a certain degree of chemical purification effected by this process. Analyses of the effluents show a reduction of the dissolved organic matter of from 30 to 60 per cent. This is brought about by the action of the bacteria, which, though existing under adverse conditions, are yet capable of producing this result in the presence of the free oxygen in the water, the amount of which is usually quite sufficient for the purpose. Now, in the case of sewage, which is only very highly polluted water, the amount of free oxygen is very small in comparison with the organic matter present. And it was found, in making experiments on the purification of sewage by passing it through beds of sand, that if air were artificially introduced a very complete reduction of the organic matter would be effected by the bacteria. This was accomplished by working the bed intermittently; that is to say, at regular intervals of time—say 24 hours—the bed was allowed to drain, and fill its pores with the air drawn in after the sewage. After taking this breath the bed rested for a day; then the sewage was again turned on to the surface, preventing the escape of the air which was necessary to provide oxygen for the next 24 hours' purification. The same method used in connection with water is what is termed *intermittent filtration*. The first filter of the kind was built at Lawrence, Mass., by H. F. Mills, C. E., member of the State Board of Health. Since then, small plants on the same principle have been built at Mt. Vernon, N. Y., and Grand Falls, North Dakota.

The results do not seem to indicate any necessity for their use, not being at all superior to those of continuous filters, while the method of operation is not suited to cold climates, and either requires a greater area of bed or a higher rate of filtration. A description of the Lawrence filter may be found in *Trans. Am. Soc. C. E.*, 1893, p. 350.

GENERAL ARRANGEMENT.

From what has been said, it will be evident that where the water is at any time liable to turbidity, a settling basin, capable of holding from 12 to 24 hours' supply at least, must be provided. Also, in order that the filter may be able to work continuously at a uniform rate, a clear water basin will be necessary of a capacity sufficient to cover the maximum fluctuations in the consumption. Fig. 17 indicates roughly

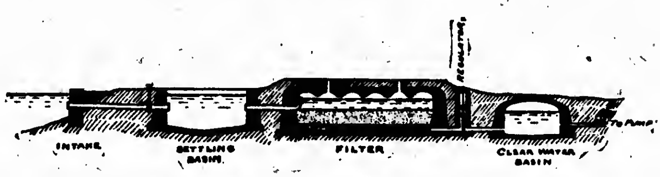

FIG. 17.—Sketch showing the relation of the parts of a filtration system.

the general arrangement of the parts of a complete system. If the supply is from a storage reservoir, the filters are placed below the dam, and are, of course, supplied by gravity. (See Fig. 18) But even when the supply is from a river or lake, the topography of the ground often admits of the same economical arrangement. If this is not possible, the water must be pumped into the settling basin by a separate pump of the low lift variety. The extra expense of two pumpings may be almost eliminated if the same station, boiler plant, etc., can be made to serve for both pumps.

The total area of filter beds required depends in the first place upon the maximum rate adopted; and, second, upon the area out of use while being scraped and refilled. The higher the rate of filtration the less the total area, and therefore the first cost of the plant. The principal item of expense connected with the operation of this plant is that for scraping; and it is found that the amount scraped for any given quantity of water filtered is independent of the rate. Also, the allowance for the area out of use will not vary with the rate to any extent. Hence an increase in the rate will not by any means produce a proportionate reduction in the cost of filtration. A rate of 3,000,000 gallons per acre of bed in use will give results entirely satisfactory from the standpoint of efficiency, and at a cost which is usually by no means excessive.

The size of the individual beds will depend in part upon the extent of the total area, the smaller plants having necessarily to use smaller beds. A large bed costs less per unit of area than a small one, on account of the proportionately greater length of wall in the latter case. With a large bed it is, however, probably more difficult to obtain a uniform rate of filtration over the whole area.

During the winter of cold climates the cost of maintenance is considerably increased by the expense of removing the ice which forms in the bed. It is also difficult to avoid injuriously disturbing the surface of the sand. Beside this when the water is drawn down, the surface sometimes freezes before it can be scraped. On account of such disadvantages as these filter beds should be covered in all cold climates. The best method of constructing these roofs has already been referred to.

The proper number, shape, and area of the beds of a system can only be determined for any particular case by careful study of the local conditions, and by making comparative estimates of the different items of cost of construction, maintenance, etc. There will be opportunities for the exercise of considerable ingenuity in the general laying out of the system, the relative placing of its parts, the arrangement of the piping, drains, etc., in order that convenience and economy may be happily combined.

THE COST OF CONSTRUCTION.

This will of course depend on the local circumstances and the kind of materials used. As in all hydraulic work, great care is required in the construction, and the best quality of materials must be used. In the main, it is the same class of work as is required in the building of distributing reservoirs.

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Fig. 10.—FILTER BEDS AND CLEAR WATER BASIN AT ILION, N.Y.

ELLEPTICAL GROINED ARCHES USED IN ROOF OF WELLESLEY (MASS.) COVERED RESERVOIR.

The following table gives the cost of construction for several European and American filters :

Place.	Cost per Acre.	
	Covered.	Open.
London		$24,000—$40,000
Berlin (1884-87)	$66,000—$70,000	
Hamburg (1893)		30,500
Warsaw (1885)	78,000	
Zurich (1885)	86,000	
Nantucket, Mass. (1892)		45,500
Hudson, N.Y. (1874-88)		73,000
Ilion (1893)		96,700
Ashland, Wis., (1897)	80,000	
Somersworth, N.H. (1898)	64.000	
Poughkeepsie, N.Y. (1872)		90,000
do do (1896)		41,000

Lindley gives the general cost of continental filters as $45,000 per acre for open, and $68,000 for covered.

The following figures, giving in detail the bids received Feb. 15th, 1898, for constructing the water filtration plant now in process of construction at Albany, N.Y., will be of more interest. When completed it will be by far the largest plant yet built in America ; and in general design and completeness of equipment it will be second to none.

It wil consist of a settling basin of 16,000,000 gallons capacity, eight covered filter beds, each with $\frac{7}{10}$ of an acre of sand surface, and a clear water reservoir with a capacity of 600,000 gallons. There will also be provided an office building containing fully equipped chemical and bacteriological laboratories.

The price for the sand and gravel included the necessary screening, washing and putting in place.

The sand washer is of the ejector type. Other details are shown in Figs.

The bids are as follows :

Material.	Quantities.	Prices of Successful Bidder.	Prices of Other Bidders.			Engineer's Estimates.
Shale Rock Excavation	5,000 cu. yds.	$ 1.20	$ 0.30	to	$ 1.50	$ 0.80
Earth excavation (above grade)	60,000 "	.27	.13¼	"	.476	.20
Earth excavation (below grade)	3,000 "	.30	.20	"	.60	.40
Rolled clay and gravel embankments	21,000 "	.52	.45	"	.30	.50
Silt and loam filling	23,000 "	.15	.15	"	.50	.20
General filling (rolled)	18,000 "	.18	.07	"	.40	.20
Puddle in place	13,000 "	.71½	.67	"	1.07	1.00
Broken stone or gravel for lining	1,900 "	.85	.99	"	1.40	1.25
Sodding	3,000 sq. yds.	.15	.15	"	.60	.15
Seeding	8 acres	25.00	12.50	"	70.00	50.00
Gravel in roadway rolled	800 cu. yds.	.60	1.00	"	1.50	1.00
Vitrified brick laid as paving	120 M.	20.00	18.00	"	30.00	20.00
Stone curbing	800 lin. ft.	.60	.75	"	1.50	.50
Concrete in floors	11,000 cu. yds.	2.31	2.34	"	3.50	3.00
Concrete in vaulting	7,000 "	3.85	3.90	"	7.50	5.00
Other concrete	3,000 "	2.13	2.50	"	4.30	3.00
Brick work	4,500 "	8.12½	7.00	"	10.00	6.00
Imp'd Portland Cement	500 bbls.	3.12½	2.35	"	3.00	2.75
American do do	14,000 "	2.14½	1.90	"	2.21	2.15
Rosendale Cement	1,500 "	.97½	.85	"	1.95	1.00
Furnishing and placing 2" drain pipe in piers.		525.00	300.00	"	1,318.00	700.00
2 in. agricultural drain pipe	2,000 lin. ft.	.04	.05	"	.10	.05
6 *ins. drain pipe open joints*	16,000 "	.11	.10	"	.12½	.10
Fur. and laying all vit. pipe cement joints		5,337.00	3,850.00	"	5,933.00	6,000.00
Placing all gates, etc. Fur. by board		1,140.00	700.00	"	2,000.00	470.00
Fur. and placing all cast iron pipe and specials		20,701.25	14,750.00	"	20,000.00	15,000.00
Iron filter covers	672 each	4.40	5.00	"	6.50	5.00
Sand washing apparatus	2 sets	393.00	250.00	"	1,000.00	800.00
Sand run fixtures	8 each	407.50	100.00	"	511.00	200.00
Regulator houses	8 each	862.24	175.00	"	900.00	500.00
Office and laboratory building		4,881.00	2,700.00	"	10,200.00	3,000.00
Filter gravel in place	7,000 cu. yds.	1.05	1.00	"	2.00	1.50
Filter sand in place	36,000 "	1.00	.90	"	1.78	1.25
Split stone lining	2,000 sq. yds.	.82	1.03	"	3.60	2.00
Rough Stone paving	200 "	.82	.93	"	2.50	.80
Fasteners fur. and placed in concrete vaulting	3,000	200.00	150.00	"	225.00	100.00
Iron fence	850 lin. ft.	2.00	1.00	"	2.00	1.00
Connection with pump-well and closing old intake		3,000.00	1,000	"	4,000	3,500.00
Total		$309.866	$322.358	"	$387.345	$322.440

The items of special interest are given in italics.

It will thus be seen that a covered filter plant of this area (5.6 acres) with settling basin, clear water basin, and all other appurtenances complete can be built for less than $56,000 per acre.

For further details and information concerning this plant see *Engineering News*, Feb. 10th and Oct. 20th, 1898.

MAINTENANCE.

The total cost of maintenance of a filtration plant is made up of the operating expenses, and the interest and sinking fund charges.

The former—the operating expenses—comprise:—

(*a*) The cost of superintendence, and of attendants to look after the regulation, etc.

(*b*) The cost of scraping and removing the sand.

(*c*) The cost of washing the sand.

(*d*) The cost of replacing the washed sand when renewal of the bed becomes necessary.

It is only in very large plants that a special superintendent is required, so that the expense for that purpose would not form a very large part of the total cost. The proper handling of the gates, and the running of the plant in general requires a degree of intelligence considerably above that of the ordinary laborer. The wages of the gatemen therefore will be from $2.00 to $3.00 per day.

Scraping and removing the sand by wheelbarrows seems to cost, under ordinary circumstances, between $40 and $50 per acre, depending upon the wages paid. At Mount Vernon, N. Y., the shovellers and barrow wheelers are paid $1.10 per day, and the scrapers $1.25. Mr. Chas. Fowler, for many years in charge of the filters in Poughkeepsie, N.Y., says that one man working 1 hour is required for every 150 square foot of surface cleaned and removed. This would cost at $1.50 per day, about $43.50 per acre. Lindley gives 30 days at 10 hours each for every acre, which at the same rate is $45.00 per acre. In the small plants at Ilion, N.Y., and Ashland, Wisconsin, the cost is at the rate of about $50 per acre.

The cost of sand washing varies with the method employed. In Poughkeepsie, when they used a simple inclined trough and water jet, it cost as high as $1.50 per yard. By improving their methods they reduced this cost, till to-day it is only 27 cts. per yard. In Hudson, the cost is 20 cents per yard, and in Ilion 18. In Germany it varies from 14 to 20 cents per yard

The periodical replacing of the sand in the bed must be done carefully of course, but should not cost, including whatever is necessary to be done to the permanent layer, more than 40 cts. per cu. yard.

The cost of these various operations will of course depend upon the scale on which they are carried on. It will obviously be easier to keep the price low with a large plant than a small one. In the case of the former a force of gatemen and laborers can be permanently employed. In the smaller plants the operations of scraping and sand washing only take place at intervals, and are performed by laborers hired temporarily for the purpose, or by employees ftom other parts of the water system.

In using the above data to make an estimate of the total operating expenses, we shall employ as a unit the cost per million gallons of water filtered.

Assuming an average yield of 50 million gallons per acre between scrapings, the total cost would be as follows:

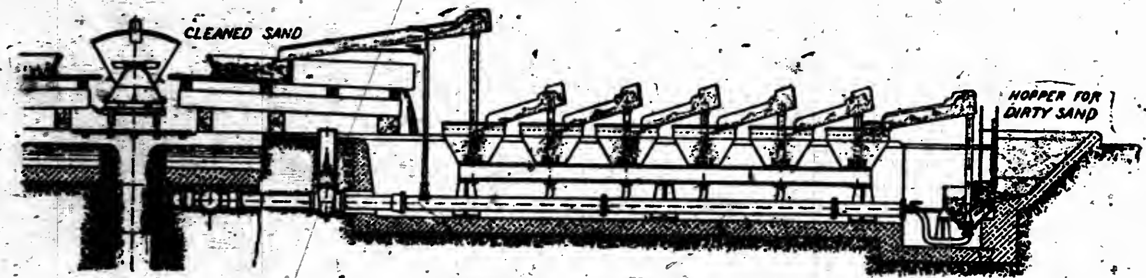
Scraping and removing @ $45 per ac.......	$0.90	per mill. gals.	filtered.
Washing 100 cu. yds. sand @ 25 cts. yd...	0.50	"	"
Replacing, etc., @ 40 cts " ...	0.80	"	"
Superintendence, etc..........	0.25	"	"
Total..............	$2.45	"	"

To this should be added the cost of bacterial analyses of the effluents which should be made as frequently as possible in order to test the working of the filters. In many of the European plants a fully equipped laboratory is included in the equipment; and some of the superintendents, like Piefké, Chief Engineer of the Berlin Works, are also expert bacteriologists.

The actual cost of the operations discussed above for some American filters is as follows:

Poughkeepsie, N.Y., for 20 years averaged	$2.90	per mill. gals.	filtered.
Hudson, N.Y., is given as	$1.38	"	"
Mount Vernon, N.Y., a little less than....	2.00	"	"
Ashland, Wisconsin, estimated to cost.....	2.25	"	"

The following table furnished by W. B. Bryan, Esq., Chief Engineer East London Water Co., gives the yearly cost of filtration of the London Water Companies from 1880 to 1895.



SAND WASHING APPARATUS IN HAMBURG.

FIG. 16.

COST OF FILTRATION PER MILLION U.S. GALLONS—LONDON WATER COMPANIES.

Name of Company.	1880–1	1881–2	1882–3	1883–4	1884–5	1885–6	1886–7	1887–8	1888–9	1889–90	1890–1	1891–2	1892–3	1893–4	1894–5
	$	$	$	$	$	$	$	$	$	$	$	$	$	$	$
Chelsea	1.17	1.20	1.10	1.01	1.06	1.15	.80	1.08	.83	.66	.72	0.75	.62	1.16	.60
East London	1.17	1.40	1.24	1.06	1.06	1.17	.97	1.22	1.29	1.56	1.42	1.54	1.42	2.63	1.69
Grand Junction	1.01	.95	1.40	1.73	1.82	1.35	1.40	1.75	1.56	1.22	1.33	1.24	1.30	2.00	1.68
Lambeth	.83	.81	.96	.93	.90	.90	.87	.90	.95	.88	.86	1.01	1.20	1.46	2.54
New River	1.34	1.15	1.41	1.11	1.02	1.01	.98	.93	.98	.90	1.02	.93	1.17	1.43	1.03
Southwark and Vauxhall	1.17	1.37	1.47	1.62	1.41	1.15	1.44	1.29	1.53	1.70	1.17	1.15	1.26	1.53	1.34
West Middlesex	1.67	1.54	1.74	1.67	1.30	1.07	1.70	1.01	.83	3.56	1.01	.97	1.42	.95	.96

To get the total cost of maintenance, we must include with the operating expenses the charges for interest and sinking funds. This will of course depend upon the cost of construction; and the latter will vary with the maximum rate of filtration adopted, and the proportion of the total area to be out of use while being cleaned. These being decided upon, it will then be easy to calculate the first cost per million gallons of daily yield. For example, if, with the rate chosen, the daily yield of the plant will be 2 million gallons per acre of the total area of beds, the first cost per million gallons will be half the cost of construction per acre, and so on. The diagram gives the cost per million gallons filtered, corresponding to different construction costs, which will pay the interest and sinking fund charges necessary to cancel the whole first cost with interest at the end of 40 years.

For example, with a first cost of $60,000 per acre, and a net yield of 2 million gallons per acre of total area, the cost per million gallons with interest at 4 per cent. would be $4.15.

The amounts taken from the diagrams added to the estimated cost of operation will give the total cost of maintenance per million gallons of water filtered. With interest at 4½ per cent. and a first cost of $80,000 per acre, this would amount to about $6. Add to this $2.50, for the expense of operation and we should have $8.50 as the total cost of filtering 1 million gallons of water, or 1,000 gallons for less than $\frac{9}{10}$ of a cent. With open filters, or more favourable local conditions, this charge would be considerably reduced.

Having now discussed the method and cost of sand filtration, the next and last question to be considered is the nature of the results which this process can be depended upon to produce. There can be no question as to its efficiency from an æsthetic point of view. The complete removal of even the most minute particles in suspension, together with a large part of the dissolved organic matter, ensures the entire elimination of any characteristics the water may possess which would be disagreeable to sight, taste or smell. Yet it is because of the effectiveness of the purification from a sanitary standpoint that this system is especially noted. This is due, as we have seen, to its destructive effect upon the bacteria, which is almost sufficient to cause their entire disappearance during the passage of the water through the filter. The average reduction in a well designed and well managed plant will be as great as 98 or 99 per cent., as shown by comparing the number of germs in the effluent with that in the applied water. But in reality it is even greater than this. For

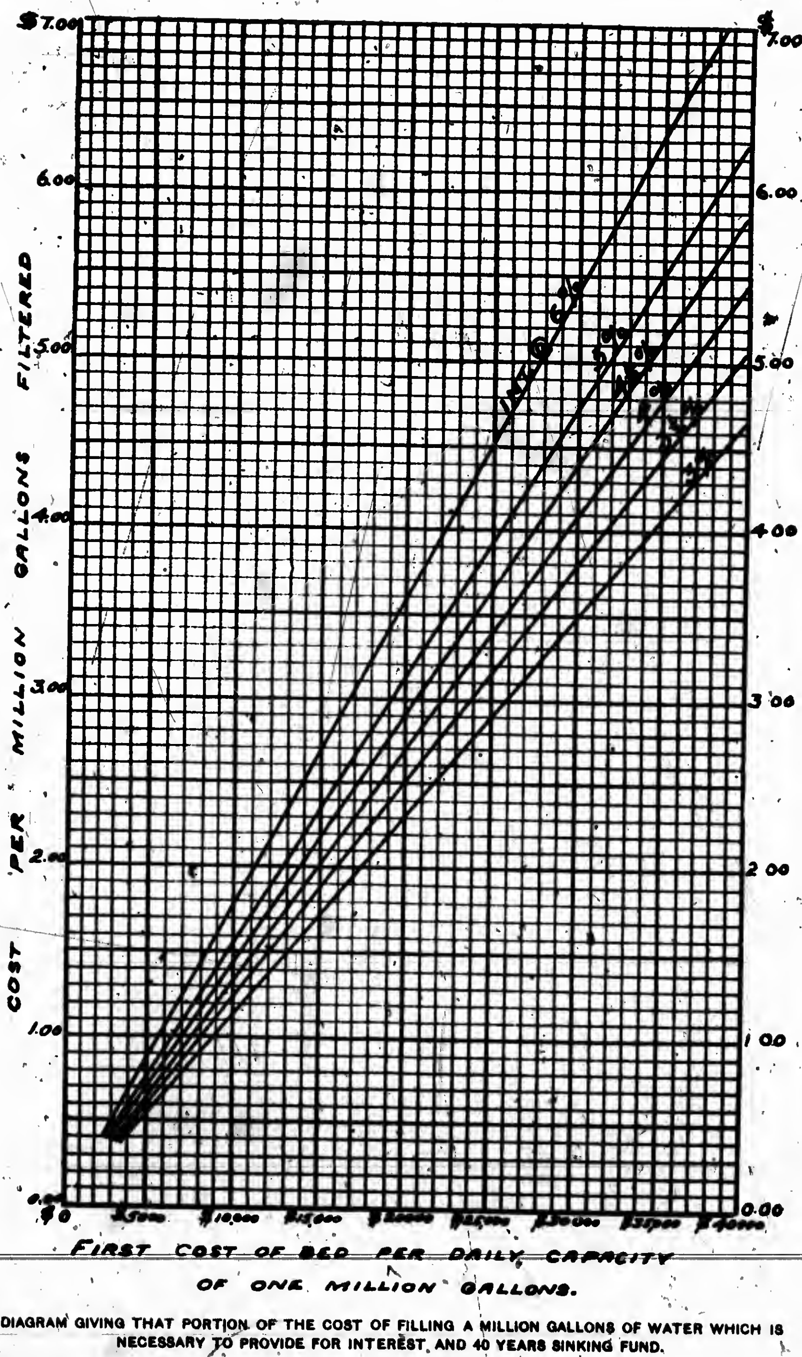


DIAGRAM GIVING THAT PORTION OF THE COST OF FILLING A MILLION GALLONS OF WATER WHICH IS NECESSARY TO PROVIDE FOR INTEREST AND 40 YEARS SINKING FUND.

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it has been shown that of the few bacteria which are present in the effluent, a certain number come from the underdrains, and have therefore not passed through the filter at all. These belong to some of the species of water bacteria, and, consequently, will be quite harmless. From tests made on the experimental filters at Lawrence with an easily recognized and hardy species, the actual reduction was found to be from 99.9 to 100 per cent. Now, when it is considered the filter is capable of producing such effects upon bacteria which exist normally in water, it will be evident that the effect upon the pathogenic or disease germs which are out of their natural habitat and in a decidedly unfavourable environment will be much greater. Thus what may be called the "hygienic efficiency" of this system must be remarkably high. The process is comparable to nature's method of purifying the surface water which furnishes the underground supplies; and if properly carried out, the water produced is probably of almost equal wholesomeness. The continued experience of places where sand filtration plants have been in operation for some time only goes to strengthen this conclusion.

In America the method is only just beginning to be employed. Up to the year 1892 there were but two plants of this description in the country, viz., those at Hudson and Poughkeepsie, which have been already referred to. Since that time 14 new ones have been completed and three others are under construction, the latter including the large plant at Albany. The experience to be derived from these plants is too limited to be of much value for some time to come; but the officials connected with the majority of them have invariably expressed their entire satisfaction with the method of working and with the results obtained.

In England and the continent, however, the experience of many years is available, this method, as we have seen, having been used long before the *rationale* of the process was understood. In England particularly, many of the supplies are from surface waters made available by means of large storage reservoirs; and in nearly every instance the stored water is filtered before being supplied to the consumers. The new supply for Liverpool, which was put into operation in 1892, comes from an artificial lake formed by damming the Vyrawy River in Wales. This lake is 68 miles from Liverpool, and lies in a sparsely inhabited district remote from railways or towns. Yet the water from this source, safe as it may appear, is also made to pass through a sand filter before being allowed to enter the distribution pipes. In Germany the use of any surface water without filtration is prohibited by law.

But in addition to the high esteem in which the method is held wherever it has been used, there are certain health and mortality statistics which are perhaps of even greater significance. The typhoid fever death rate is now considered to be a pretty good index of the purity of a city's water supply. Keeping this in mind the following * tables prepared by John W. Hill, M.Am.Soc.C.E., will be found to furnish interesting information in this connection.

TABLE I.—TYPHOID FEVER DEATH RATE.

CLASS I.—10 or less per 100,000 of Population.

CITY	SOURCE OF WATER SUPPLY.	1890	1891	1892	1893	1894	Average for Five Yrs.
The Hague..	Filtered from sand dunes...........	3	12	4	2	3.4	4.9
Rotterdam ..	Filtered from River Mease...........	6	4	6	5	4.8	5.2
Christiania..	....	12	9	4	6	3	6.8
Dresden.....	Filter Gallery by River Elbe..........	9	8	5	4.5	8.2	6.9
Vienna......	Springs in the Schneeberg...........	9	6	8	7	5	7.0
unich.	Spring Water from Mangfall Valley...	8	7	3	15	2.5	7.1
Copenhagen.	....	9	8	7	9	6.7	7.9
Berlin.......	Filtered from L. Teg-l and River Spree.	9	10	8	9	4	8.0

CLASS II.—10-20 per 100,000 of Population.

CITY	SOURCE OF WATER SUPPLY.	1890	1891	1892	1893	1894	Average for Five Yrs.
Breslau	Filtered Water from River Oder.........	15	12	15	10	6.1	11.6
Amsterdam .	Filtered from Haarlam Dunes.........	19	11	15	16	8.5	13.9
Stockholm ..	....	18	18	19	8	8.3	14.3
Brisbane....	....	....	....	....	19	9.6	14.3
London......	Kent Wells, 17%. Filtered from Thames and Lea, 83%...	16	15	11	16	15	14.6
Edinburgh...	Filtered from Reservoir in Pentland Hills..........................	19	18	13	14	15	15.8
Trieste	....	12	11	26	17	19	17
Brooklyn....	Impounded and Well Water..........	26	20	17	17	15	19

CLASS III.—20-30 per 100,000 of Population.

CITY	SOURCE OF WATER SUPPLY.	1890	1891	1892	1893	1894	Average for Five Yrs.
New York..	Impounded from Croton and Bronx Rivers..........................	21	22	22	20	17	20.4
Davenport...	Filtered from Mississippi River....	19	10.8	34.6	16.7	26	21.4
New Orleans	Rainwater from Tanks and Cistern..	20	23	21	15	28	21.4
Sydney, N.S.W	Impounded from Upper Nepean.....	....	....	20	19	29	21.6
Hamburg. ..	From River Elbe, filtered since May, 1893......................	28	23	34	18	6	21.8
Buda Pesth.	Ground Water from Wells..........	34	23	26	15	14	22.4
Glasgow. ...	Lake Katrine	26	31	18	20	24	23.8
Brussels	....	26	41	23	27	14	26.2
Paris........	Rivers Seine, Marne, Vanne, Ourqc Canal, Art. Wells and Springs....	30	20	28	25	29	26.4
Manchester .	Lake Thirlmere....................	31	39	25	25	18	27.6

* From an address on "Water Supply for Cities," given by J. W. Hill, C E., before the Faculty and Students of the University of Illinois, Jan. 21, 1896.

TABLE I—*Continued.*

CLASS IV.—30-40 per 100,000 of Population.

Venice	....	44	33	30	26	18	30.2
Milwaukee	Lake Michigan	33	33	31	37	26	32.0
Rome	Fontanadi Trevi, Aqua Felice & Paoli	35	36	26	34	30	32.2
Boston	Lake Cochituate and Sudbury River	43	33	29	30	28	32.6
Detroit	Detroit River	18	13	51	61	26	33.8
Dayton, O	Driven Wells	20	32	44	64	20	36.0
Turin	....	46	41	44	29	24	36.8
Liverpool	Lake Vyrnwy	24	25	25	53	58	37.0
Buffalo	Niagara River	....	50	34	37	36	39.2
Providence	Pawtuxet River	29	47	39	34	47	39.2
Covington	Ohio River	43	45	40	27	42	39.4

CLASS V.—40-50 per 100,000 of Population.

S. Francisco	Impounded from Mountain Streams	59	41	34	32	35	40.2
Prague	....	33	37	53	36	57	43.2
Minneapolis	Mississippi River	81	45	36	60	45	45.4
Baltimore	Lake Roland, Gunpowder River	57	34	42	47	49	45.8
Newark	Impounded from Pequannock River since April, 1892	60	81	45	28	15	45.8
St. Louis	Mississippi River	34	30	37	103	31	47.0
Newport, Ky	Ohio River	....	....	....	58	37	47.5
Philadelphia	Schuylkill and Delaware River	64	64	40	41	32	48.2
Denver	South Platte River	....	....	53	57	35	48.3
Cleveland	Lake Erie	66	52	54	47	27	49.2

CLASS VI.—50-60 per 100,000 of Population.

St. Petersburg	Filtered from River Neva	57	....	....	51	49	52.3
Cincinnati	Ohio River	67	62	40	43	50	52.4
Moscow	Springs, Ponds, Moscov and Yanza Rivers	73	75	68	40	29	57.
Toronto	Lake Ontario	93	94	43	42	17	57.8
Quincy, Ill	Filtered from Mississippi River	76	28	48	58	79	58.
Dublin	Filtered from River Vartry	62	58	39	87	48	58.8

CLASS VII.—Over 60 per 100,000 of Population.

Knoxville	Filtered from Tennessee River	101.5	45	36	67	59	61.9
Milan, Italy	....	....	....	62	62	....	62.
Jersey City	Passaic River	91	95	53	60	76	75.
Washington	Potomac River	83	83	70	66	71	76.6
Louisville, Ky.	Ohio River	88	81	72	84	72	79.4
Chattanooga	Tennessee River	145	66	55	86	48	80.
Chicago	Lake Michigan	83	160	104	42	31	84.
Pittsburgh	Allegheny River	....	100	100	111	56	91.7
Lowell, Mass	Driven Wells, Merrimac River	158	98	90	61	55	92.4
Atlanta, Ga	Filtered from Chattahootchie River	149	119	87	66	43	92.8
Lawrence, Mass	Filtered from Merrimac River	123	115	102	93	48	96.2
Alexandria, Eg't	River Nile	208	348	77	79	100	162.4
Cairo, Egypt	River Nile	260	233	163	154	135	189.4

Table II.—Typhoid Fever Death Rate.

Death Rate per 100,000 of Population, arranged upon Basis of Death Rates for 1894.

Class I.—Less than 10.		Class II.—10-20.		Class III.—20-30.	
Munich	2.5	Brussels	14	Dayton, O	20
Christiania	3.0	Buda-Pesth	14	Turin	24
The Hague	3.4	London	15	Glasgow	24
Berlin	4.0	Edinburgh	15	Milwaukee	26
Rotterdam	4.8	Brooklyn	15	*Davenport	26
Vienna	5.0	Newark	15	Detroit	26
Hamburg	6.0	New York	17	Cleveland	27
Breslau	6.1	Toronto	17	Boston	28
Copenhagen	6.7	Manchester	18	New Orleans	28
Dresden	8.2	Venice	18	Moscow	29
Stockholm	8.3	Trieste	19	Sydney, N.S.W	29
Amsterdam	8.5			Paris	29
Brisbane	9.6				

Class IV.—30-40.		Class V.—40-50.		Class VI.—50-60.	
Rome	30	Covington, Ky	42	Cincinnati	50
St. Louis	31	*Atlanta, Ga	43	Lowell, Mass	55
Chicago	31	Providence, R.I	47	Pittsburgh	56
Philadelphia	32	Lawrence, Mass	48	Prague	57
Denver	35	*Chattanooga, Tenn.	48	*Knoxville	59
San Francisco	35	Dublin, Ireland	48		
Buffalo	36	Baltimore	49		
Newport, Ky	37	St. Petersburg	49		

Class VII.—Over 60.	
Milan	62
Washington City	71
Louisville	72
Jersey City	76
*Quincy, Ill	79
Alexandria, Egypt	100
Cairo, Egypt	135

*Mechanical filters.

These figures show that the lowest rates are for those cities deriving their supply either from springs or from surface waters which have been subjected to sand filtration carried out in accordance with the strictest modern requirements. They also indicate the general inferiority of the water supplied to American cities when compared with European supplies. Chicago and Berlin have about the same population, yet the typhoid death rate of the former is more than ten times that of the latter; or, in other words, the chances of contracting typhoid fever in Chicago are ten times as great as in Berlin.

Out of the many instances showing the beneficial effect of filtration with regard to the prevalence of certain infectious diseases, two of the most noted will be cited, one in Europe and the other in America.

Hamburg and Altona, though under separate governments, practically form one continuous city with a joint population of about 800,000. They both draw their water supplies from the sewage polluted Elbe River upon which they are situated. Altona is the nearest to the mouth of the river, and its water intake being three or four miles further down is below the outfall of both its own sewers and those of Hamburg. The Hamburg intake is about two miles above the city. In 1892 an epidemic of cholera occurred, during which Hamburg, with a population of 622,530, had 17,975 cases with 7,611 deaths, while Altona, with 143,000 population, had during the same time 562 cases and 328 deaths, and in many of the cases credited to Altona the disease was contracted in Hamburg. Wandsbeck (20,000), just across the river from Hamburg, enjoyed the same immunity as Altona. Both of these places purify their water supplies by sand filtration, while in Hamburg the only attempt in that direction was the employment of settling basins. A filtration plant was, however, in process of construction at that time, and was put in operation in May, 1893, since when the typhoid rate has diminished from about 30 to 6 per 100,000.

The other case is that of Lawrence, Massachusetts, which is situated on the Merrimac River a few miles below Lowell. In spite of the great dilution, the water of this river which supplies both cities is seriously polluted by the sewage draining into it from the towns built along its banks; and as a consequence the typhoid fever rates in both places were unusually high.

In Sept., 1893, a system of intermittent sand filtration was completed. The effect upon the health of the citizens is shown in the following figures:

Year.	Deaths from Typhoid Fever per 100,000 Population.	
1887	114	
1888	114	
1889	127	
1890	134	
1891	119	
1892	105	
1893	80	
1894	47	(23)
1895	31	(17)
1896	19	(4)
1897	16	

For the last four years the figures in the brackets represent the number of deaths among people (principally mill operatives) who were accustomed to drink canal water without filtration; so that the actual reduction in the death rate which should be credited to the filters is much greater even than the figures indicate.

Many attempts have been made during the last 12 or 15 years to improve upon the sand filter, but so far without success. Some of the methods invented involve less expense for construction or give better chemical results; but the thoroughness of the bacterial purification effected by the sand bed has not been equalled by any.

The only one of these methods which has been used to any considerable extent is the American or Mechanical System of Filtration, which is employed in several places in the United States. Sand is the material used in this process also, but it is contained in cylindrical iron tanks. The water enters the tanks, usually under pressure, and is driven through the sand at a rate 50 times as great as the maximum allowed in the case of the filter bed. For this reason the latter method is sometimes referred to as Slow Sand Filtration. With such a high rate the surface film must be formed artificially; and this is done by adding a solution of alum to the water, which forms with the carbonates present a white flocculent precipitate. Such a filter will, of course, soon become clogged; but it can be quickly and easily cleaned without removing any of the sand from the tank. The results produced, under test conditions at least, are undoubtedly good; and it has the advantage over the filter bed of somewhat lower first cost. On the other hand, the charges necessary for repairs and depreciation wil be considerably higher on account of the less permanent character of its construction; so that if proper allowance could be made for this, the difference in the actual cost of filtering a given quantity of water by either process would not be very great. In any case it will probably not involve an addition of more than 10 per cent. to the ordinary cost of the water. Indeed, calculations have been made showing that if a proper valuation is put upon the lives saved by its use, the construction of a filtration plant is often in the long run a source of economy. Such considerations, however, seem quite unnecessary. A city's water supply should be pure, wholesome, and attractive in appearance, just as the streets should be clean and well paved, and the public buildings architecturally beautiful. Besides, having gone to the expense of obtaining a public water supply, indifference with regard to its purity or unwillingness to provide for it would seem to be utterly unreasonable; especially when it can be secured for such a comparatively small increase in the total cost as sand filtration involves.

It would be much cheaper, of course, to purify only that part of the supply which is used for purely domestic purposes. But that would require a double set of distribution pipes; and we should also lose the satisfaction of knowing that the whole of the public supply could be used for any purpose with perfect impunity so far as health is concerned. And when we consider that the expense of filtering the whole supply only amounts to two or three cents per month for each consumer, it will scarcely be considered excessive.

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