DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

WATER-SUPPLY PAPER 315

THE PURIFICATION OF PUBLIC WATER SUPPLIES

BY

GEORGE A. JOHNSON

WASHINGTON
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CONTENTS.

Water purification—Continued.

Slow sand filtration—Continued.

ILLUSTRATIONS.

THE PURIFICATION OF PUBLIC WATER SUPPLIES.

By George A. Johnson.

INTRODUCTION.

This paper has been written in response to a strong demand by officials of municipalities and institutions and by interested citizens for a simple and direct statement of the principles and practices governing the purification of waters used for domestic purposes. The work is in no sense a treatise; it states the more vital features of the subject and seeks to indicate how best to deal with the various problems involved in water purification.

The manuscript was submitted by the author in July, 1911, and publication has been unavoidably delayed. The science of water purification progresses rapidly. Therefore the text is, in some relatively unimportant respects, behind the most approved practice of to-day.

POLLUTED WATER.

Polluted water, in the sense in which the term is used in connection with municipal water supplies, is water that contains sewage or industrial waste of such a character that if the water be used for drinking by man it causes or is likely to cause discomfort or actual disease. Pollution of this kind is the result of human processes, whether the polluting material be personal waste or waste resulting from industrial activity. It follows that wherever man lives the water draining from or passing through the land on which he dwells or works must in smaller or greater measure be polluted. It is obvious that the greater the number of people occupying a given area, the greater will be the amount of polluting substances in the water in or adjoining that area. The greatest amount of polluting waste must therefore be derived from large cities, and the rivers, lakes, or other bodies of water into which that waste is discharged must therefore carry the largest amount of foreign matter.

Two kinds of pollution may conveniently be distinguished, first, inorganic pollution, such as the acid waste from coal mines and steel mills, the lime from soap factories and soda pulp mills, and the dye wastes from textile mills; second, organic wastes, such as the grain slop from distilleries, the wool scourings from woolen mills, the gums and resins extracted from wood in sulphite pulp mills, the drainage from stables, household wastes, and the bodily wastes of man. All of these wastes are objectionable, though in different degree. Inorganic wastes, unless they consist of mineral poisons, have no necessarily prejudicial effect on the health of those who use the water for drinking. Many of them, however, impart certain appearances to the water that render it objectionable for domestic use, for, as will be shown further on, one of the requisites of a good water supply is good appearance of the water. Many organic wastes are prejudicial to health, but if they occur in water in large proportions they render it so foul that its condition itself becomes a protection to the public, so far as its use for drinking is concerned. If they occur in proportion so small that their presence can not be detected by the person using the water they may or may not be dangerous. Whether dangerous or not, the idea of drinking such water is abhorrent and will not be tolerated in a civilized community. More important than all these considerations, however, is the fact that household and bodily wastes contain the germs of disease, and when these are discharged into water that s afterward used for drinking they reproduce their kind within the body of the drinker and thus widely disseminate disease.

The purification of water supplies therefore involves the removal of inorganic matter, the removal of organic matter, and the removal of the specific germs of disease.

Society is thus confronted by two necessities—first, the inevitable pollution of water resulting from man's occupation of the land; second, the necessity for a supply of pure water for drinking.

In this statement of conditions no mention has been made of organic pollution resulting from the natural growth in water of small vegetable and animal organisms, which impart color, odor, or taste, or all three, to the water. These further complicate the question.

People who live in towns and cities therefore have, as a result of their urgent necessities, a most important problem to solve—a problem which without suitable solution becomes progressively more and more difficult and urgent. Consideration will now be given to the various sources of public water supply and their liability to pollution.

SOURCES OF WATER SUPPLY.

SUPPLY OF CITIES IN THE UNITED STATES.

In the selection of a source of water supply two features are considered; first, a water must be satisfactory as to quality, and second, it must be available in sufficient quantity. In the Northern and

Middle Atlantic States the use of lake and spring water is common. The Great Lakes are sources of water supply for some of the largest cities in the United States, and the waters of smaller lakes are used abundantly by others. In the more southerly States waters from rivers are more commonly used, and in the upper Mississippi and the Ohio Valley districts ground waters are used to a considerable extent.

Statistics concerning municipal water supply[1] disclose some striking facts. In nearly 400 cities located in all parts of the United States and southern Canada, 40 per cent of the public water supplies are drawn from wells; 25 per cent from lakes, ponds, or springs; 24 per cent from rivers; and 11 per cent from mountain streams, impounded or otherwise. In 56 out of the 93 cities in the Ohio River valley and in 46 out of 85 cities in the upper Mississippi River valley water supplies are derived from wells. Of 131 cities in the New England and Middle Atlantic States, 56 take their supplies from lakes or springs; 28 from wells; 26 from mountain brooks; and 21 from rivers. The total volume of water taken from other sources is, of course, greatly in excess of that taken from wells.

GROUND WATERS.

If data could be obtained from all cities and towns in this country it appears certain that the majority would be found to take their water supplies from ground sources; that is, from wells, as distinguished from rivers, brooks, lakes, and other surface sources. Such wells are either sunk in gravelly soil or drilled in the rock, all of them extending into or through the water-bearing stratum.

Well waters, as a rule, are pure, clear, and colorless, although many are very hard and others contain much iron in solution. Such waters are not particularly objectionable for drinking, but hard waters are unsatisfactory for steam raising and many other industrial uses, and waters containing much iron are objectionable on account of the stains left upon fabrics washed in them. In many places means have been found to remove these objectionable constituents from the water.

The amount of water continuously available from wells is more uncertain than the amount of run-off from a given catchment area. In practically every part of the country a new problem is presented. If one well yields a daily minimum of 500,000 gallons it by no means follows that another well close by the first will double this yield. There is always a limit to the quantity of water which can be obtained constantly from a given area and it varies from place to place. Under the favorable conditions found on Long Island the yield from tubular wells is about 80,000,000 gallons daily. The catchment area

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[1] Municipal Journal and Engineer, vol. 24, No. 19, May 6, 1908.

on which these wells are located is over 100 square miles in extent, and the yield is equivalent to about 750,000 gallons daily per square mile. This is the largest well supply in the country. Lowell, Mass., Camden, N. J., Meadville, Pa., Canton, Ohio, Memphis, Tenn., and San Antonio, Tex., are among the larger cities which now use well water, but the most extensive use is made of it by smaller cities, where the daily volume required is comparatively small.

The capacity of a given well supply obviously depends on the size of the catchment area from which the water is drawn, the precipitation which falls on this area, and the perviousness of the soil or underlying rock. When a well is pumped water is drawn from the sides as well as from the bottom. It follows, therefore, that by continued pumping the ground-water level will be lowered, but immediately around the well this level will be depressed in the shape of an inverted cone. In locating wells it is necessary to space them so far apart that the cones of depression do not intersect, for in the event that they do intersect the individual yield of each well will be reduced. Furthermore, it is necessary to locate the wells in a line across the direction of flow of the ground-water current, for if placed on a line in the direction of this current, the upper wells may draw the bulk of the flow.

There is no way of predicting what the yield of a well will be except by considering the yields of other wells in the same locality. Furthermore, the yield of a well depends to a certain extent on the facility with which water can enter it, and in many wells the flow has become greatly diminished or completely stopped by the clogging of the inlet openings.

LAKE SUPPLIES.

Chicago, Cleveland, Buffalo, Detroit, Erie, Duluth, and Milwaukee are among the larger cities which draw their water supplies from the Great Lakes, and millions of dollars have been spent in extending the intakes to points in the lakes where it is expected that pure water may be obtained. Along the shores of the lakes in the vicinity of cities the waters are of course badly polluted by the discharge of city sewage.

The Great Lakes receive the sewage of millions of people, and from them in turn millions draw their water supply. In most places these waters are consumed in their unpurified state. The danger should be obvious, but nevertheless these conditions continue to be common. The sewage of lake cities is usually discharged into the lakes near the shores. Considerations of cost often prevent the extension of sewer outlets far enough into the lakes to take full advantage of the diluting power of such bodies of water. The engineers in some cities located on lake fronts have consequently made careful study of prevailing currents and winds for the purpose of locating the intakes of their waterworks at points unlikely to be reached by sewage. The ineffectiveness of such a safeguard is illustrated subsequently by citing the experience of Chicago and Cleveland.

When water is drawn from small lakes the possibilities of obtaining a pure supply are usually good. The purity of such supplies may be maintained by keeping all sewage out of the streams that feed the lakes and by enforcing strict sanitary measures on the drainage area. Rochester, N. Y., and St. Paul, Minn., are examples of cities still using lake water and maintaining it in a pure and wholesome condition. The fact remains, nevertheless, that all waters derived from surface sources require sharp and incessant watching, and even with such attention are liable to accidental pollution, which may result disastrously.

IMPOUNDED SUPPLIES.

Utility of impounding reservoirs.—Where the most suitable source of water supply is one or more comparatively small streams, it is frequently necessary to build impounding reservoirs in which to store the heavy spring and fall flow for use during the low periods of summer and winter. In this way use may be made of streams whose normal flow frequently falls below that necessary to supply the demand during certain seasons. Storage is also beneficial in other ways. It greatly minimizes the danger from such pathogenic pollution as the water may be subjected to before it reaches the reservoir, and it effects a substantial improvement in the physical quality of the water.

It is a well-established fact that sewage bacteria, and particularly the pathogenic organisms, die off rapidly in water. The pathogens die for numerous reasons, most important among them being unfavorable and unnatural surroundings, osmosis, an insufficient or unsuitable food supply, and the antagonistic influences of other bacteria and of some forms of animal life. Furthermore, bacteria do not persistently multiply in water, at least not under the climatic conditions of this country. It is a fact that although for a brief period there may be positive indications of bacterial propagation in standing water, this condition rapidly disappears and the bacteria show a rapid and steady diminution and in a few days or weeks may almost entirely disappear. The data already published on this point are abundant. For example, at Lawrence, Mass., the bacterial removal effected in the city reservoir, where the period of storage is about two weeks, amounts to over 93 per cent. At Washington, D. C., where the maximum period of storage is five or six days, the bacterial removal is the same as at Lawrence. In the Boonton Reservoir, where the water supply of Jersey City is impounded, there is storage capacity for over 200 days' supply, and it has been found that during the time the water remains in the reservoir the average bacterial purification effected is 99 per cent.

The physical improvement in water resulting from storage consists of the subsidence of the fine suspended particles that give the water a turbid appearance and the reduction of color due to substances held in solution. The latter effect is produced in the main by the bleaching effect of the sun.

The foregoing comments are made in order to show the salutary effect of storage upon the quality of water. There are further important questions to be considered, however, such as the care which should be given to catchment areas above lakes and impounding reservoirs used for domestic purposes, and stagnation of lake and impounded water, which produces disagreeable tastes and odors in water.

Care of catchment areas above lakes and impounding reservoirs.—The most effective manner of preventing the pollution of an impounded water supply is to purchase the entire catchment area. This is rarely possible or feasible. It should also be emphasized that possession of the whole catchment area and the enforcement of sanitary regulations thereon does not preclude accidental or incidental pollution, such as might come from a chance trespasser suffering from a light case of typhoid fever or in the initial or convalescent stages of a severe case. Many watersheds well regulated and patrolled have been polluted in this way, causing such epidemics as those at Plymouth, Pa., in 1885; New Haven, Conn., in 1900; and Ithaca, N. Y., in 1903. Such epidemics show clearly how necessary and how impossible it is to always keep a vigilant eye on all sources of pollution in a drainage area.

The chief drawback to the acquirement of entire catchment areas usually is the cost. It is rare indeed that such cost will not far exceed that of a system of strict sanitary regulation over the area under the authority of suitable State laws combined with some form of purification of the water before it is supplied to the consumer. It is the usual and commendable custom, therefore, for those in charge, be they municipal officers or officials of a private company, to acquire the shores of the lake or impounding reservoir from which the water supply is drawn, and then to see to it not only that sewage or waste of otherwise dangerous character is not deposited in the reservoir or its affluent streams, but that it is not stored or deposited on any part of the catchment area from which it may at some time be washed into the reservoir. With such ownership and with an efficient system of sanitary patrol by diligent inspectors, it is possible properly to avoid the great expense of purchasing the whole catchment area and to allow a rural population to remain undisturbed.

To recapitulate, it is always well to do all that can be done to keep the catchment area clean and to keep all sewage waste out of the water that enters the reservoir. Then, if the storage period is insufficient to allow the water to be satisfactorily clarified and decolorized, the water should be filtered before it is delivered to the consumers. If the water is physically satisfactory as it leaves the reservoir but still subject to sudden incidental or accidental pollution, sterilization is the cheapest and surest remedy.

Stagnation of impounded waters with particular reference to the production of objectionable tastes and odors.—It is well known that some waters, if not all, on being stored for long periods in lakes or impounding reservoirs, become stagnant. Such stagnation does not ordinarily occur throughout the body of the water in the reservoir but is particularly confined to the bottom layers, where, through the action of bacteria upon the deposits of organic matter, the oxygen in the water is entirely consumed, and foul tastes and odors are produced. A comprehensive report on this general subject by Hazen and Fuller was published in 1907, and to this the reader is referred.[1] Many attempts have been made in the past to overcome this undesirable feature in stored water. At perhaps a dozen places in Europe and this country, the top soil has been removed from the reservoir site before it was allowed to fill with water, the expectation being that the organic matter, which ultimately undergoes decay and produces stagnation, would be eliminated. Such stripping is always costly, ordinarily approaching probably $1,000 an acre of surface, and appears to have been of but temporary benefit wherever tried. In such reservoirs a deposition of organic matter from the water is always going on, and in time the conditions at the bottom will be quite as bad as though it had not been stripped. Hazen and Fuller recommended aeration and filtration to remove tastes and odors from stagnated water. It is desirable to point out, however, that in the majority of reservoirs odors and tastes due to stagnation are not as troublesome as those from certain forms of animal and vegetable life, commonly known as algæ. These tastes and odors are caused by the essential oils which those organisms secrete during their growth. For a thorough work on this subject the reader is referred to Whipple's "Microscopy of drinking water." Much practical benefit may be derived from the treatment of reservoir waters with copper sulphate during periods of trouble from growth of algæ. A good summary of the evidence bearing on the effectiveness of copper compounds in the destruction of algæ is contained in the Journal of the New England Waterworks Association, December, 1905, and in Bulletin No. 100, part 7,

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[1] Rept. Board Water Supply New York, 1907, pp. 181–255.

Bureau of Plant Industry, United States Department of Agriculture, issued October 20, 1906.

Fortunately such troubles as may arise from the growth of algæ in reservoirs extend over comparatively short periods of time—that is, during the summer months of the year. Furthermore, with the judicious use of copper compounds such growths may be effectively and cheaply stopped. The growth of these algæ may not only of itself produce tastes and odors in water, but if they are allowed to grow undisturbed and to die naturally they add to the organic matter which brings about the stagnation of the lower strata of the water therein. By their elimination at the outset, therefore, a twofold good is effected.

RIVER SUPPLIES.

With the rapidly increasing population in the United States it is certain that in the future more and more use will be made of river waters as sources of public supply. It is also certain that the amount of polluting matter which practically all rivers of size in this country are obliged to carry is increasing year by year. This single fact requires the sanitary aspects of river-water supplies to be commented on at some length.

One of the first facts to be recognized in connection with the discharge of sewage into running water and the use of such water as a source of public supply is that no practical method of sewage purification will remove absolutely all danger from pathogenic germs. In the construction of a sewerage system, however complete and tight, provision must always be made for storm or emergency overflows. In "separate" sewerage systems, which are designed to collect all of the house wastes in one system of pipes and all of the street wash and much of the industrial waste in another system of pipes, it is necessary to provide emergency overflows at outlets or pumping stations, which become operative in the event of great inflows of storm water or the disarrangement of the pumping machinery, or of any part of the purification works if such works are provided.

In "combined" systems, which carry in the same pipes household and industrial wastes and street washings, storm overflows directly connected with the river are always built and become operative at times of heavy storms, when the capacity of the sewers becomes overtaxed. It is clear, therefore, that in any system of sewerage it is impossible to depend absolutely on all of the dangerous material being kept out of the river. In addition to this, sewage purification works, even when operated in the most careful manner, occasionally allow the escape of some material of a dangerous character.

It is therefore apparent that the primary object of a sewage disposal plant is merely to render as nearly inoffensive as possible the more offensive parts of the sewage, and to purify it to the highest degree commensurate with the benefits to be derived under existing conditions. Public waterways must continue to receive the sewage of cities, and the one thing which remains to be done is to see that such wastes are made as unobjectionable as possible before their discharge. That is practically all that any community should be required to do.

The capacity of a stream to dispose of sewage without creating offense depends on the initial pollution of the stream, on its volume, and on its velocity of discharge. If the stream receiving the sewage is large enough and the time allowed for natural purification to take place is long enough, no nuisance will be created. In some parts of the country, however, so many cities are located on one stream, that the capacity, particularly during the warmer months of the year, is overtaxed, and the water of the stream becomes ill-smelling and unsightly. To ameliorate such obnoxious conditions, but more often to avoid litigation brought or threatened by riparian owners below, some cities have been forced to purify their sewage before discharging it into the stream, and, owing to the proximity of one city to another, all the cities have been driven to consider ways of obtaining a pure water supply from some other source or of purifying the badly contaminated water of the stream.

The ideal state of affairs, toward which American sanitarians are working, is to permit all cities to discharge their sewage into the nearest stream but to require them first to purify it to a degree which will preclude the establishment or maintenance of obnoxious conditions in the stream. Rarely are two problems of this kind found to be alike. The sewage of some cities should be purified to a far greater degree than that of others, dependent on the initial pollution of the stream, its minimum volume and velocity of discharge, and the distance to the next city, or, more exactly, to the intake of the next waterworks.

The partial purification of all the sewage entering a stream being effected, and the water of this stream being afterwards used for public supply, it becomes necessary finally to purify the stream water before it is delivered to the consumer. This it is always possible to do.

DEVELOPMENT OF WATERWORKS IN THE UNITED STATES.

Developments in public water supply in the United States have been rapid since 1850, although the first municipal works were built in Boston nearly 200 years before that date. Creditable progress has been made both in the number of works and improved equipment. In his "Manual of American waterworks" (1900) Baker records in tabular form the development of waterworks in this country from 1850 to 1896, as follows:

Development of waterworks in the United States, 1850–1896.

Year.	Number of works.	Number of works built during the period.	Year.	Number of works.	Number of works built during the period.
1850	53	....	1875	422	179
1855	106	53	1880	598	176
1860	136	30	1885	1,013	415
1865	162	26	1890	1,878	865
1870	243	81	1896	3,196	1,318

Commenting on these statistics, Turneaure and Russell in their work entitled "Public water supplies" (1901) state as a matter of record that the total population supplied in 1880 was 11,809,231, and that in 1890 it was 22, 814,061. The total estimated cost of the works up to 1891 was $543,000,000. H. M. Wilson in a paper on fire wastes[1] gives the total cost of waterworks systems in 1907 as $1,129,247,532. From available information it appears that about one-quarter of the communities having populations between 1,000 and 5,000 are provided with public waterworks, and that 90 per cent of the cities having populations between 5,000 and 25,000 are similarly provided. Comparatively few cities of over 25,000 inhabitants do not now have public supplies.

WATER CONSUMPTION.

The average American citizen is wantonly wasteful in the use of water. Statistics of water consumption show a great difference between the amount consumed by cities in Europe and in America. The average daily consumption in 17 large cities in England, Germany, and France is about 37 gallons per capita, the highest being about 66 gallons, at Glasgow, and the lowest about 20 gallons, at Nuremberg. The per capita consumption in the average American city is nearly four times as great. In New York City the daily per capita consumption is about 130 gallons; in Chicago, Philadelphia, and Pittsburgh it is close to 200 gallons.

The Municipal Journal and Engineer has gathered interesting statistics on this point from different parts of the country. These data are given in condensed form in the next table. The figures in the column showing water consumption were obtained by dividing the total gallons consumed by the total population of the cities, and not by the number of actual consumers, otherwise the per capita daily consumption shown would be considerably higher.

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[1] Read at the convention of the American Waterworks Association held at Milwaukee in June, 1909.

Average per capita consumption of water in representative American cities.

Region.	Number of cities.	Daily consumption in gallons per capita.
New England	49	85
Middle Atlantic States	44	137
South Atlantic States	15	90
Ohio Valley	55	88
Upper Mississippi Valley	53	73
Lower Mississippi and Gulf region	6	53
Rocky Mountain region	5	283
Pacific coast	5	204
Canada	9	108
Total	241	[a] 100

[a] Weighted average.

The excess of the per capita consumption of water of America over Europe can be traced almost directly to the personal habits and financial status of the two peoples. Bathtubs are found in but few houses of people of the middle class in Europe and in no houses of people of the poorer classes. Water closets are rare and have much smaller flush tanks than in this country. The water waste occasioned by plumbing systems, an enormous waste in America, is cut to a minimum in Europe. The average European is habitually more economical than the average American and for many reasons endeavors to utilize to completeness all things which are necessary to existence. In Japan, where the water-closet is virtually unknown, and where the water of a bath is used by several people, one after another, and where, finally, there are no sewers except in small parts of the larger cities, the average consumption of water is even lower than in western Europe and amounts to about 25 gallons per capita daily. Although water for toilet use should not be stinted in amount, and although there is no disposition among the advocates of water economy to discourage habits of cleanliness, it is a fact, established beyond all disproof, that the present consumption is largely in excess of the amount necessary to secure the desired end. Consequently the use of water meters on house service has become very common, not, it should be emphasized, to reduce the necessary consumption, but to impart to the householder the habit of giving thought to needless waste.

The use of meters to prevent water waste is said to date back to the reign of the Emperor Claudius. Progress in meter use has been slow until very recent years. There has always existed in this country a prejudice against any restriction on the individual use of water. Many claims relative to the alleged disease-breeding qualities of water meters have been made, but all have been shown to be unfounded. Probably the most common and at any rate the most sincere objection to the use of meters advanced by those who are relatively uninformed on the subject is that the effort of persons in whose homes the water is metered to reduce as much as possible the charge for water service would result in diminished personal cleanliness, which might indirectly contribute to disease. There is no evidence that such an effect was ever produced, and a moment's consideration will show that such occurrence would be most unlikely. The difference between personal cleanliness and personal uncleanliness is represented by a relatively small amount of water—so small, in fact, that the difference in water charges under a metered service would be almost negligible.

The Buffalo Chamber of Commerce published in its journal, The Live Wire, for February, 1911, some interesting results of an investigation of the use of water meters. Replies to a request for information regarding the advisability of installing water meters were received from 49 health officers and 60 superintendents of waterworks. These officials represented municipalities having populations of more than 50,000 people each and a total population of 16,000,000. Forty-two of the forty-nine health officers and fifty-eight of the sixty water-works superintendents were in favor of meters.

TYPHOID FEVER IN THE UNITED STATES.

DEATH RATE FROM TYPHOID FEVER.

Typhoid fever is the most common of all water-borne diseases in this country. The United States Census report for 1900 gave the total number of deaths from typhoid fever during that year as over 35,000. More recent information from the same source is now available and is brought together herein in tabular form. These data were largely compiled from reports of the Census Bureau, and are of more than usual accuracy for the reason that they were taken from the returns of such cities as have approximately complete registration of deaths, based upon the compulsory requirements of burial permits.

According to bulletins of the Bureau of the Census,[1] the total estimated population of the aggregate registration area was 45,028,767 in 1908, or nearly 52 per cent of the total estimated population of continental United States. The total number of deaths from typhoid fever for the entire registration area was 10,722 for 1909 (22 per 100,000 population), as against 12,670 for 1907, and 11,375 for 1908. The lowest death rates from this disease in 1908 were found at Worcester, Mass., 10.5; Jersey City, N. J., 9.7; and Paterson, N. J., 9.2. All the other large cities in this country had death rates from typhoid fever in 1908 exceeding 10 per 100,000 population.

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[1] Mortality statistics for 1908: Bull. Bur. Census No. 104, 1909, pp. 7, 13. Mortality statistics for 1909; Bull. Bur. Census No. 108, 1910, pp. 7, 22.

In 1910 the average death rate from typhoid fever in the 48 cities in the United States having populations in excess of 100,000, and representing a total population of nearly 20,000,000, was 23.3 per 100,000 population. In the same cities the average death rate from typhoid fever for the five years ending with 1910 was 27.6 per 100,000 population. The lowest rates in 1910 per 100,000 population were 6 in Cincinnati, Ohio; 7 in Paterson, N. J.; 9 in Bridgeport, Conn.; and 10 in Jersey City, N. J.

Attention is drawn to the possibility of reducing the death rate from this disease even below 10 per 100,000, as shown in death rates from enteric (typhoid) fever taken from the statistics of Scottish, Irish, colonial, and foreign cities, in the Annual Summary for 1908, published by the registrar general of England and Wales. In this document the following low death rates are found: The Hague, 1; Stockholm, 1; Edinburgh, 2; Munich, 3; Berlin, 4; Hamburg, 4; Vienna, 4; Breslau, 5; London, 5; Rotterdam, 5; Dresden, 6; Copenhagen, 7; Glasgow, 8; and Paris, 8. Other foreign cities have higher death rates from this disease, but the list given by the registrar general discloses no cities with death rates from typhoid fever as high as the average of American registration cities (25.3) in a most favorable year (1908), except St. Petersburg, 126; Moscow, 56; Milan, 38; Montreal, 35; and Toronto, 28.

In the following table are presented statistics of the death rate from typhoid fever in some of the more important cities in this country. The 48 cities named in the table had a total population in 1910 of nearly 20,000,000.

Death rates from typhoid fever in cities of the United States with populations in 1910 of 100,000 or more.[a]

City.	Death rate from typhoid fever per 100,000 population.							
	1906	1907	1908	1909	1910	Average for 6 years 1900–1905, inclusive.	Average for 5 years 1906–1910, inclusive.	Average for 11 years 1900–1910, inclusive.
Albany, N.Y.	20	20	11	19	15	25	17	21
Allegheny, Pa.	136	97	40	28	47	107	70	90
Atlanta, Ga.	50	64	47	44	43	65	50	58
Baltimore, Md.	34	41	31	23	41	36	34	35
Birmingham, Ala.	39	71	64	44	51	50	54	52
Boston, Mass.	22	10	26	14	11	23	16	20
Bridgeport, Conn.	10	13	13	13	9	15	12	14
Buffalo, N. Y.	24	29	21	23	20	29	23	26
Cambridge, Mass.	18	10	10	9	12	18	12	15
Chicago, Ill.	18	18	15	12	14	27	16	22
Cincinnati, Ohio	71	46	19	13	6	54	31	44
Cleveland, Ohio	20	19	13	12	19	51	17	36
Columbus, Ohio	45	38	110	17	13	61	45	54
Dayton, Ohio	28	38	16	24	18	29	25	27
Denver, Colo.	68	67	58	24	30	37	49	42

[a] Statistics gathered by correspondence and taken from Bull. Bur. Census Nos, 104, 1909, and 108, 1910.

Death rates from typhoid fever in cities of the United States with populations in 1910 of 100,000 or more—Continued.

City.	Death rate from typhoid fever per 100,000 population.							
	1906	1907	1908	1909	1910	Average for 6 years 1900–1905, inclusive.	Average for 5 years 1906–1910, inclusive.	Average for 11 years 1900–1910, inclusive.
Detroit, Mich	22	28	22	19	16	17	22	19
Fall River, Mass	8	18	13	14	15	19	14	17
Grand Rapids, Mich	39	30	30	17	27	34	28	31
Indianapolis, Ind	39	29	26	22	31	76	30	55
Jersey City, N. J	20	14	10	8	10	19	12	16
Kansas City, Mo	38	40	35	23	38	48	35	42
Los Angeles, Cal	18	23	19	18	12	35	18	27
Louisville, Ky	63	79	49	43	31	55	53	54
Lowell, Mass	7	9	24	11	21	19	14	17
Memphis, Tenn	39	35	33	41	28	37	35	36
Milwaukee, Wis	31	26	17	21	45	19	28	23
Minneapolis, Minn	33	26	18	20	58	38	29	34
Nashville, Tenn	66	85	62	53	48	54	58	56
Newark, N. J	18	24	12	11	13	17	16	17
New Haven, Conn	54	30	34	20	17	44	31	38
New York, N. Y	15	17	12	12	12	19	14	17
New Orleans, La	30	56	31	25	28	40	34	37
Oakland, Cal	26	28	18	7	13	19	18	19
Omaha, Nebr	28	24	22	31	75	20	36	27
Paterson, N. J	4	11	10	5	7	25	7	17
Philadelphia, Pa	74	60	36	22	17	47	42	45
Pittsburgh, Pa	141	135	[a] 53	[a] 13	[a] 12	132	71	104
Providence, R. I	19	8	16	12	18	20	15	18
Richmond, Va	44	41	50	24	22	66	36	53
Rochester, N. Y	17	16	12	9	13	15	13	14
St. Louis, Mo	18	16	15	15	14	33	16	25
St. Paul, Minn	21	17	12	20	20	14	18	16
San Francisco, Cal	....	57	27	17	15	20	29	24
Scranton, Pa	11	76	11	11	14	18	35	26
Syracuse, N. Y	10	16	15	12	30	14	17	15
Toledo, Ohio	45	36	40	31	32	36	37	36
Washington, D. C	52	36	39	33	23	59	37	49
Worcester, Mass	12	14	10	8	16	17	12	15

[a] Filtered-water section. Allegheny district not included.

The foregoing table shows that the general tendency in these 48 large cities was in the direction of lower death rates from typhoid fever. During the period 1900–1905, inclusive, the average death rate from this disease in these cities was 37 per 100,000 population; in 1906 it was 36; in 1907, 36; in 1908, 27; in 1909, 20; and in 1910, 24. This consistent reduction in the typhoid death rate is significant, and if future years show as great improvement it will not be long before the cities of this country will be as free from this disease as the best European cities.

The reduced rates at Albany, Cincinnati, Columbus, Indianapolis, New Haven, New Orleans, Paterson, Philadelphia, Pittsburgh, and

Washington are undoubtedly due in a very large measure to the new water-filtration works at those places. The improved lake water supply at Cleveland was undoubtedly the cause of the marked fall in the typhoid death rate of that city, and the same was true of Chicago. Coagulation followed by sedimentation of the water supply proved beneficial at St. Louis, and the already low death rate in Jersey City underwent another reduction, due perhaps to the sterilization of the impounded but unfiltered water supply with hypochlorite of lime, which was begun in the autumn of 1908.

FINANCIAL ASPECTS OF IMPURE WATER SUPPLIES AND TYPHOID FEVER.

The number of cases of typhoid fever resulting directly from infection through polluted water supplies can not be precisely stated. Large European cities with the most carefully watched water supplies, such as Berlin, Hamburg, Vienna, and London, have annual typhoid death rates as low as 4 or 5 per 100,000 population. In this country, even in cities which have water supplies of acknowledged high standard, the death rate is two to five times as high as this. In Boston, Fall River, Jersey City, Newark, New York, and other cities the death rate from typhoid fever has for years been about 15 or 20 per 100,000, and this rate has come to be accepted by sanitarians in this country as strong indication of a pure water supply.

It has been shown repeatedly that the substitution of a pure for a polluted water supply results in a drop of about 75 per cent in the death rate from typhoid fever, accompanied by a material reduction in death rates from other intestinal diseases. The United States census reports give the total number of deaths from typhoid fever in the United States in the year 1900 as 35,000. With this figure as a basis, the computation shows that the introduction of pure water would save 26,000 lives annually. On the common assumption of $5,000 as the average money value of a human life, about $130,000,000 of vital capital is dissipated by typhoid fever each year. Again, to cause these 26,000 deaths not less than 260,000 people must have suffered from typhoid fever, as a conservative estimate of the mortality in this disease is about 10 per cent. If the average cost of a case of typhoid fever in the event of recovery, including lost time and charge for medical attendance, is taken at $300, a very low figure, $78,000,000 more is dissipated in this way, a total loss to the country of over $200,000,000 each year. Such figures as these have only a general significance, of course, but they serve to indicate what might be the result of a general improvement in the water supplies of this country.

The question of lost vital capital may be more specifically approached in another way. Between 1900 and 1905 the average typhoid death rate in the United States was about 50 per 100,000 population, but it is to be borne in mind that this high rate was in a large measure due to the prevalence of this disease in small villages and small isolated communities which would be difficult to reach in a widespread campaign for purer water. But in the larger cities of over 50,000 population the average typhoid death rate for the same period was about 35 per 100,000. This rate has been obtained by reviewing the statistics for the period 1900–1905, inclusive, in 74 cities having an aggregate population of 18,000,000. Only 24 of these cities had typhoid death rates of 20 or less per 100,000 population. Fifty cities, having an aggregate population of 11,000,000, had a typhoid death rate of 41 per 100,000. In other words, 4,510 people in these 50 cities died annually during the years 1900–1905 from typhoid fever. If it is correct to assume that for American conditions and manner of living, a death rate from typhoid fever as high as 20 indicates a satisfactory water supply, then each year 2,310 people were killed by impure water in these 50 cities. If a life is worth $5,000, then the deaths of these people caused a waste of $11,600,000 in vital capital. The total number of cases of fever required to destroy this number of people was over 20,000, and the cost of these cases, estimated at $300 each, adds $6,000,000 to the unnecessary waste. The total waste was therefore $17,600,000 each year for these 50 cities.

The cost of water filtration works for all of these 11,000,000 people, in order to save the lives of those sacrificed to impure drinking water would be about as follows: At 100 gallons per capita daily consumption, a total daily filtering capacity of 1,100,000,000 gallons would be required as a minimum. Although plants vary in cost, a fair average of the total cost of filtered water, exclusive of pumping charges but including all costs in connection with the operation of the filters, supplies, interest on the investment, and a reasonable sum for depreciation, is $10 per million gallons. The total cost of 1,100,000,000 gallons daily, therefore, would be $11,000 a day, or $4,015,000 a year. When this is compared with the $17,600,000 given above and the figures considered from every point of view, there is every argument in support of pure water to cut down the ravages of typhoid fever. Not the least of these is the financial aspect, as shown.

WATER SUPPLY OF CHICAGO.

Some interesting facts concerning the agency of polluted water in the occurrence of typhoid fever are shown by the experience of Chicago, Ill., and Cleveland, Ohio, which, as already stated, take their supplies from the Great Lakes.

The city of Chicago is located on Lake Michigan and has always drawn its water supply from that lake. Up to 1901 all of the sewage of the city was discharged at points along the entire water front. Chicago River, which was then a most foully polluted stream, also discharged into the lake about midway or a little to the north of the middle of the city's water front.

The water supply was drawn from several "cribs," located from 1½ to 4 miles from the shore, and it was the custom to keep the water about these cribs under close observation from day to day. When it appeared that winds or currents were carrying the sewage toward the crib from which the supply was then being drawn a shift was made to some other crib not then so affected. It is clear that such a plan must have resulted in polluted water being supplied to the city at times, for there was no way of positively detecting contamination until the mischief had been done, and for years the city paid a heavy toll to typhoid fever. In the early nineties it was common for 1,500 people, or 90 per 100,000 population, to die of this disease in Chicago every year.

To ameliorate this highly unsatisfactory state of affairs the Chicago Drainage Canal was built. The object was to divert the sewage of the city from the lake into Chicago and Desplaines Rivers. The canal was put into service in 1901 and at the present time the bulk of the sewage of Chicago is cared for by it. A marked decrease in typhoid fever in the city has resulted. A more or less indefinite portion of sewage still enters the lake, and the city is still liable to epidemics from typhoid fever in consequence of this. It is also true that a limited opportunity for pollution is caused by boats which traverse the lake in the vicinity of the water cribs. At this date the question of purification of the city water supply is being agitated to some extent. There seems to be little doubt that further treatment of the water is necessary to free the city from danger from this source.

WATER SUPPLY OF CLEVELAND.

The city of Cleveland takes its water supply from Lake Erie, and has always been troubled with an abnormal amount of typhoid fever, much of it due to the contaminated condition of the water supply. The sewage of the city is discharged into the lake along the water front.

The old intake was located about 1¼ miles from the shore of the lake and was used up to 1904, when a new intake, 4 miles from the shore, was substituted for the old. The improvement was almost immediately apparent and was made the more so by the fact that the city was in the grasp of a particularly severe typhoid epidemic at the time the new waterworks were put into service. In his book on typhoid fever (p. 171) Whipple has shown the improvement effected by the introduction of the new supply, as follows:

Average number of new cases of typhoid fever reported daily in Cleveland, Ohio, in 1904.

Jan. 1–31, 1904: Period prior to the epidemic caused by flood	2.84
Feb. 1 to Mar. 5: Period of epidemic corresponding to exclusive use of old supply	20.91
Mar. 6–15: Period of epidemic corresponding to use of one-half of supply from new intake and one-half from old intake	11.10
Mar. 16 to Apr. 21: Period of epidemic corresponding to use of three-quarters of supply from new intake	2.89
Apr. 22 to Dec. 31: Period corresponding to exclusive use of water from new intake	1.03

The new supply (1911) is a very material improvement over the old, but there is no doubt that further treatment of the lake water is necessary before the city will be assured of a supply constantly pure and wholesome in character and not subject to occasional contamination.

The typhoid epidemic of 1910 at Milwaukee, Wis., and of 1911 at Erie, Pa., are proof enough of the danger in using the waters of the Great Lakes without purification of some sort. This danger must soon become generally recognized. It is not improbable that simple sterilization of the waters, which are ordinarily satisfactory physically, may be the next step taken in the direction of a safe water supply for many lake cities.

WATER PURIFICATION.

HISTORICAL SKETCH.

The ruins of antiquity show that large storage reservoirs were common in ancient times, and it is well known that the Chinese for thousands of years have used alum as a coagulant in muddy water in order to accelerate clarification. Perhaps the earliest literary reference to filtration appears in the "Ousruta Sanghita," a collection of medical lore written in Sanskrit probably 4,000 years ago. In a letter to the British Journal of Preventive Medicine, Mr. Francis E. Place, of Jaipur, Rajputana, India, calls attention to this reference, in which the following statement appears: "It is good to keep water in copper vessels, to expose it to sunlight, and to filter it through charcoal."

Modern history does not record any attempt at filtration until 1829, when the 1-acre slow sand filter was built by James Simpson for the East Chelsea Water Co., at London, England. The germ theory of disease was then unknown, and the filter was built to perform the offices of a mechanical strainer for the purpose of removing the turbidity from the water. This filter is still in service, however, and is doing work of a nature far exceeding the purpose for which it was designed and built.

Typhoid fever as a specific disease was discovered in 1829, but it was not until 1849 that the germ theory of disease was seriously advanced. An act of the British Parliament of 1852 made compulsory the filtration of the entire water supply of the metropolitan district. This action was the result of the severe cholera epidemic of 1849 and was the first of a series of attempts to purify water for hygienic reasons.

The first noteworthy movement in this country for the purification of a public water supply was made in 1866, when the city of St. Louis sent James P. Kirkwood to Europe with instructions to investigate the art of the purification of water as there practiced. On his return Mr. Kirkwood made an elaborate report, which will always remain one of the classics on the subject. His recommendations for St. Louis were not adopted, however, apparently for sound reasons, as none of the purification works in Europe which came under Mr. Kirkwood's observation had a water to treat that was similar to the water at St. Louis. The waters of western Europe are almost uniformly clear, whereas that of the Mississippi is extremely turbid.

In 1872, about five years before Mr. Kirkwood's death, a plant was built at Poughkeepsie, N. Y., in accordance with his plans. This was the first practical attempt at purification of a municipal water supply in America. Plants of a type similar to that built at Poughkeepsie were built somewhat later at Lowell, Mass., Columbus and Toledo, Ohio, and elsewhere, but most of them failed of the purpose for which they were intended.

Quite extensive experiments on slow sand filtration were also made at Boston, Mass., Louisville, Ky., and elsewhere.

The classic investigations of the Massachusetts State Board of Health at Lawrence, Mass., were begun in 1887 and are still in progress. Up to a few years ago the work at the Lawrence Experiment Station, so far as water purification is concerned, was limited to studies on slow sand filtration. The construction of the Lawrence city filter, first placed in operation in 1893, was one of the results of these investigations.

In 1893 the first carefully conducted experiments with the newer process of mechanical water purification were made by Edmund B. Weston on the water supply of Providence, R. I., and in 1895 the much more elaborate studies in the same line were begun at Louisville, Ky., and continued through 1897. These Louisville experiments, conducted under the direction of George W. Fuller, formed the beginning of practical demonstrative investigations into the various methods of water purification. Similar studies followed successively at Pittsburgh, Pa.; Cincinnati, Ohio; Washington, D. C.; New Orleans, La.; Philadelphia, Pa.; and elsewhere.

All of this experimental work gave a great impetus to water purification in this country, and not only has the number of cities installing water-purification works increased rapidly during the last 10 years but the design and construction of such works has now reached a high plane of excellence. The more advanced ideas in this regard were first manifested in the works at Albany, N. Y., designed by Allen Hazen, and in the works of the East Jersey Water Co., designed by George W. Fuller and built at Little Falls, N. J. The former plant was first used in 1899 and the latter in 1902. At Albany the filters are of the slow sand type, and at Little Falls of the mechanical or rapid sand type.

In 1900, according to Hazen, 1,860,000 people, or 6.3 per cent of the urban population of the United States were being supplied with filtered water. In 1904 the number of people so supplied had increased to 3,160,000, or 9.7 per cent of the urban population of the country. Since that time many large cities have installed filter plants until now (1911) about 8,000,000 people, or over 20 per cent of the urban population, are being served with filtered water.

KINDS OF FILTRATION.

Considerable confusion has arisen as to the proper nomenclature for different types of filters for municipal water supplies, particularly as regards the older type, which originated in England, and the newer type, which was first applied in the United States. There are other kinds of filtration processes, but they are either modifications of the established and approved types mentioned, or else they have been shown to be of limited applicability in the treatment of public water supplies on a large scale.

The first type of filter, built at Chelsea, England, has been variously styled the "English," the "slow sand," or the "sand" filter; and the newer type, also originating in England but first applied and developed in the United States, has been called the "American," the "mechanical," the "rapid," or "rapid sand" filter. The essential differences in the two types of filters are as follows: In the English or slow sand filter a coagulating chemical is seldom used in preparing the water for filtration; the sand grains comprising the filter proper are small in size; the rate at which water is allowed to pass through the filters is slow; and in cleaning the beds a thin surface layer is removed from the bed, washed, and returned. In the American or rapid sand filter a coagulating chemical is always used in preparing the water for filtration; the sand grains of the filter bed are much coarser and more uniform in size than in the slow sand filter; the rate of filtration is approximately 40 times that used in the slow filter; and the filter bed, when dirty, is cleaned in the filter itself by mechanical means. After all, however, the distinguishing difference between the two filters is the rate of filtration. They are both of English origin, and they are both sand filters. It would seem, therefore, that they would be sufficiently distinguished from each other if they are called "slow sand filters" and "rapid sand filters," and these names will be used throughout this paper.

The waters of the United States present a wide variety of conditions. The waters of the New England States are normally clear; those of the Central States are often highly charged with suspended matter. Many waters are clear but highly colored with vegetable stain. Others are both colored and turbid. In some the turbidity is caused by particles of clay of microscopic fineness; in others, as in the Missouri River water, the suspended mud is for the most part very coarse. Every water seems to possess peculiar characteristics, and even these characteristics are subject to wide variation.

As late as 12 years ago the opinion was generally held that one or another system of filtration was applicable to the satisfactory solution of all water-purification problems. More particularly did opinion lean toward the older and therefore better-established slow sand filter, as used with success in many places in Europe and in a few places in America. Careful experimentation with different systems of filtration, carried on at Louisville, Ky.; Pittsburgh, Pa.; Cincinnati, Ohio; Washington, D. C.; and elsewhere, demonstrated 10 years ago that the slow sand filter, which had proved successful in the treatment of European waters and the practically clear waters of the northeastern United States, was not strictly applicable in the treatment of very turbid waters—that is, waters carrying in suspension large quantities of mud. The chief difficulties to overcome were the physical imperfections of the raw water. These refer particularly to the mud contained in the waters of the South and the Central West. In the experimental work it was definitely shown at Louisville and Cincinnati that, owing chiefly to the muddy character of the Ohio River water, the newer process of rapid sand filtration would accomplish the required result more efficiently and economically than would slow sand filtration, and plants of the former type have been built and are now in successful operation in both those cities.

PREPARATORY TREATMENT OF WATER FOR FILTRATION.

Waters which in their raw state are normally clear and colorless practically require no preparatory treatment before filtration. Waters which are comparatively clear but highly stained by decaying vegetation, and which require treatment for the removal of bacteria, may also be purified satisfactorily by slow sand filtration. This treatment, however, will remove only a relatively small part of the coloring matter dissolved in the water, and if it is desired to remove all of this color a coagulating chemical must be used. By coagulation the stains are thrown out of solution and are easily removed in a coagulated state by sedimentation and filtration. Under these conditions it is usually more economical to make use of the rapid sand filter as the final step in the purification process, for unless prefiltration is employed or a long period of settling follows the addition of a coagulant to the raw water, much of the coagulant will be deposited on the slow sand filter and the surface will speedily be clogged. Frequent and expensive scraping of the filter is necessary under such circumstances. The waters of the Missouri, the Mississippi, and the lower Ohio basins contain suspended materials largely mineral in character but varying greatly in the size of the particles. Some particles are comparatively coarse and settle out readily when the water is allowed to stand; others are of exceeding fineness, many of them less than 0.00001 inch in average diameter, which is smaller than the ordinary bacterium. Such turbid waters when applied to filters without preliminary treatment can not be satisfactorily purified.

It is in the purification of these muddy waters that the engineer finds some of his most difficult problems. The turbidity of the raw water shows abrupt changes from comparative clearness following long periods of drought, when the suspended matter it contains may be less than 50 parts per million (422 pounds to the million gallons) to great muddiness during freshets, when the suspended matter may amount to 2,000 or more parts per million (17,000 pounds to the million gallons). These changes from comparatively clear to very muddy water occur very suddenly, and the character of the suspended particles is subject to great variation. To remove the bulk of this suspended matter prior to filtration and to do it economically is no simple problem. If it is done by plain sedimentation, then the basins in which subsidence takes place must be large enough to deal satisfactorily with the water when in its worst condition (Pl. IV, p.42). If sedimentation is to be aided by preliminary coagulation, then the basins must be made large enough to permit adequate subsidence of the bulk of the coagulated matters before the water reaches the filters (Pl. VI, p. 48). With some waters several days' plain subsidence are required. Where coagulants are used, this period may be reduced to several hours.

In some places, as at Albany, N. Y., coarse "roughing" filters have been installed for the purpose of clarifying the water before filtration. Filters of a somewhat similar type treat the water at Philadelphia, Pa., before it goes to the final filters. At Wilmington, Del., the water is prepared for filtration by being first passed through layers of broken stone and sponge clippings. In none of these places is a coagulating chemical made use of.

The old practice of clarifying muddy water by coagulation with compounds of aluminum, following this with a period of subsidence, probably originated in China thousands of years ago. For many centuries it has been the practice in that country to treat tubs of turbid water with alum by inserting a crystal of the chemical in the split end of a stick and then moving the crystal up and down through the water until enough is dissolved to effect a satisfactory coagulation. Where aluminum sulphate is used it reacts with the carbonates in the water and a practically insoluble precipitate of aluminum hydroxide, a magma of flocculent appearance, results. As coagulation goes forward the particles of mud and silt are drawn together in comparatively large aggregates and afterwards subside with considerable celerity. Many of the bacteria in the water also become entangled in the coagula and are likewise removed by subsidence.

Slow sand filters are seldom installed where waters of high turbidity are to be purified, although at Albany, Pittsburgh, Philadelphia, and Washington filters of this type are called on every year to treat waters which contain large quantities of sediment. At Albany the works as originally built provided for a period of plain sedimentation of about eight hours, but later a battery of coarse roughing filters was added to relieve the occasional heavy load on the filters. At the Torresdale works in Philadelphia no provision is made for preliminary sedimentation. Here preliminary filters of the rapid sand type, but in connection with which no coagulant is used, effect a substantial removal of suspended matter from the raw water before it reaches the slow sand filters. The Philadelphia works at Upper and Lower Roxboro and at Belmont include apparatus for plain sedimentation and prefiltration through various kinds of coarse material before the water goes to the final filters. At Pittsburgh there are no prefilters, but the raw water is clarified during a period of preliminary sedimentation of about one day (Pl. IV, p. 42). At none of these places is use made of a coagulating chemical at any stage of the process.[1]

At Washington, D. C., where the filters are also of the slow sand type, it was recommended by the expert commission, Messrs. Hering, Fuller, and Hazen, that a coagulant be applied to the unfiltered water during the very muddy periods. This recommendation was not followed in the works as originally laid out and built. A preliminary period of plain sedimentation is provided in three reservoirs, two old and one new, the combined time allowed for sedimentation being between three and six days. There are no prefilters in these

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[1] These statements apply to conditions existing in June, 1911.

works, but provision is being made for the application of a coagulant to the water before filtration.

It has frequently been contended that the use of coagulants, such as ferrous sulphate or aluminum sulphate, may be deleterious to the health of persons who drink the water. Such a contention is not valid, and may best be refuted by pointing out the fact that no such deleterious effects have ever been observed among the millions of people in this country who have for years been drinking water treated with coagulants.

The prejudice against coagulants has, however, led to the adoption of slow sand filters, suitably equipped for coagulant use in times of high turbidity. There are reasons both for and against such a plan, the details of which will not be discussed here. Let it merely be said that the use of coagulants in conjunction with slow sand filtration has never been regarded with much favor in this country. In some places where the conditions are particularly favorable coagulants have been successfully used. At Indianapolis, Ind., for instance, the water has been treated with coagulating chemicals for the last five years or more. After adding the chemicals the water is allowed a period of 24 to 48 hours for subsidence. The results have been generally satisfactory. At Tokyo, Japan, potash alum is used during periods of muddy water, and the water so treated is allowed 36 hours for coagulation and subsidence before it is applied to the slow sand filter. From the officials in charge of these works in 1906 the writer was unable to elicit any but the most favorable reports regarding the use of chemicals under these circumstances. At Calcutta, India, alumino-ferric is successfully used during the rainy season of the year, namely, July, August, and September. After being treated with this chemical the water is allowed to flow into large settling basins, which are worked on the fill-and-draw plan but in which the average period of sedimentation can not be less than three or four days. After this sedimentation the clarified water is applied to slow sand filters. Alumino-ferric has also been used in small slow sand filter plants in Europe.

Double filtration is to-day practiced abroad in Altona, Bremen, Schiedam, Zurich, and Singapore. At Altona it is not of much benefit and its usefulness at Schiedam is debatable. At Singapore it is used chiefly to effect the removal of tastes and odors from the water, but has not proved particularly efficient. In slow sand filters the turbid raw water, if only for reasons of economy and whether coagulants are used or not, must first be passed through preliminary filters or be subjected to comparatively long periods of sedimentation. In rapid sand filters, whether the raw water is turbid, colored, or clear, it is always necessary to make use of a coagulating chemical. The reason for this is that the sand grains in such filters are larger than those in the slow sand filter and the rate of filtration is much higher. Consequently it is necessary that the water as it flows to the filter should be thoroughly coagulated; that is, that the suspended matter, and the color if any is present, should be coagulated into aggregates of considerable size and that practically no suspended matter or color be present at such time in its natural finely divided or semi-soluble state. It is further necessary, in order to obtain the highest efficiency commensurate with economy in the operation of a rapid sand filter, that during and after coagulation the water be allowed a suitable period for the subsidence of the bulk of the suspended matter. The suspended matter which is left in this process, however, is or should be flocculent in character and not granular and finely divided, as it is where subsidence is unaided by coagulation. With such preparatory treatment of the raw water the cost of operating the filters should be reduced to the lowest practicable minimum.

SLOW SAND FILTRATION.

GENERAL DESCRIPTION.

A slow sand filter consists of a water-tight basin, usually 1 acre or less in extent, supplied with suitable underdrains and filled to a certain depth with stone, gravel, and sand. The floor and walls are of brick, stone masonry, or concrete, and in northern latitudes it is necessary, in order to get the best results, to roof the filter over to prevent it from freezing. Such roofs or covers are usually made up of a series of concrete groined arches, as shown in Plate I.

Along the bottom of the basin, as shown in Plate I, *A*, is placed a main drain, and leading into this from both sides and at regular intervals are lateral drains. The floor is covered with graded stone, as shown in Plate II, *A*, sufficiently deep to cover the lateral drains, and over this is placed a layer of fine gravel, as shown in Plate I, *B*. All this material is merely a part of the underdrain and takes no part in the water purification process. Above the gravel fine sand is laid smooth to a depth of about 3 to 4 feet (Pl. II, *B*). This sand is the real filtering material; that is, it is the sand, together with the gelatinous film formed at the surface of the sand by organic matter and sediment from the water, which gives the filter its efficiency as a water purifier.

When the filter is ready for service the water is permitted to flow into it to a depth of about 3 feet and is allowed to percolate through these beds at a rate of about 75 gallons a day on 1 square foot of filter surface. This rate corresponds to a yield of about 3,000,000 gallons daily to the acre of filter surface. When a new filter is put into service it does not at once do its best work, but after a few weeks' operation the sand grains throughout the bed become coated with an organic film and a slimy sediment collects on the surface of the sand layer. The filter is then most efficient. After a time its surface becomes so badly clogged that it is impossible to maintain a rate of filtration sufficiently high to be economical, and then the filter is shut down and allowed to drain, after which a thin layer of the top surface of the sand, from one-half to 1 inch in thickness, is scraped off (Pl. II, *B*). The filter is then refilled and filtration resumed, the water being first passed through at a low rate, which is gradually increased until the desired rate is obtained. On the basis that one such filter purifies 3,000,000 gallons each day, it is merely necessary to build a sufficiently large number of units to supply the amount required at any given place, but it is also necessary to install a sufficient number of extra units to take the place of those which are temporarily out of service and being cleaned.

UNIFORM RATES OF FILTRATION NECESSARY.

Experience has shown that if a slow sand filter is efficiently operated the speed at which the water passes through the sand, or, as it is usually designated, the rate of filtration, must be uniform over all parts of the filter. It was formerly the belief that a slow rate of filtration would give a greater certainty of removing the foreign ingredients in the water than a rapid rate of filtration. It has been found, however, as explained further on, that very high rates of filtration can be maintained so long as the gelatinous film on the surface of the sand is not broken and if methods are used by which the filter can be cleaned more frequently at a low cost. The maximum rate at which filtration can be maintained varies with the condition of the water, the fineness of the sand, and certain other factors, but within reasonable limits the rate of filtration is controlled by the method and cost of cleaning the filter. Many slow sand filters in the country afford an inferior effluent on account of bad management and inadequate filter capacity. They are operated primarily to meet a demand for a certain quantity of water. Quality of effluent seems at these filters to be a secondary consideration.

A moment's consideration will show that a uniform rate of filtration must be maintained over the entire surface of the filter. If the rate be suddenly increased the fragile gelatinous film at the surface will be broken and at the immediately surrounding points the rate of filtration will increase sharply to the detriment of the quality of the effluent. If by such sharp increase in the rate even a small part of a filter bed is disturbed, the water passing through that part is imperfectly purified, and even though all the remainder of the filter is doing excellent work, there passes into the effluent this inferior

A. MAIN COLLECTOR AND LATERALS BEFORE SAND AND GRAVEL WERE PUT IN.

B. MAIN COLLECTOR AND LATERALS, WITH GRAVEL IN PLACE.

THE PITTSBURGH FILTRATION PLANT.

Photographs furnished by Bureau of Filtration, Pittsburgh, Pa.

A. QUEEN LANE PLANT, WITH COARSE GRAVEL IN PLACE.

B. TORRESDALE PLANT, SHOWING METHOD OF CLEANING WITH NICHOLS SEPARATOR.

PHILADELPHIA FILTRATION PLANTS.

Photographs furnished by Department of Public Works, Philadelphia, Pa.

water, which perhaps contains the germs of typhoid fever. This disturbance of the filter surface is further undesirable in that the continued operation of a filter which has suffered such disturbance will cause the penetration of mud and other suspended ingredients into the sand layer, the penetration taking the form of an inverted cone if the break is merely a puncture, or of a wedge if the break takes the form of a crack. When the filter is scraped or cleaned it is impracticable to remove all of this clogged portion, and it follows that at those particular parts of the bed the filter will remain virtually inoperative and the remainder of the bed will be forced to do correspondingly more work. On the other hand, if the rate of filtration in a slow sand filter is suddenly diminished to a marked extent there is a likelihood, particularly in the wintertime, of entrained air being released from the sand layer due to the abruptly diminished pressure in the filter. The release of air in this way may be violent and the filter bed and surface film badly broken in places. The consequences of such breaks, if the filter is continued in operation, are quite as serious and annoying as those caused by abruptly increasing the rate.

In most of the recent slow sand filter plants the rate of filtration is largely under automatic control through special devices, but in many filters of this type the rate is adjusted at more or less indefinite intervals by filter attendants.

SAND HANDLING.

One of the most expensive features of the operation of a slow sand filter plant is that of sand handling. It is necessary to scrape the surface of the average slow sand filter about once a month, and the sand removed is either stored until a sufficiently large quantity is obtained for washing or else it is washed and replaced at each scraping. It is rarely more economical to throw away the sand scraped from the beds and make up the deficiency with entirely new sand than to wash such sand and replace it in a clean condition. The sand itself is usually expensive. When first procured it must be washed free from clay and screened before it is ready to be placed in the filter tank. Under favorable conditions in this country sand may be secured at $1.50 to $2.50 a cubic yard. Under very favorable circumstances such as obtained at Albany, N. Y., during the construction of the filters at that place, the sand cost about $1 a cubic yard; at Washington, D. C., in 1904, it cost $2.65 a cubic yard. The sand for the filters at Yokohama, Japan, cost $2.75 a cubic yard in 1906, a very high figure for sand in that country where labor is so cheap, but this cost resulted from the fact that the sand had to be transported a long distance uphill to the filter plant from the shores of Mississippi Bay, where it was dredged. At Osaka, Japan, the sand is dredged from the bed of Yodo River immediately opposite the waterworks, brought to the shore in scows, spread out on the beach, sun dried, and afterward pan screened by coolies, who receive from 1 to 2 cents an hour for their labor. The cost of the sand in place at Osaka is about $0.65 per cubic yard, a figure so low that no attempt is made to recover by washing the sand scraped from the filters, and it is used for fill. So far as the writer knows, however, this is the only place where washing and replacing the sand scraped from filters is dispensed with.

The cost for labor in removing sand from a filter and washing and replacing it has thus far averaged around $1.50 a cubic yard. George W. Fuller gives some instructive figures gathered from some of the older plants on this point, as follows: [1]

Cost per cubic yard of handling sand in older filters and date filter was placed in service.

Lawrence, Mass. (1893)	$1.70
Mount Vernon, N. Y. (1894)	1.51
Albany, N. Y. (1899)	1.38

Another method of cleaning a slow sand filter is known as the "Brooklyn" method and was first used in 1905 by the New York City Department of Water Supply, Gas, and Electricity, at the suggestion of V. C. Brower, superintendent of the Hempstead filter plant at Rockville Center, Long Island. This method has been continued in use at several of the city filter plants on Long Island up to the present time, with very satisfactory results, both as to bacterial efficiency and as to freedom from subsurface clogging. The method consists in lowering the water to 1 inch in depth above the surface of the sand on the filter. Unfiltered water, generally taken from an adjacent filter in service, is then run in a stream over the surface of the sand to the outlet drain, a depth of about 1 inch of flowing water being maintained over the section to be cleaned. Men in rubber boots agitate the surface of the sand with long-toothed garden rakes, thus stirring the dirt from the sand and having it carried away to the drain. In order to secure the necessary velocity of flow with moderate quantities of water on a filter having large sand areas, the bed is cleaned in sections, the section undergoing cleaning being temporarily cut off from the rest of the bed by boards set on edge and driven down into the sand, forming a sort of flume with board sides and having a width of about 10 or 12 feet. After cleaning one section the boards are removed to a new position. When the dirt is removed the drain is closed, the filter is filled to its normal height with raw water, and filtration is resumed. William B. Fuller, who first tested this method experimentally, states that it requires

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[1] Trans. Am. Soc. Civil Eng., vol. 46, 1901, p. 336.

about 1 per cent of wash water under the conditions of the New York City supplies, that the bacterial efficiency of filters so cleaned is apparently as high as that of filters cleaned by other methods, and that there is no subsurface clogging noticeable in five years' use of this method at Hempstead. This method has also been used by the city of Philadelphia at the Torresdale plant with successful results.

Fred C. Dunlap, chief engineer, Philadelphia Bureau of Water, states that 14 men and a foreman clean a three-quarter acre bed in eight hours, and that such a bed averages 19 hours a month out of service, including all elapsed time for draining, washing, and refilling.

More recent information of this point from large plants has been made available at Philadelphia, Washington, and Pittsburgh. At Washington, the dirty sand after being scraped is shoveled into portable ejectors (see Pl. II, *B*, p. 33, smaller device near center of picture) on the beds, to be thence forced by water pressure through pipes to stationary sand washers. After being washed the sand is discharged into concrete storage bins, from which carts, driven underneath, may be loaded. Until April, 1909, the washed sand was replaced in the filters by carts, which took the sand over the top of the filter and dropped it through manholes on revolving chutes for distribution over the filters. The total cost of sand handling is given by Hazen and Hardy[1] as $0.42 per cubic yard, this total being made up as follows:

Cost per cubic yard of sand handling at Washington, D. C.

Scraping (5 cents) and leveling (3 cents)	$0.08
Ejecting	.14
Washing	.04
Storing and replacing	.16
	.42

Since April, 1909, the washed sand has been restored to the filters by a hydraulic method in which an ejector is placed under the sand storage bin and the sand then ejected through pipes and hose to the filter. This method is considerably more economical than the old method and gives satisfactory results.

MACHINES FOR SAND WASHING.

An improved apparatus for sand cleaning was given a thorough trial at Philadelphia in 1911. The apparatus is known as the Nichols separator (Pl. II, *B*, p. 33) and with it the dirty sand can be washed and restored to the bed without removing the scrapings to sand washers outside the filters. This machine weighs about 700 pounds and is

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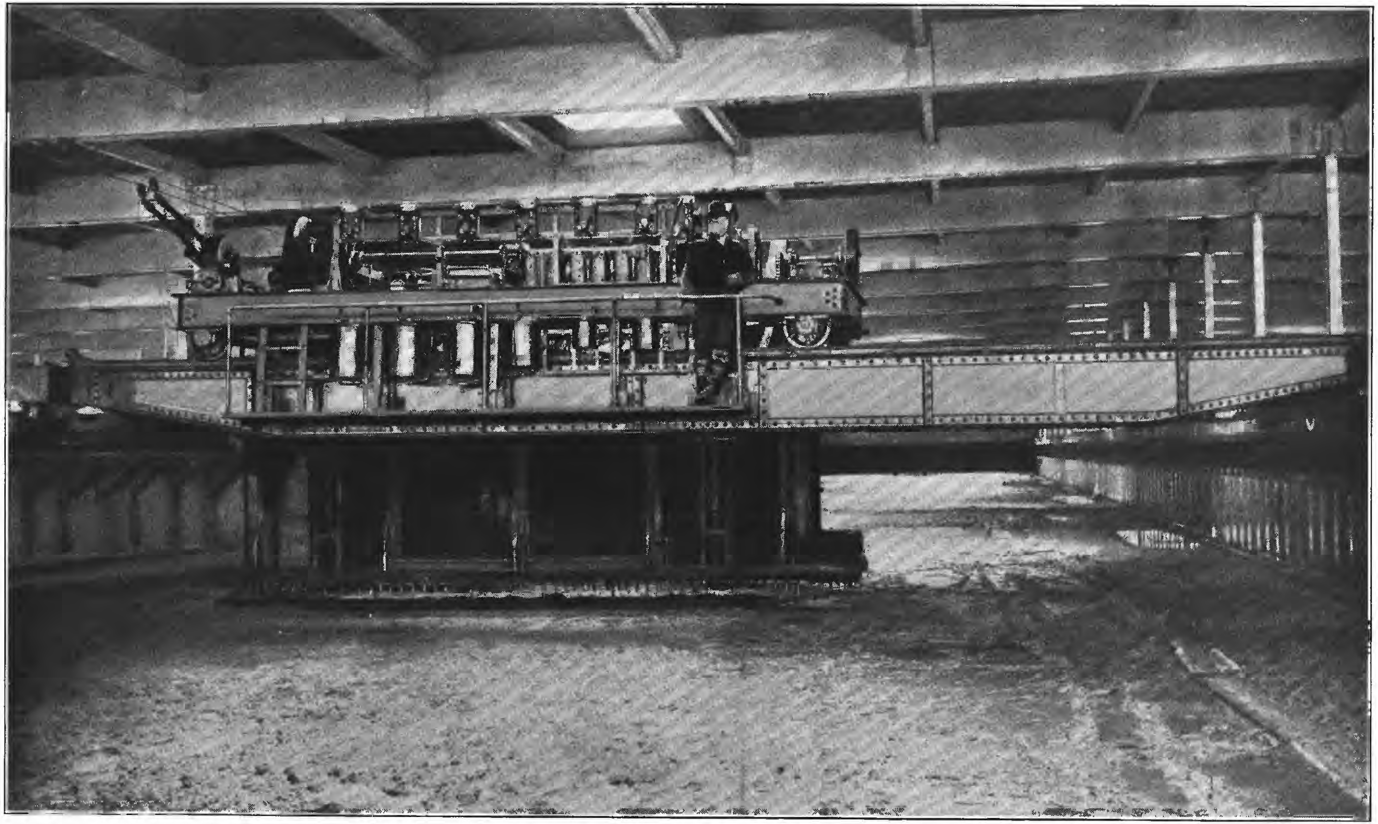
[1] Hazen, Allen, and Hardy, E. D., Works for the purification of the water supply of Washington, D. C.: Trans. Am. Soc. Civil Eng., vol. 57, 1906, p. 349.

moved from point to point on the bed on short lengths of channel rails which can easily be shifted by four men. It has been demonstrated at Philadelphia that with one of these machines it is possible to clean and replace 10 cubic yards of sand an hour, using 1,200 gallons of water to the cubic yard of sand washed. The cost of sand washing by the new method is materially lower than formerly, when the sand was first ejected to the courts, there washed, and afterwards restored to the filter. By the old method the cost for scraping, removing, and washing the sand was 52 cents a cubic yard, and for restoring the washed sand to the bed 24 cents a cubic yard, a total of 76 cents a cubic yard. With the Nichols separator, where the sand is washed and restored at the filter, the total cost during two years' operation of the machine was about 50 cents a cubic yard. Furthermore, less than half as much water is used in the new process.

Still another method was carefully studied at New York during 1907 and 1908. This device is known as the Blaisdell filter-sand washing machine, and was first given a trial at Yuma, Ariz., on a slow sand filter treating the turbid waters of Colorado River. It had been in successful operation at Yuma for about four years before it was investigated in connection with the experimental slow sand filters treating the Croton water supply of New York City at high rates of filtration. The results of the investigation, carried on at Jerome Park in 1907 and 1908, were so favorable that the machine was recommended for adoption in the proposed new Croton filtration project. It was also adopted and is in successful use at the Wilmington, Del., filtration plant. (See Pl. III.)

In construction this washing machine is comparatively simple. It consists of an inverted box about 4 feet square and 2 feet deep. The box contains a revolving hollow axle and a hollow head from which hollow teeth project. In operation the box is sunk in the water of the filter to the surface of the sand and is held in position and operated from a platform above. The platform is movable on rails supported by the walls of the filter. By means of electrically driven mechanism controlled by one operator the box can be lowered and raised and moved backward, forward, and sideways at will. In operation the box is made to slide over the surface of the sand at a speed of about 10 feet a minute and at the same time the hollow teeth are revolved, agitating the sand mechanically. Water is introduced into the hollow axle, head, and teeth under a pressure of 10 to 20 pounds to the square inch and passes in fine streams into the sand. A suction pump connected with the top of the box draws away just a little more water than is supplied through the teeth, and thus carries away and discharges to a sewer all of the dirt which has been stirred and washed from the sand. For further details regarding this



FILTER AT WILMINGTON, DEL., WITH BLAISDELL SAND-WASHING MACHINE.

Photograph furnished by Board of Water Commissioners, Wilmington, Del.

machine the reader is referred to an article by William B. Fuller in the Engineering News.[1]

The possibilities of such a machine as this are readily apparent. By other methods of cleaning a slow sand filter it is first necessary to drain the filter, which consumes much time, and afterwards to set a gang of men at work scraping off the clogged surface layer, and then carefully to refill the filter from below. This machine makes it possible to clean the sand layer without draining the filter. The time saved by the new process may be explained briefly as follows:

Assume that a slow sand filter operating at a rate of 3,000,000 gallons daily to the acre, exclusive of the time used in cleaning, yields a daily average of 60,000,000 gallons. Make a further conservative assumption that three days are required for the scraping, washing, and restoring operations under the older methods. This is equivalent to the assumption that the filter will be out of service 13 per cent of the time, and that the reserve filter area required to maintain the normal yield under these circumstances can not safely be less than 15 per cent of the total area actually required. Experiments made in connection with the New York City water supply have established the fact that a slow sand filter can be operated up to a daily rate of 10,000,000 gallons to the acre and produce an effluent of satisfactory quality. If such a filter were cleaned according to the older methods it would be out of service 33 per cent of the time if operated at the 10,000,000-gallon rate, and it would be unsafe to install a reserve filtration area less than 50 per cent of that required to supply the average daily demand for water. The New York investigation showed further that by use of the sand-washing machine, and by adjusting the unit area of the separate filter beds so that they can be effectively cleaned, the 10,000,000-gallon rate can be maintained. Suspension of operation for each filter would not exceed two or three hours. In other words, by the use of the washing machine a great reduction in first cost of the filter could be accomplished by the consequent diminishing of the reserve area required, which would also involve a proportionate reduction in the area of land that must be purchased for a filter site. The final result is therefore a smaller necessary filtration area with all the consequent advantages as to first cost and maintenance. Experimental work with these machines is still in progress, and further economies and advantages will no doubt result.

FILTER SURFACE RAKING AT PITTSBURGH.

When a filter becomes clogged at the surface by an accumulation of mud and miscellaneous matter derived from the unfiltered water, it is the common practice in rapid filter operation, where the filters are

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[1] Eng. News, vol. 59, No. 11, 1908, pp. 287-288.

circular in plan and are stirred by a mechanical agitator when they are washed, to trail the teeth of the rakes lightly over the surface of the filter, thereby breaking up the surface accumulation and prolonging the "run" to a greater or lesser extent. Until recently such a procedure had not been applied to slow sand filters, it being considered necessary to drain the filter and actually remove a portion of the surface of the bed. Experience at Washington, where raking of filter beds was first tried on a large scale, showed that the process prolongs the periods of service of the slow sand filters between actual scrapings.[1]

Surface raking of slow sand filters was first tried at Pittsburgh in the autumn of 1910. The procedure consists in partly draining a filter and in sending men into it to score the surface lightly with common garden rakes having teeth about 1 inch long. An acre bed can be treated in this way by four men in about eight hours at a cost of about $8. The filter is then refilled and filtration resumed.

The important result of this operation is that the filtering capacity of the bed is almost as effectively restored as it would have been by a scraping, which would have consumed much more time and cost a great deal more money. A second raking is much less effective, as might be expected, and a third raking is of little use. The immediate result is to cause a deeper penetration of the suspended matter into the filter. This was expected; but at Pittsburgh, as at Washington and Philadelphia, such penetration was found by repeated examinations not to extend deeper than about 2 inches from the surface. When the filter is ultimately scraped, a deeper layer has to be removed, of course, but it is manifestly cheaper to remove one deep layer at one operation than to remove separately several thinner layers of an equal aggregate thickness.

It has been clearly demonstrated at Pittsburgh, as at other places where the raking process has been used, that the filter is in no way injured, nor is its hygienic efficiency diminished. This somewhat radical departure from standard practice in slow sand filter operation is one of the most valuable steps taken in the field of water filtration in many years. Without increasing the rate of filtration it makes possible larger yields per unit area of filter surface and materially reduces the total loss of time for cleaning the filters. Smaller areas of filter surface will be required than formerly in order to obtain a stipulated daily volume of filtered water, which means economy in construction. Fewer actual scrapings in a year, made possible by relatively inexpensive surface rakings, means economy in operation. From the results obtained thus far it appears certain that in this de-

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[1] Proc. Am. Soc. Civil Eng., vol. 36, No. 10, Dec., 1910.

partment of filter operation alone a saving of about $50,000 will be shown for 1911 at Pittsburgh.

RELATION OF FILTER CLEANING TO RATE OF FILTRATION AND EFFICIENCY OF SLOW SAND FILTERS.

The regulations of the German Imperial Board of Health, based largely on the thorough studies of Peifke, place the maximum rate at which water should be passed through a slow sand filter at 60 gallons a day to the square foot of filtering surface, a rate which has been almost universally adopted throughout Europe and America, This corresponds to a column of water 4 inches in depth per hour, or a total yield to the acre of filtering surface of 2,614,000 gallons daily.

The rate of filtration is obviously controlled by the fineness of the sand grains comprising the filter and the quality of filtered water desired. Long experimentation and practical operation of large filters seemed to make it plain years ago that no slow sand filter, no matter what character of water it was called on to treat, should be expected to yield more than about 3,000,000 gallons of water to the acre daily under the best conditions of friction and loss of head in the filter and of physical and hygienic quality of the filtered water. Furthermore, it must be remembered that this yield is based on the actual rate of filtration while the filter is in operation. During a considerable portion of the time (from 10 per cent upward) the filter is out of service for cleaning, and the net rate of filtration through a period of several months will show a reduction proportionate to this time. Generally speaking, it has been considered proper in planning a slow sand filter to figure on a reserve area of 15 to 25 per cent in excess of that required when all of the filters are in active service. Naturally this feature, involving a materially increased first cost of the plant, has been an incentive to engineers to find some method whereby filters of this type can be more speedily cleaned and a less area of reserve filters be required.

That filters of this type can be successfully operated at rates materially higher than 3,000,000 gallons to the acre daily has been clearly demonstrated by the good results obtained in practice at Zurich, Switzerland, Yokohama, Japan, and elsewhere. Carefully conducted experiments at Lawrence, Mass., Louisville, Ky., Cincinnati, Ohio, New Orleans, La., Springfield, Mass., and New York, N. Y., have indicated clearly that where the raw water is given proper preparatory treatment much higher rates than 3,000,000 gallons to the acre daily are perfectly feasible without endangering the quality of the filtered water. As before stated, the great drawback to the adoption of higher rates has been the more speedy clogging of the sand surfaces and the consequent increased cost for reserve filter area. Obviously higher rates must cause speedier clogging of the filters, but generally speaking the yield between scrapings of the filters, whether operated at rates of 3,000,000 or 6,000,000 or even 9,000,000 gallons to the acre daily, will be approximately the same. The chief difficulty has been the time required for cleaning the filters. The last few years have been fruitful in showing that certain well-defined advances are being made in the more rapid cleaning of slow sand filters, as indicated in the foregoing pages under the caption "Machines for sand washing."

COST OF CONSTRUCTION OF SLOW SAND FILTERS.

Many attempts have been made to compare the cost of construction of slow sand filter plants in this country, but local conditions control so largely that comparative figures have little value. To illustrate this point a few examples are given.

ASHLAND, WIS.

The plant at Ashland, Wis., was built in 1895 and was the first slow sand filter in America to be covered by masonry. It is located near the shore of Lake Superior, and on that account it was necessary to build a pile bulkhead around three sides of the plant. The bottoms of the filters are below the lake level and consequently a cofferdam was required during construction. The filters are three in number and are built of concrete and brick. The roofs are groined elliptical brick arches and rest on brick pillars. The filter bottoms are of concrete. The work was all done by day labor and the total cost of construction was $40,178, or $80,356 per acre of filtering surface.

BERWYN, PA.

The filter at Berwyn, Pa., was built in 1898 and consists of three filter units, all uncovered, having a total area of 0.5 acre. The walls of the filter are of rubble masonry backed up with earth, and the floor is of concrete. The total cost of construction was $18,536, which corresponds to $33,070 per acre of filtering surface, or $12,000 per million gallons daily capacity.

NYACK, N. Y.

The filter at Nyack, N. Y., was built in 1899 and consists of two units, both uncovered, having a total area of 0.38 acre. It is located in a swamp near a creek from which the supply is drawn, and in order to get the water to the filters by gravity it was necessary to excavate for the filter beds 10 feet of wet tenacious clay. The concrete and brick side and division walls are supported on piles. The work was done by contract and the total cost was $29,094, which is equal to $76,550 per acre of filtering surface, or about $39,000 per million gallons daily capacity. It should be mentioned that this cost includes a small filtered-water basin having a capacity of about 3,500 gallons.

SUPERIOR, WIS.

The plant at Superior, Wis., was built in 1899 for the purpose of removing iron in the water from driven wells. Because of the fact that the water was bacterially satisfactory a high rate of filtration (10,000,000 gallons an acre daily) was used.

The plant consists of three units having a total area of 0.5 acre and a filtered-water basin of about 300,000 gallons capacity. The floors and walls of the filter tanks and filtered-water basin are of concrete and both are under one groined-arch concrete roof, which rests on brick piers and is covered with 2 feet of earth. All excavation was in red clay. The works were built by day labor and the total cost was $89,484.

ALBANY, N. Y.

The plant at Albany, N. Y., has a daily capacity of 15,000,000 gallons; it was completed in 1899 and originally consisted of a pumping station and intake, sedimentation basin, slow sand filter, and filtered-water reservoir. Recently, roughing filters have been added to aid in the preparation of the water for final filtration. The cost of this plant when it was built, as given by the designer, Allen Hazen, was as follows:[1]

Cost of slow sand filtration plant at Albany, N. Y.

Land	$8,290
Pumping station and intake, complete	49,745
Filters, eight beds, each 0.7 acre in area, covered; sedimentation basin, capacity 37,000,000 gallons; and filtered-water reservoir, complete	324,217
Conduit and connections with Quackenbush Street pumping station	86,638
Engineering and contingencies	31,000
Total approximate cost of works	499,890
Cost of filters, per acre	45,600
Cost of uncovered sedimentation reservoir per million gallons capacity	4,100
Cost of filtered-water reservoir per million gallons capacity	15,000
Cost of filters per million gallons gross daily capacity	15,200
Cost of works per million gallons daily capacity	33,320

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[1] Trans. Am. Soc. Civil Eng., vol. 43, 1900, p. 294.

WASHINGTON, D. C.

Summarized data as to the construction cost of the 75,000,000-gallon slow sand filter plant at Washington, D. C., taken from a paper by Allen Hazen and E. D. Hardy,[1] are as follows:

Cost of slow sand filtration plant at Washington, D. C.

Land	$619, 900
Pumping station, including intake, Venturi meter, electric generating plant, stack, etc., complete	183, 600
Twenty-nine filters, covered, each 1 acre in area, complete	2, 197, 000
Filtered-water reservoir, capacity 14,200,000 gallons, including gatehouse and regulating apparatus, complete	150, 000
Lower gatehouse and pipe line	24, 300
Engineering and clerical work	181, 500
Total cost of works	3, 356, 300
Total cost, excluding land	2, 736, 400
Cost of filters per acre	75, 700
Cost of filtered-water reservoir per million gallons capacity	10, 600
Cost of filters per million gallons gross daily capacity	25, 250
Cost of plant per million gallons daily capacity	44, 750

PITTSBURGH, PA.

The works at Pittsburgh, Pa., consisting of covered slow sand filters, covered filtered-water basin, and open sedimentation reservoirs, were completed in 1908 (Pl. IV). The total cost as awarded the contractors by the arbitrators in July, 1910, and not including engineering and a small portion of daywork done by the city, was as follows:

Cost of slow sand filtration plant at Pittsburgh, Pa.

River crossing and connections	$298, 589
Low-lift pumping station	357, 513
Low-lift pumping machinery, boilers, etc	284, 169
River well and intake	207, 673
Brilliant pumping station (additional machinery)	221, 472
Pipe lines to Highland reservoir	555, 250
Filters[2] (46 1-acre units, covered) and open sedimentation basins	3, 586, 245
Filtered-water reservoir, 45,000,000 gallons capacity	460, 060
Total cost of works	5, 970, 971
Cost of filters (including settling basins) per acre	78, 000
Cost of filtered-water reservoir per million gallons capacity	10, 200
Cost of filters (including settling basins) per million gallons daily capacity	26, 000
Cost of plant per million gallons daily capacity	42, 600

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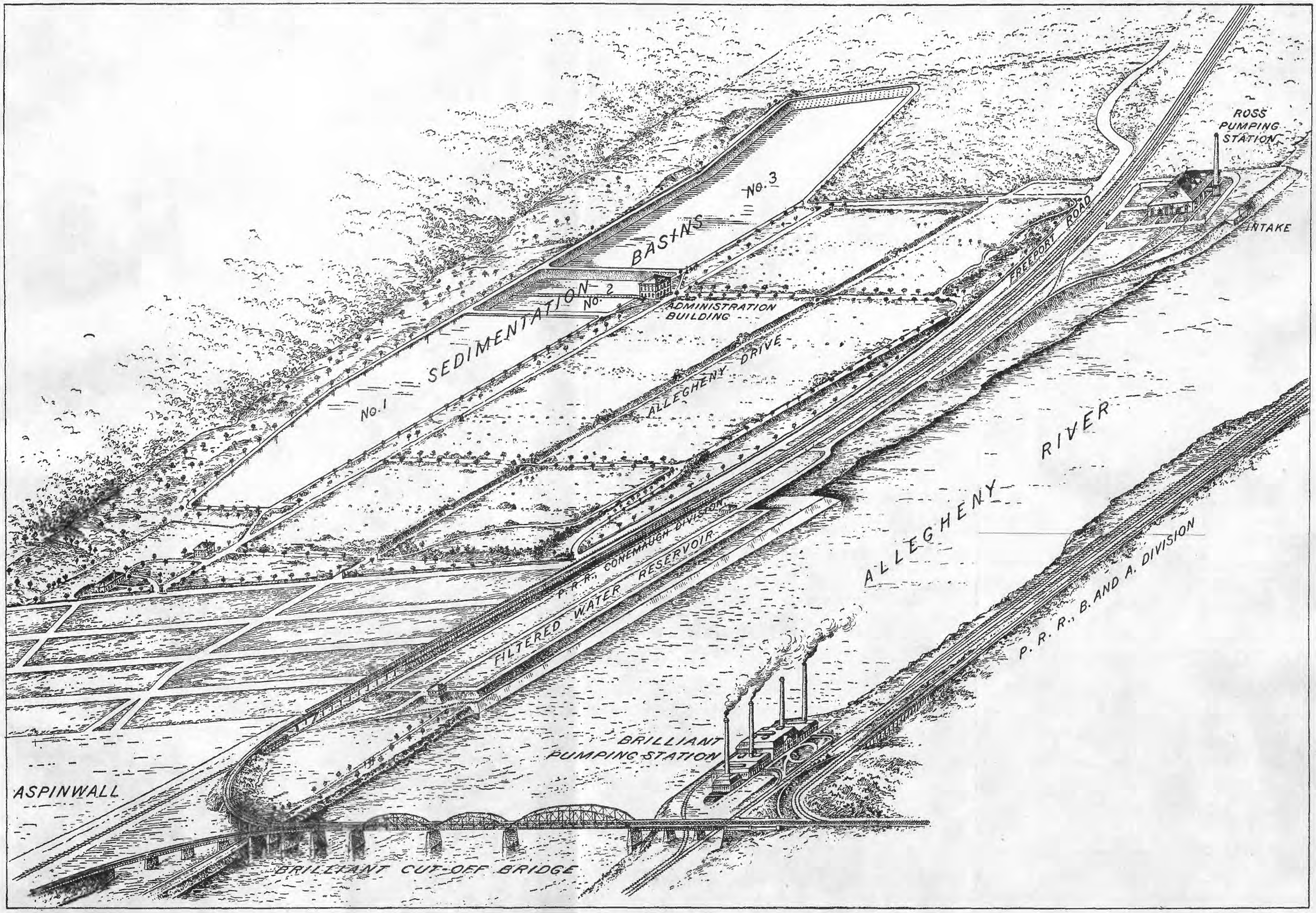
[1] Trans. Am. Soc. Civil Eng., vol. 57, 1906, p. 307.

[2] Ten more acres of filters have since been built but have not been placed in service.

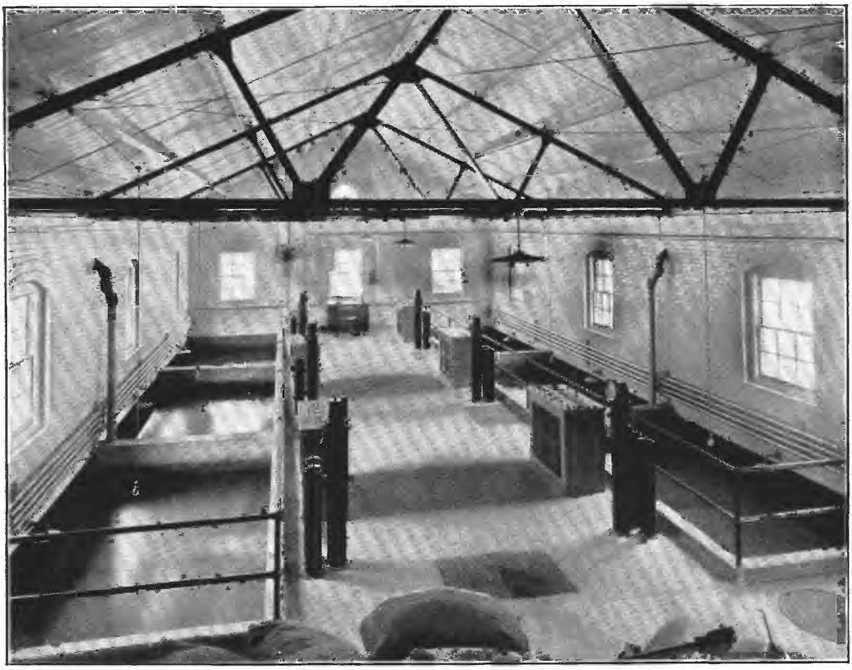


ISOMETRIC VIEW OF FILTRATION WORKS, PITTSBURGH, PA.

From print furnished by Bureau of Filtration, Pittsburgh, Pa.

A. OPERATING GALLERY OF THE TORRESDALE PREFILTER, PHILADELPHIA, PA.

Photograph furnished by Department of Public Works, Philadelphia, Pa.



B. OPERATING FLOOR AND RAPID SAND FILTERS OF THE CHINCHILLA FILTRATION PLANT, SCRANTON, PA.

Photograph furnished by Scranton Gas & Water Co.

PHILADELPHIA, PA.

The works at Philadelphia (Pl. II, p. 33, and Pl. V, *A*), the largest in the world, are not completed as a whole. There are five separate plants, four of which are completed and one is still in process of construction. The following construction costs of the several plants built and the one still building are taken from the report of the Bureau of Water, Philadelphia Department of Public Works, for 1909:

Lower Roxboro plant.—The plant at Lower Roxboro has a capacity of 12,000,000 gallons daily. The works include a pumping station, a sedimentation basin of about 12,000,000 gallons capacity, 11 covered preliminary filters of slag and sponge containing about 0.28 acre in total filtering area, 5 covered slow sand filters, about 2.7 acres in total filtering area, and a covered filtered-water reservoir of 3,000,000 gallons capacity. Total cost, $580,000; cost per million gallons daily capacity, $48,330.

Upper Roxboro plant.—The capacity of the Upper Roxboro plant is 16,000,000 gallons daily. The works include an administration building, a low-lift pumping station with equipment, eight covered filters, about 5.6 acres in total filtering area, and a filtered-water reservoir of 8,000,000 gallons capacity. Total cost, $1,080,000; cost per million gallons daily capacity, $67,500.

Belmont plant.—The capacity of the Belmont plant is 67,000,000 gallons daily. The works consist of two settling basins of 72,000,000 gallons total capacity, 9 preliminary filters of coke and sponge, 18 covered final filters about 13.25 acres in total area, and a filtered-water basin of 16,500,000 gallons capacity.

Cost of Belmont slow sand filtration plant, Philadelphia, Pa.

Total cost of works	$3,292,000
Cost per million gallons daily capacity	49,120
Cost of sedimentation basins per million gallons of capacity, about	8,340

Torresdale plant.—The capacity of the Torresdale plant is 240,000,000 gallons daily. The works include an intake, gatehouses, and pumping station, 120 covered mechanical preliminary filters about 3.35 acres in total area, and a filtered-water basin of 50,000,000 gallons daily capacity.

Cost of Torresdale slow sand filtration plant, Philadelphia, Pa.

Total cost	$9,208,000
Cost per million gallons daily capacity	38,370
Cost of intake	225,000
Cost of pumping stations, including building and pumps	723,000
Cost of preliminary filters per acre, about	346,300
Cost of preliminary filters per million gallons daily capacity	4,830
Cost of final filters per acre	145,000
Cost of final filters per million gallons daily capacity	39,600

Queen Lane plant.—The Queen Lane plant, now building, is to have a capacity of 70,000,000 gallons daily. The works will include 40 covered preliminary filters about 1.7 acres in total area, 22 covered final filters about 16.7 acres in total area, and a filtered-water basin of 50,000,000 gallons capacity. Estimated cost of works, $1,900,000; cost per million gallons daily capacity, about, $27,100.

OSAKA, JAPAN.

The water-purification works at Osaka, Japan, having a daily capacity of about 25,000,000 gallons, include open sedimentation basins and slow sand filters. One of the sedimentation basins, completed in 1903, of about 10,000,000 gallons effective capacity, cost $83,370, exclusive of the cost of the land. One of the uncovered slow sand filters, finished in the same year, has a filtering area of about 1.45 acres and cost $45,050, or about $31,000 per acre of filtering surface.

SUMMARY.

If the examples given can be considered as approximately representative, the average cost of building a slow sand filter is about $60,000 per acre of filtering surface. If conditions are favorable the cost may be less; if they are unfavorable it will be greater.

If a slow sand filter costs $60,000 an acre to build, and if the gross capacity of a 1-acre filter is 3,000,000 gallons daily and its net capacity about 2,500,000 gallons daily, then in a community which consumes 125 gallons per capita daily an acre of filter will supply 20,000 people. If the cost of the filter is $60,000, the first cost to each consumer will be $3. At 6 per cent the interest charges on this investment will be 18 cents per capita per annum. Settling basins and filtered-water reservoirs may increase the first cost of the works to about $4 per capita, and on this the annual interest at 6 per cent would be 24 cents per capita. These figures are of necessity approximate, but may serve fairly well to indicate what purification plants, including slow sand filters, will cost each taxpayer.

During epidemics of typhoid fever it is the custom in this country for the local health authorities to send out a wholesale warning that all water used for drinking should be boiled. Such warnings are heeded by the thinking citizen for at least six weeks after publication. Now, if gas is used to boil this water at $1 a thousand cubic feet, it may be estimated that the cost of making the drinking water safe during these six weeks will be about 21 cents per capita on the basis that a person will drink half a gallon of water a day. An ordinary gas-range burner will use about 20 cubic feet of gas per hour, and at least 25 minutes will be consumed in bringing a gallon vessel of water to a boiling point and in maintaining it that point until the water is sterile of bacteria. The per capita cost for boiling drinking water for six weeks may be roughly estimated as about the same as that given above as the annual per capita interest charge on the first cost of water-purification works, which will protect the water consumer from water-borne diseases not only at the time of epidemics but every day in the year.

COST OF OPERATION AND MAINTENANCE OF SLOW SAND FILTERS.

The cost of operating slow sand filters and maintaining them in good repair will vary considerably, depending on the size of the plant and on the character of water the works are called on to purify. In a general way such costs will average about $3 for each million gallons of water treated, a sum which does not include interest on the investment or pumping charges. For the sake of comparison the actual annual cost of operation of several slow sand filter plants is given.

ALBANY, N. Y.

The cost of operation of the Albany filter plant, which treats the frequently muddy water of Hudson River, is well shown in the following table. These data were kindly furnished by Mr. H. J. Deutschbein, superintendent Albany Bureau of Water.

Comparison of cost per million gallons of single and double filtration at Albany, N. Y.

	Single filtration, 1899–1907 (8 years).	Double filtration, 1910–11 (11 months).
Sedimentation basin: Removing sediment	$0.01	$0.03
Slow sand filters:		
Scraping sand	.17	.07
Removing sand	.33	.09
Washing sand	.27	.04
Replacing sand	.30	
Reforking sand	.03	.01
Wash water	.08	(a)
Incidentals and lost time	.38	.54
Removing ice		.03
Supplies and repairs	.13	.19
Total	1.69	.97
Preliminary filters:		
Attendance		.45
Washing sand		.08
Supplies		.05
Total		.58
Total cost of filtration	1.70	1.58
Pumping:[a]		
Enginemen and firemen	1.13	1.19
Labor	.13	.03
Supplies	1.26	1.36
Total cost of pumping	2.52	2.58
Office: Superintendence and watchmen	.50	.30
Laboratory:		
Chemist	.25	.24
Assistants	.01	.22
Supplies	.06	.10
	.32	.56
Total cost per million gallons	5.04	5.02
Average quantity filtered per day gallons	13,200,000	20,342,000

[a] Cost of wash water is included in cost of pumping.

PHILADELPHIA, PA.

The one hundred and eighth annual report of the Philadelphia bureau of water, F. C. Dunlap, chief engineer, gives the cost of operation of the four filtration plants now in operation in Philadelphia as follows:

Cost of operation of Philadelphia slow sand filters per million gallons of water filtered.

Plant.	Lower Roxboro.	Upper Roxboro.	Belmont.	Torresdale.
Average million gallons filtered daily	13	14	38	202
Prefilters: Cost for filter attendants, labor, maintenance, and repairs	$1.45	....	$0.60	$0.26
Final filters: Cost for office, filter attendants, sand handling, labor, and laboratory	2.79	$3.18	2.63	1.44
	4.24	3.18	3.23	1.70

PITTSBURGH, PA.

For the year ending January 31, 1911, the cost of operation of the Pittsburgh filtration works, according to Charles A. Finley, superintendent Pittsburgh bureau of water, was as follows:

Cost of operation per million gallons of water filtered at Pittsburgh, Pa.

Supervision, filter attendants, and laboratory	$1.39
Filter cleaning	2.00
Care of galleries, buildings, and grounds	.80
	4.19

The cost of filter operation at Pittsburgh, as shown above, was somewhat high in 1910, but recent improvements made in the sand-handling department will effect a substantial decrease in this figure for 1911.

WASHINGTON, D. C.

The cost for labor and supplies in the operation of the 75,000,000-gallon slow sand filter plant at Washington, D. C., is given for 1909–10 by Capt. W. T. Hannum, Corps of Engineers, the charge being itemized as follows:

Cost of operation per million gallons of water filtered at Washington, D. C.

Offices and laboratory	$1.13
Filter operations (sand handling, repairs, etc.)	.75
Care of grounds, etc	.53
	2.41

TOTAL COST OF SLOW SAND FILTRATION.

The statement has already been made that to construct slow sand filter plants will cost about $60,000 an acre. The net capacity of an acre slow sand filter is ordinarily about 2,500,000 gallons daily, which corresponds to a cost of $24,000 per million gallons capacity. Settling basins and filtered water reservoirs will increase this amount to about $30,000, which, at 6 per cent, corresponds to a fixed charge of $4.93 a million gallons. Adding to this a fairly average sum for operating cost makes the total cost for filtered water, exclusive of pumping charges, about $8 a million gallons.

On a basis of 125 gallons per capita daily consumption, the actual cost of water filtration would therefore be about 36 cents per capita per annum.

RAPID SAND FILTRATION.

GENERAL DESCRIPTION.

Rapid sand filtration first attracted attention as a method for purifying public water supplies in 1885, when a rapid filter plant was built to treat the supply of Somerville, N. J. Since that time this method has come into use in more than 350 cities in different parts of the world and supplies a total daily demand of considerably over 700,000,000 gallons. The largest plant of this type is installed at Cincinnati, Ohio, and has a daily capacity of 112,000,000 gallons. Others are located at Columbus, Ohio, capacity 30,000,000 gallons daily; Hackensack, N. J., capacity 24,000,000 gallons; Harrisburg, Pa., capacity 20,000,000 gallons; Little Falls, N. J., capacity 32,000,000 gallons; Louisville, Ky. (Pl. VI), capacity 36,000,000 gallons; Toledo, Ohio, capacity 39,000,000 gallons; and New Orleans, La. (Pl. VII), capacity 40,000,000 gallons. Among the larger rapid filter plants under construction in 1911, were those at Minneapolis, Minn., daily capacity 39,000,000 gallons, and at Grand Rapids, Mich., daily capacity 16,000,000 gallons.

Of the three score rapid filter plants in foreign countries the largest is that at Alexandria, Egypt, capacity 12,000,000 gallons daily. Similar works of even greater capacity are under construction at Kyoto, Japan, and at Cairo, Egypt.

The essential differences between rapid sand filters and slow sand filters are as follows: In the rapid sand filters, the filter units are much smaller; the sand grains comprising the filter bed are much coarser; a coagulant is always used in preparing the raw water for final filtration; the rate of filtration is in round numbers forty times that ordinarily used in slow sand filters; and the whole filter bed, when dirty, is cleaned in the tank itself by forcing water upward through the sand instead of scraping off the surface layers as in slow sand filters.

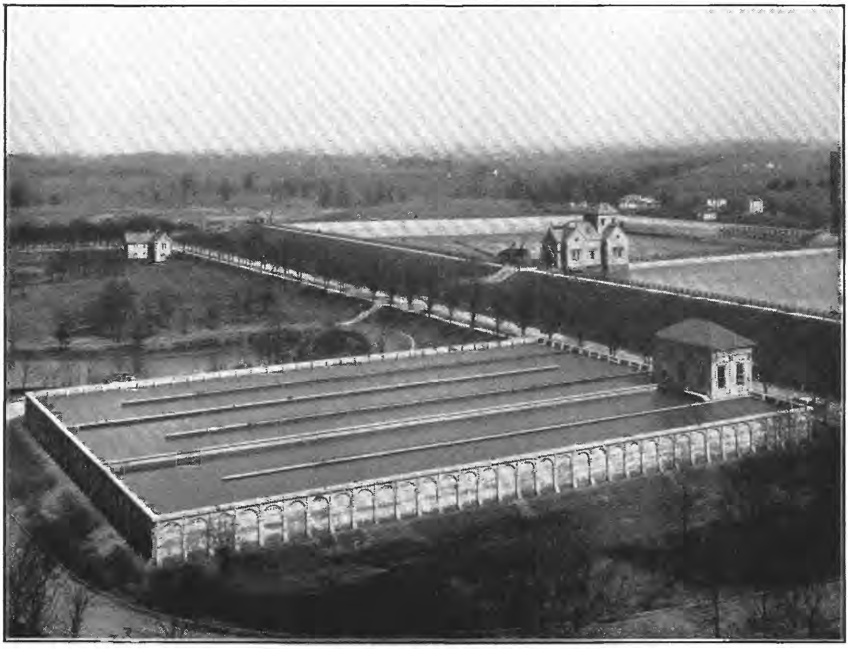
Up to 1902 rapid sand filters were of more or less uniform design. They were contained in wooden or steel tanks of comparatively small diameter, and the more economical concrete construction had not as yet been attempted. At the commencement of the classic investigations into this process of water purification, conducted at Louisville, Ky., under George W. Fuller, in 1895–1898, even the process itself had not proved its usefulness in the purification of large volumes of water. Provisions for adequate preparatory treatment of the raw water were rarely made, and the whole subject of the suitable design and operation of such works was but little understood.

The need of adjusting the design of rapid filter plants to meet local requirements began to be fully realized when the plant at Little Falls, N. J., was built in 1902 for the East Jersey Water Co. In this plant suitable provision was made for the accurate application of the coagulating chemical (sulphate of aluminum) to the raw water. A basin of adequate size was provided in which coagulation and sedimentation of the raw water could take place. The filter tanks themselves were built of concrete, for the first time, and were rectangular in plan. Improved facilities were installed for agitating the sand layer with compressed air during washing. Neat operating tables, from which all valves could be operated and motors started and stopped by hydraulic power, took the place of the less neat and convenient wheel stands. With the Little Falls plant the modern ideas of proper design for rapid filter plants began to be realized, and its construction marked a most important epoch in municipal water filtration.

Nearly all rapid filter plants are now built of concrete, although wooden and steel tanks are still used for small installations. The filter tanks are ordinarily built monolithic, and embedded in the floor of the tanks is the underdraining system, composed of perforated pipes or strainer cups, designed to permit the filtered water to pass out without allowing sand to escape and to permit an even distribution of water throughout the sand layer when the filter is being washed. Over the strainer system a shallow layer of coarse sand or gravel is placed, and on this rests the sand layer which forms the filter proper.

When the raw water has been sufficiently clarified by coagulation and sedimentation it is passed on to the surface of the filter, over which water ordinarily stands to a depth of several feet, and allowed to pass downward through the bed at a rate of 100,000,000 to 120,000,000 gallons an acre daily, such rates being automatically controlled by special devices. This corresponds to a rate of 2,310 to 2,760 gallons a day on 1 square foot of filtering surface.

The water applied to the filter always contains a considerable amount of coagulated matter, such as mud, vegetable stain, and bacteria, which is retained at or near the surface of the bed. As operation is continued the frictional resistance in the sand layer increases to a point where it is necessary to close the filter for washing. At such times the water standing over the bed is drained down to the level of the overflow gutters, which are located a foot or more above the



A. BIRD'S-EYE VIEW.

B. VIEW SHOWING DETAILS.

COAGULATING BASINS AT LOUISVILLE, KY.

Photographs furnished by Louisville Water Co.

FILTRATION PLANT AT NEW ORLEANS, LA.

sand layer, and filtered water is then forced upward through the filter, being evenly distributed by means of the strainer system. The material which has accumulated on the top of the sand is thus washed out, and the dirty wash water overflows into the gutters, thence to pass to the sewer. Such a washing operation ordinarily consumes about 10 minutes from the time the filter is closed down until it is again thrown into service.

The rapid filters just described are the type more commonly used; they are known as "gravity" filters and are contained in open tanks.

There is another type, known as "pressure" filters. Such filters are contained in closed steel shells. This type of filter is more extensively employed for household and industrial use, and in some places it is found to be more economical and convenient than the gravity filter. The largest municipal plants of the pressure type are located at Davenport, Iowa, capacity 9,000,000 gallons daily, and at San Diego, Cal., capacity 5,000,000 gallons daily.

COAGULATING CHEMICALS.

The chemicals most commonly used for the coagulation of water are compounds of aluminum and iron, and of these potash alum, sulphate of alumina, alumino-ferric, and sulphate of iron are the most extensively employed.

The manufacture of alum is of great antiquity, and for many centuries this chemical has been used in far eastern countries for coagulating water as an aid to clarification. The manufacture of aluminum sulphate from bauxite and alum clay is of more recent origin. The process of making alumino-ferric from bauxite was patented by P. and F. M. Spence in 1875. The sulphate of iron used in water coagulation is for the most part a by-product of iron and steel industries.

The choice between the different coagulating chemicals is properly based on their efficiency as coagulants, and this refers directly to the percentage of available aluminum or iron which they contain. Potash alum, sulphate of aluminum, and alumino-ferric cost about 1 cent a pound; sulphate of iron costs about half a cent a pound. In this country sulphates of aluminum and iron are the most widely employed in water purification, but at the waterworks at Tokyo, Japan, potash alum is used. Sulphate of aluminum is the coagulant in the works at Alexandria, Egypt, and also in practically all rapid filter plants in Europe, India, and Egypt, except at the waterworks at Calcutta, India, where alumino-ferric is used.

In composition these chemicals show considerable variation, but they may be bought on a basis of a guaranteed percentage of available alumina or iron oxides. The essential feature is that the chemical shall be basic, that is, shall contain more aluminum or iron than the equivalent of the sulphate radicle present. The approximate composition of these chemicals now on the market is as follows:

Approximate percentage composition of coagulating chemicals.

Constituent.	Pure potash alum.	Sulphate of aluminum.	Alumino-ferric.	Sulphate of iron.
Matter insoluble in water	....	0.30	0.06	0.50
Alumina (Al_2O_3)	10.77	17.00	14.26	....
Iron oxides (Fe_2O_3 and FeO)	....	.25	.60	57.50
Potash (K_2O)	9.93	....	....	....
Sulphur trioxide (SO_3)	33.76	38.70	35.81	28.80
Water (H_2O)	45.54	43.75	49.27	13.20

When potash alum, sulphate of aluminum, or alumino-ferric are applied to a turbid water the chemical is rapidly decomposed. The strong sulphate radicle of the chemical displaces the weak carbonate or bicarbonate radicle in the water, and an equivalent amount of carbon dioxide is liberated. The white, insoluble, and gelatinous aluminum hydrate that is formed absorbs the dissolved color and envelops and brings together into comparatively large aggregates the mud and the bacteria in the water. These flocks of coagulated matter are removed with comparative speed by subsidence.

Generally speaking, the application of these coagulating chemicals to a water will bring about a slight increase in the amount of incrustants in the water and a decrease in temporary hardness. The total hardness of the water—that is, the sum of the temporary hardness and the incrustants expressed in terms chemically equivalent—will remain unchanged. The increase in incrustants has some significance as regards corrosion of uncoated iron and incrustation in boilers; but, practically speaking, these are factors of comparatively little importance in view of the relatively small amounts of the coagulating chemical ordinarily employed.

Most surface waters naturally contain more than sufficient carbonate and bicarbonate radicles to make possible complete decomposition of the chemical which is applied for coagulation. In some waters, however, the natural alkalinity is so low, particularly at times of floods, that this is not true, and for such waters it is necessary to make up the deficiency by applying soda ash or lime water before the coagulant is added.

Sulphate of iron, known commercially as copperas, is obtained in two grades, namely, the ordinary commercial by-product from iron and steel manufacturing, and the higher-grade sugar copperas manufactured by a vacuum crystallizing process.

The use of copperas in water purification introduces more complicated features than alum compounds, chiefly for the reason that lime is required for the precipitation of the iron. When added to a natural water the copperas is decomposed somewhat like alum except that the formation of the hydrate of iron takes place very slowly. By adding lime in the form of limewater or milk of lime rapid formation of insoluble iron hydrates is induced. In general terms it may be stated that to obtain satisfactory results from the use of lime and iron as coagulants it is necessary to make use of sufficient lime to neutralize and precipitate the iron. The use of too little lime results in poor coagulation, caused by the incomplete precipitation of the iron, some of which is usually left in solution and appears in the effluent of the filters. The use of too much lime results in the formation of lime incrustants, which deposit in the air and strainer systems and cause much trouble through clogging.

Water treated with lime and iron will show an increase in permanent hardness, as compared with the effect of the use of compounds of aluminum. In general the aluminum salts are considered more satisfactory as coagulants; they remove color from water more rapidly and completely and make it possible to obtain by filtration a more brilliant water than do iron salts.

DEVICES FOR APPLICATION OF COAGULANTS.

No department in a filtration plant is more important than that wherein the coagulating chemicals are applied to the water. To obtain satisfactory results from the plant as a whole and the filters in particular, it is necessary that the application of the coagulating chemicals be at all times under strict and accurate control and be adapted to the quality of the water to be filtered. Material variation in the dose of the chemical applied to the water or in the quality of the water means overdosing or underdosing. The former results in a waste of the chemical and sometimes in undecomposed coagulant in the filtered water, and the latter results in incomplete coagulation and impaired efficiency. Owing to the high rates of filtration used in rapid filters undercoagulated water will leave the filter in a less purified state and will possess an undesirable turbidity. The filter will run longer without washing because of the slower accumulation of coagulated material, but the efficiency will be poor.

The different types of device for the control of the application of chemicals are very numerous and are all designed to be as nearly automatic as possible. The appliances which have given the best results are those wherein provision is made for the application of the solution under a practically constant head through an orifice which can be adjusted at will. The depth of solution over this orifice should not be less than 6 inches, and this depth may be maintained by allowing slightly more of the solution to be delivered into the orifice tank than is allowed to escape through the orifice, the excess being discharged back into the main solution tank through an overflow, or by means of a float valve (Pl. VIII, *A*, p. 60). The overflow is by all odds the more reliable.

The sulphates of iron and aluminum have a corrosive action on almost all metals, and it has been found advisable to make all of the metal parts which come in contact with the solutions of lead, copper, or special bronze. It is sometimes found advantageous to use hard rubber piping, valves, and orifices, but the cost may preclude the use of such material. Rubber piping and valves are easily broken, and the cost of replacement may prove no inconsiderable item. Generally speaking, however, the decision as to the kind of metal to use depends on the relative cost of the cheaper iron and its correspondingly higher cost for repairs and replacements and the ease with which repairs can be made, and the higher first cost of more expensive materials and the lower cost for upkeep.

IMPROVED DEVICES FOR OPERATING RAPID SAND FILTERS.

As already pointed out, it was not until 1902 that marked improvement was made in the direction of making easier the manipulation of valves and other apparatus, which has so much to do with the successful and economical operation of a rapid-filter plant. Until that time all valves, without exception, were opened and closed by hand. When a filter required washing, it was necessary to close the influent and the effluent valves, and to warm up the steam wash-water pump preparatory to supplying wash water to the filter. Now the operator moves a lever at an operating table, and by means of hydraulic cylinders valves are opened or closed with practically no manual effort or loss of time (Pl. V, *B*, p. 42). Electrically driven wash-water pumps have largely supplanted the steam pumps, and the operator starts and stops this pump merely by pressing a button at the same operating table. Air compressors, which supply air to the filters during washing for the purpose of agitating the sand layer, have in most large plants taken the place of the steam-driven rotary agitators, and these compressors are also started and stopped by pressing a button on the operating table.

As time savers these various improvements more than pay for themselves, and the neat appearance of the newer plants is a vast improvement over the older plants with their multitude of wheel stands.

FILTER WASHING.

When a rapid filter has become so clogged with coagulated matter that the normal rate of filtration can no longer be maintained, the influent valve is closed and the water standing over the sand layer is drawn down to the top of the wash-water gutters. The effluent valve is then closed and the wash-water pump is started. This pump forces filtered water up through the sand layer until it is freed of practically all of the accumulated matter. The pump is then stopped, the influent and the effluent valves are opened, and filtration is resumed. In some places the filters are washed by water delivered under the requisite pressure from an elevated tank. (See Pl. VIII, *B*, p. 60.)

During the process of washing a filter it is the practice in the majority of the newer rapid-filter plants to break up the sand layer with compressed air before turning in the wash water in order to facilitate and accelerate the cleaning of the sand grains. In some places, as at Cincinnati, Ohio, and New Orleans, La., no provision is made for agitating the sand layer during washing other than such agitation as is induced by the upward flow of wash water. In the older plants, and in some of those recently built, wherein the filter tanks are circular in plan, the sand is agitated during washing by means of rake teeth attached to arms which revolve, driving the teeth through the sand.

When washing a filter the rate of application of wash water must not be too low, and on the other hand it must not be too high, or sand will be carried from the bed with the wash water. Ordinarily the best rate of application of wash water is about 6 to 8 gallons to the square foot a minute, which corresponds to a vertical rise of about 1 foot a minute. This is equivalent to three to four times the rate of filtration. When wash water is driven upward through a filter bed of normal construction at these rates, the sand layer will rise from 3 to 5 inches, but practically no sand will escape from the bed except during the early stages of operation of a new filter.

Before the modern appliances for facilitating the labor of operation were installed it was not unusual for periods out of service for washing as great as 30 minutes to be recorded, and frequently the time consumed was even longer. In the more recent filters this period rarely exceeds 10 minutes from the time the effluent valve is closed until it is again opened.

CONTROL OF RATE OF FILTRATION.

If uniform rates of filtration are required for the successful operation of slow sand filters, then uniform rates are of even greater importance in rapid sand filters. The reason for this is plain. Slow sand filters are operated at actual rates of about 3,000,000 gallons an acre daily; rapid filters are operated at rates from 30 to 40 times as high as this. A sudden fluctuation in these higher rates means a correspondingly greater shock, and impaired efficiency naturally follows.

Although within certain limits there is no particular objection to the rate of filtration in a rapid filter gradually diminishing, a sudden increase in rate will cause an almost immediate deterioration in the appearance and hygienic quality of the effluent. If the rate increases or decreases slowly and steadily no harm may result, but should the rate increase abruptly, even as much as 20 per cent, the effect of the change will usually be apparent from the inferior appearance of the filtered water.

Therefore, to maintain a constant rate of filtration in the rapid filter, automatic controllers are always used. There are many such devices, but the object of all is to maintain a uniform rate of discharge from the filter independent of the head on the outlet pipe on which the controller is located. Although many improvements in these devices have been made in recent years, the best of them subject the filter to fluctuations in rate of at least 10 per cent. Furthermore, on account of the tendency of floats and butterfly valves in these controllers to stick, such fluctuations may occur within a very few seconds. In drawing up specifications for controllers it is frequently stated that such variations from the normal rate shall not exceed 2 per cent, but this requirement is rarely if ever met. Nevertheless the controllers do practically the work required of them, and without them a rapid filter would be unable to maintain a high standard of efficiency.

COST OF CONSTRUCTION OF RAPID SAND FILTERS.

It is almost as difficult to state the comparative cost of construction of rapid sand filters as of slow sand filters. Local conditions largely govern, and it is possible and feasible to build some plants much more cheaply than others, and at the same time obtain plants which will prove as efficient as those which are more complete and ornate. In illustration of the cost of such plants a few examples of existing works may be given.

LITTLE FALLS, N. J.

The plant at Little Falls, N. J., was completed and placed in operation in the fall of 1902, and here, for the first time, a radical departure was made in the construction of the filters, which are rectangular in plan and built monolithic of reinforced concrete. In fact, the entire plant, including the coagulating and the filtered-water basins, was built of concrete, as were also the walls of the buildings.

The works have a capacity of 32,000,000 gallons daily, and are capable, for short periods, of yielding 48,000,000 gallons daily. The works are so built that the raw water is led by gravity to the coagulating basin from a headrace canal taking water from Passaic River.

From the time the raw water enters the building until the filtered water is delivered to the main pumps which raise the filtered product to the distributing reservoirs, the flow is entirely by gravity. This made it possible to avoid the cost of extra pumping equipment but compelled the adoption of relatively expensive deep structures.

The coagulating and settling basin is 130 by 42 by 43 feet deep on inside lines, and has a capacity of 1,700,000 gallons, thus providing a period of coagulation of about one and one-third hours when the plant is working at its full capacity. The filtered-water basin, located beneath the filters, has an effective depth of about 18 feet and a capacity of about 3,500,000 gallons.

The filter tanks are arranged in two separate galleries over the filtered-water basin. In each gallery there are two rows of 8 filters each, making 32 filters in all. Between and beneath the two rows of filters in each gallery is a pipe gallery, above which is the floor on which the operating tables are located.

In the machinery room, located over the coagulating basin, are rotary blowers for supplying compressed air to the filters while being washed, pumps and devices for applying the coagulant, a storage room for the coagulant, laboratories, wash room, tool room, lockers, and offices. All machinery is operated by electric motors, and current is obtained from generators located in the main pump house.

The raw water is delivered to the filtration works through a 66-inch steel main, which discharges into a concrete standpipe 10 feet in diameter, located at one end of the coagulating basin. The coagulant is applied to the water in this standpipe and is discharged from the bottom into the coagulating basin. The clarified water is collected in a pipe at the other end of the basin and delivered to the filters.

The plant was built entirely by contract and cost as follows:

Cost of Little Falls rapid sand filter plant.[a]

	Total cost.	Cost per million gallons daily capacity.
Coagulating basin and clear-water basin, including piping within the walls and grading the grounds	$172,800	$5,400
Supply and suction pipes inside the structure	25,600	800
Filter tanks, including covers	48,000	1,500
Main building and wings, including floors, piers, and entire superstructure, except the last item	64,000	2,000
Filter equipment complete, including machinery within the buildings	153,600	4,800
Power equipment and outside wiring	25,600	800
	489,600	15,300

[a] Trans. Am. Soc. Civil Eng., vol. 50, 1902, p. 443.

BINGHAMTON, N. Y.

The plant at Binghamton, N. Y., which has a daily capacity of 8,000,000 gallons, was also completed and placed in operation in 1902. It was built by contract. The plant is contained in a brick building 180 by 53 feet, resting on concrete foundations and with a steel-trussed slate roof.

The coagulating and settling basins are two in number, are built of concrete, and have a daily capacity of 200,000 gallons. The filter units, of which there are 12, are each 21½ by 15 feet in area and are arranged in two rows between which is a pipe gallery, covered with an operating platform. The filter tanks are built monolithic of concrete. Beneath the filters is the filtered-water basin, which has a capacity of 350,000 gallons. This is a weak feature in the plant, for the reason that the service is by pumping direct into the mains, and the storage of filtered water thus provided is so small that it was deemed necessary to design the filter-rate controllers so that they might be opened wide in case of fire, an operating feature which must at times impair the efficiency of the plant.

The contract price of the plant, which included an engine room, two centrifugal pumps, tanks, and appurtenances for applying the coagulant solution, an air compressor to supply air to the filters while being washed, and a storage room for chemicals, etc., was $86,292, or about $10,800 per million gallons of daily filtering capacity.

NEW MILFORD, N. J.

The plant at New Milford, N. J., built by the Hackensack Water Co., which supplies water to the city of Hoboken and 33 smaller communities in New Jersey (total population served, about 250,000), was built in 1905 and has a capacity of 24,000,000 gallons daily.

The settling basin of excavation and embankment is 285 by 41½ by 20½ feet deep (height of the water line) and has a capacity of about 12,000,000 gallons. The filters are eight in number and built monolithic of reenforced concrete. Each filter tank is 46 feet 8 inches by 25 feet 10 inches by 9 feet 6 inches deep. The tanks are arranged in two rows on either side of a pipe gallery. Each filter has a capacity of 3,000,000 gallons daily.

The filtered-water reservoir is located beneath the filters. It is built of concrete, has a depth of about 12 feet, and a capacity of 1,200,000 gallons.

A novel feature in this plant is the strainer system. On each side of the central wash-water trough, with a main effluent collector in the center, are four strainer and collector units. The lateral collectors are oval passages 4 inches wide and 5 inches high, formed in concrete blocks which are each 5 feet ⅞ inch by 8½ inches wide and 9 inches high. These blocks, when assembled side by side, form a strainer floor, consisting of a checkerwork of square hopper-shaped depressions 3 inches deep. The bottoms of these depressions are 3 inches square and each supports a strainer, consisting of a square plate of sheet brass, perforated with 137 holes one-sixteenth inch in diameter, and pressed into the form of a flat truncated pyramid. Below the strainer is a pocket about 2⅛ inches square, connected with the lateral collector by a piece of ⅜-inch brass pipe. The strainer is fastened down with a ⅛-inch brass bolt, screwed into a special brass net, set in the concrete at the bottom of the pocket. Each of the eight units of the strainer system has a central main collector to which the oval lateral collectors connect.

The total cost of this plant was approximately $175,000, which included the buildings, filters, and equipment, clear-water basin, wash-water tank, and the necessary machinery within the filter building. Charges for engineering and the cost of the settling basin and of the main pumping station are excluded. The cost for each million gallons' daily capacity for the filter plant proper was about $7,300. When the cost of the settling basin and the charges for engineering are added, it is estimated that the total cost of the plant was about $11,000 per million gallons' daily capacity.

WATERTOWN, N. Y.

The Watertown plant was completed in 1904 and has a capacity of 8,000,000 gallons daily. The filter building is of stone, with slate roof and wooden floors. The filter tanks are eight in number, each 13 by 21 by 8½ feet deep. The coagulating basin and the filtered-water reservoir are located outside the filter building, are covered, and have capacities of 1,000,000 and 8,000,000 gallons, respectively.

The total cost of this plant, exclusive of low-lift pumping machinery, was about $90,000, or $11,250 per million gallons daily capacity. The plant was built by contract.

HARRISBURG, PA.

The Harrisburg plant is another reenforced-concrete plant, completed in 1905 (fig. 1). The capacity is 16,000,000 gallons daily. The coagulating basins are of earth excavation with concrete covers, are located outside the filter building, and have a capacity of 4,000,000 gallons.

The filter building is of reenforced concrete, with brick walls and slate roof, and contains 12 concrete filter units, each 16 by 27 by 9 feet deep. The filtered-water basin, beneath the filters, is of concrete and has a capacity of 700,000 gallons.

The total cost of the plant, including three 12-inch centrifugal pumps and pumping station, was $216,000, corresponding to $13,500

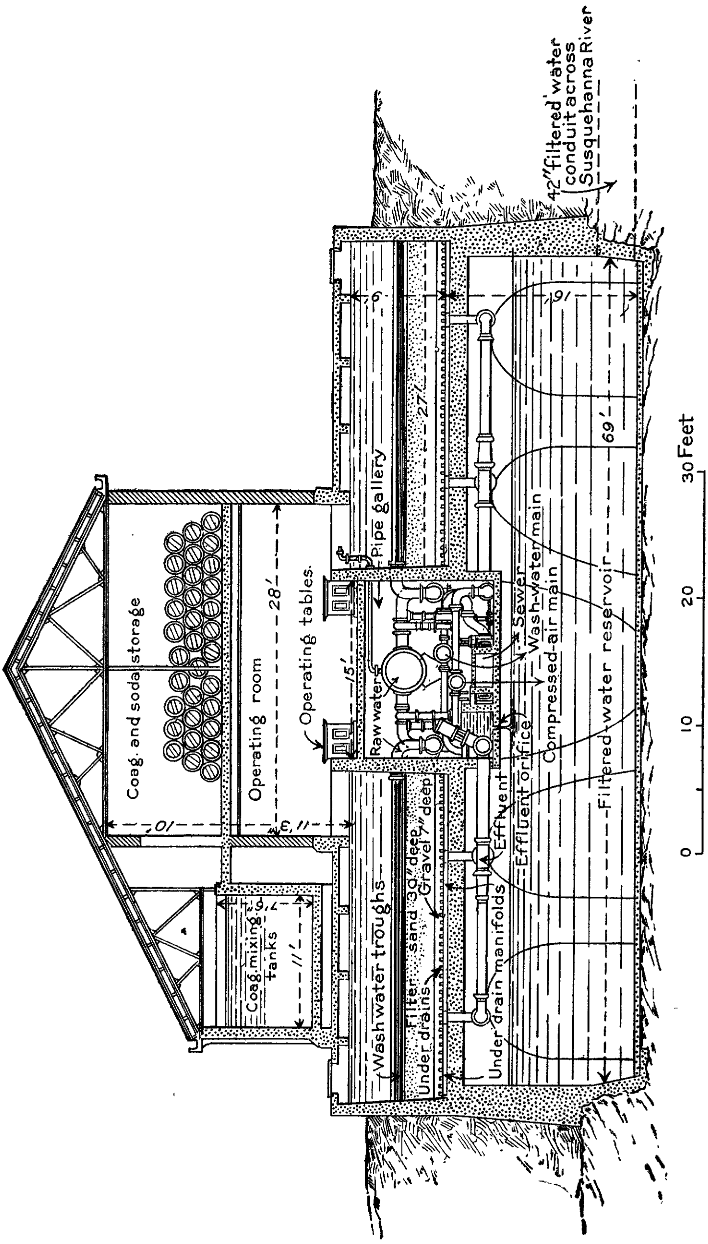


FIGURE 1.—Cross section through filtration plant at Harrisburg, Pa.

per million gallons daily capacity. Without the low-lift pumping station the cost was $164,590, or about $10,300 per million gallons daily capacity.

COLUMBUS, OHIO.

The combined water-softening and filtration works at Columbus, Ohio, were completed in 1906 and have a capacity of 30,000,000 gallons daily. The works are of reenforced concrete, and the buildings are of brick with tile roofs.

The main reaction chamber, wherein the bulk of the softening takes place, is of concrete and is located in the filter building. It is covered and has a capacity of 1,250,000 gallons. The main settling basins, outside the filter buildings, are 12 in number, all uncovered, and are built of concrete. They have a total capacity of 12,000,000 gallons.

The filters, of reenforced concrete built monolithic, are 10 in number, each unit having a capacity of 3,000,000 gallons daily. Each filter tank is 26 feet 2 inches by 46 feet 8 inches by 9 feet 6 inches deep. They are arranged in two rows, between which the pipe gallery is located. The main operating floor covers the pipe gallery, and on it are placed operating tables opposite each filter unit.

The filtered-water basin, built of concrete, is located underneath the filters and the pipe gallery and has a capacity of 10,000,000 gallons.

This plant was built entirely by contract and cost $556,000, a sum which included the softening works, with all of the various devices required for chemical application, and machinery exclusive of all pumping machinery. This outlay corresponds to $18,500 per million gallons. Excluding the cost of the softening works and making an allowance for the extra large settling basins required on account of the softening process, a fair estimate of the cost of the filtration works proper would be $13,000 per million gallons daily capacity.

CINCINNATI, OHIO.

Cincinnati has the largest rapid-filter plant in the world. It was completed in 1907 and has a capacity of 112,000,000 gallons daily. The filters and basins are built of concrete and the buildings of brick. The preliminary settling reservoirs have a total capacity of 330,000,000 gallons, corresponding to a period of sedimentation of nearly three days, when the plant is being operated at its full capacity. From these reservoirs the partly clarified water flows to coagulating basins having a total capacity of 22,000,000 gallons. These basins are so arranged that periods of coagulation may range from half an hour to five hours. The preliminary settling reservoirs and the coagulation basins are earth excavations, lined with concrete and faced with brick and asphalt. They are all uncovered.

The filters, with all appurtenances, coagulant apparatus, storerooms, laboratories, and offices, are located in a brick building with a flat concrete roof. The filter tanks, 28 in number, are divided into four groups of seven each by the pipe gallery. The tanks were built monolithic of reenforced concrete. Each filter unit is 28 by 50 feet in filtering area and has a capacity of 4,000,000 gallons daily.

The filtered-water basin is located outside the filter building and has a capacity of 19,000,000 gallons.

The total cost of the filtration works proper, as outlined above, was $2,681,601, being distributed as follows:

Cost of rapid-filter plant at Cincinnati, Ohio.

	Total.	Per million gallons—	
		Holding capacity.	Filtering capacity.
Preliminary settling basins, open, with piping connections to filters	$1,474,234	$4,467	$13,163
Coagulating basins, open, including piping	331,730	15,080	2,962
Filters, including buildings and piping	724,573	....	6,468
Filtered-water basins, open, including piping	151,064	7,951	1,349
Total	2,681,601	....	23,942
Total, exclusive of preliminary settling basins	1,207,367	....	10,779

LORAIN, OHIO.

The Lorain plant was built in 1907 and has a capacity of 6,000,000 gallons daily. The basins and filters are of concrete and the filter building is of brick with slate roof on steel trusses.

The coagulating basin is located partly under the filters and has a capacity of 580,000 gallons. The filters, six in number, are each 18 by 24.5 feet in filtering area, and each has a capacity of 1,000,000 gallons daily. The filtered-water basin has a capacity of 290,000 gallons.

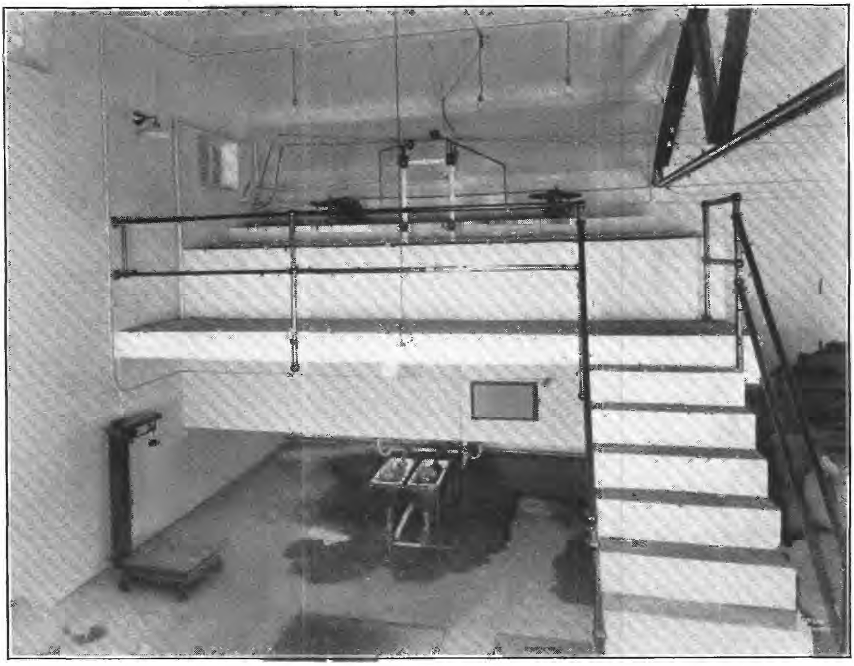
The total cost of the plant, including two low-lift centrifugal pumps, was $85,000, corresponding to about $14,200 per million gallons daily capacity.

SCRANTON, PA.

This rapid sand filtration plant (Pls. V, *B*, p. 42, and VIII), owned by a private company and completed in 1911, was built for the purification of the Providence supply, one of the sources of water supply of the city of Scranton; it has a normal capacity of 6,000,000 gallons daily.

The filtration plant is constructed throughout of reenforced concrete and the superstructure is of brick laid in Flemish bond. The roof is steel trussed and slate covered. The interior finish of the building is in white enamel.

A. WATER AND AIR STORAGE TANKS.



B. COAGULANT STORAGE AND FEEDING DEVICES

CHINCHILLA FILTRATION PLANT, SCRANTON, PA.

Photographs furnished by Scranton Gas & Water Co.

The coagulating basin, in duplicate, is baffled and has a capacity of one to two hours' flow. The coagulant storage tanks are also of reenforced concrete. The clear-water basin is located under the filters and discharges by gravity into Providence Reservoir. The filters are six in number and each has a normal capacity of 1,000,000 gallons a day when operated at 125,000,000 gallons an acre daily. There are two batteries of filters, three on a side, separated by the pipe gallery, which runs the length of the building. The valves are hydraulically operated. Automatic filter controllers of the Weston type are located on the filtered-water outlet of each filter.

The filters are washed by water pressure from an elevated storage tank, and during washing the beds are agitated with air from rotary blowers of the Sturtevant type. The level of wash water in the storage tank is kept practically constant by two Kingsford pattern centrifugal pumps, automatically controlled to start or stop according to the depth of water in the storage tank.

The particular feature which distinguishes this plant from other recent rapid sand filter plants is the manner of cleansing the sand layer. The elevated storage tank for supplying wash water to the filters is not new, but it is a great advantage to have the water level in the storage tank automatically controlled as in this plant, for this insures a uniform pressure of wash water at all times. The aerometer tank for storing air (Pl. VIII, *B*) is a distinct departure in rapid-filter practice, and the results which have attended the use of stored air have been most gratifying. The total cost of this plant was about $80,000.

SUMMARY.

The foregoing examples indicate that unless some unusual features are encountered, like the deep structures at Little Falls or the abnormally large preliminary settling basins at Cincinnati, the cost of a rapid-filter plant, exclusive of high-lift and low-lift pumping equipment, will be about $12,000 for each million gallons daily capacity. On the basis that the water consumption is 125 gallons per capita daily, the first cost to each consumer of such a plant would be about $1.50. At 6 per cent, the interest charges on such an investment would be 9 cents per capita annually.

The above-mentioned fixed charge on the cost of construction of rapid-filter plants is materially lower than that of slow sand filter plants, as would be expected. As a general proposition, it is not usually thought necessary to build large sedimentation reservoirs in which the raw water may be first settled before the coagulating chemical is applied and the water is allowed to flow into relatively small coagulating basins. Where turbid waters are to be purified by slow sand filter plants, large sedimentation reservoirs must be provided or preliminary filters made a part of the system in order to remove the bulk of suspended matter, which would speedily clog the slow sand filters and make the cost of operation of such filters unnecessarily high. The preliminary treatment factor has a great deal to do with increasing the first cost of construction of slow sand filter plants, and, furthermore, the much greater area of filtering surface required for these filters also explains why it costs so much more to build them. It must be borne in mind, however, that all figures of cost herein given are not to be considered as strictly comparable, but only as examples of what has actually been obtained in the construction in this country of filters of the slow sand and the rapid types.

COST OF OPERATION AND MAINTENANCE OF RAPID SAND FILTERS.

Range of cost.—In the cost of operation of rapid sand filter plants the size of the plant and the quality of the raw water are the main controlling features. Privately owned works are usually operated at lower cost than are those owned by municipalities. As a general proposition, however, the total cost of operation and maintenance of rapid sand filter plants, exclusive of the interest on investment and pumping charges, ranges in this country from about $3 to $5 for each million gallons of filtered water. For some plants the cost is even less than $3, and for others it is in excess of $5 for each million gallons. The following examples will show the cost of operation of several plants in this country.

Little Falls, N. J.—The Little Falls plant is now (1911) filtering about 30,000,000 gallons daily. The charge for superintendence and labor includes the salaries of the superintendent, one filter foreman, four filter attendants, an analyst, and a boy. On a basis of a yield of 30,000,000 gallons daily, the cost of operation for each million gallons of water filtered is as follows:

Cost per million gallons of water filtered at Little Falls, N. J.

Labor	$0.80
Coagulant	1.43
Heat	.35
Power	.22
	2.80

Binghamton, N. Y.—No itemized costs of operation of the plant at Binghamton, N. Y., are available, but it is understood that the total cost is about $6 for each million gallons of water filtered.

Harrisburg, Pa.—During 1910 the Harrisburg filters (fig. 1, p. 58) were operated at an average rate of slightly over 9,000,000 gallons a day. The cost of operation for each million gallons during 1910 was $5.31 and was divided up as follows:

Cost per million gallons of water filtered at Harrisburg, Pa., in 1910.

Labor	$2.52
Coagulant	1.06
Supplies	.28
Repairs	.38
Coal	.63
Oil and waste	.07
Laboratory	.37
	5.31

Cincinnati, Ohio.—During the year 1910, which was a representative year, the average yield of the Cincinnati rapid-filter plant was 49,000,000 gallons daily. The total cost of operation and maintenance was $4.19 for each million gallons of water filtered, this charge being made up as follows:

Cost per million gallons of water filtered at Cincinnati, Ohio, in 1910.

Supervision and attendance	$1.98
Coagulant	1.93
Repairs	.28
	4.19

TOTAL COST OF RAPID SAND FILTRATION.

It has been stated above that the average cost of rapid sand filter plants is about $12,000 for each million gallons daily capacity, which cost will include the necessary filter building, the filters, and the coagulating and filtered-water basins. At 6 per cent this cost corresponds to a fixed charge of about $2 for each million gallons. The addition to this charge of a fairly average figure for operation and maintenance makes the total cost of filtered water by the rapid sand filter system, exclusive of pumping charges, about $6 for each million gallons. On the basis of 125 gallons per capita daily consumption, the total cost of water filtration will be, according to these figures, about 27 cents per capita per annum. This estimate is approximate and is subject to considerable variation according to the conditions in various places. It is obvious that the larger the filter plant the lower will be the cost of operation per million gallons; and also that where waters require a great deal of coagulating chemical the cost of operation will necessarily be increased in proportion.

EFFICIENCY OF FILTRATION.

Slow sand filters will render water clear and practically free from turbidity and will remove a material percentage, probably from 20 to 30 per cent, of the dissolved color in waters stained by decaying vegetable matter. They are not able to treat successfully and economically the very muddy waters of the central western and the southern portions of this country unless such waters are first subjected to long periods of plain sedimentation or to shorter periods if coagulants are used. Rapid sand filters are capable of treating successfully practically all kinds of water, but are particularly applicable to the treatment of waters heavily charged with suspended matter or which are highly colored. The final effluent from such filters will contain practically no residual color or turbidity. Both types of filters will ordinarily remove all but about 1 or 2 per cent of the bacteria originally present in the raw water.

In the following table are given a few representative samples of the efficiency of slow and rapid sand filters in cutting down the typhoid-fever rate in communities where they are used. This is one of the best indices to the bacterial efficiency of filters. In addition to the reduction of typhoid fever effected by filters, it appears to be a fact that the death rate of a community is materially reduced by the substitution of a pure for a polluted water supply. At the International Engineering Congress, held at St. Louis in 1904, Allen Hazen made the following statement:[1]

> * * * Where one death from typhoid fever has been avoided by the use of better water, a certain number of deaths, probably two or three, from other causes have been avoided. This seems the clear and logical conclusion from the statistics. It is not easy to explain how the water is connected with the deaths other than those from typhoid fever. It may be that a good water supply, used freely and with confidence, results in a better general tone in the system of the population, and so indirectly to a lower death rate, and that a part of the reduction is represented by diseases having no recognized connection with the quality of the water supply.

Death rate from typhoid fever per 100,000 population in cities using filters.

City.	Kind of filter.	Plant completed.	Years, in average—		Typhoid-fever death rate—	
			Before filtration.	After filtration.	Before filtration.	After filtration.
Albany, N. Y	Slow	1899	10	10	90	21
Binghamton, N. Y	Rapid	1902	5	5	47	15
Cincinnati, Ohio	Rapid	1908	4	2	50	13
Columbus, Ohio	Rapid	1908	11	2	78	15
Lawrence, Mass	Slow	1893	7	15	114	25
Paterson. N. J	Rapid	1902	5	8	32	10
Pittsburgh, Pa	Slow	1907	8	3	133	[a] 26
Watertown, N. Y	Rapid	1904	5	5	100	38
York, Pa	Rapid	1899	2	8	76	22

[a] Filtered-water section. Allegheny not included.

STERILIZATION OF WATER.

RECENT DEVELOPMENT.

During the last three years (1908–1911) there has been developed a very efficient and entirely harmless method of sterilizing water. The chemical used is hypochlorite of lime or soda, the former being

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[1] Trans. Am. Soc. Civil Eng., vol. 54 D, p. 153.

obtained in the form of powder, known commercially as chloride of lime, the latter by electrolyzing solutions of common salt. As early as 1892 the efficiency of hypochlorites as water-sterilizing agents was more or less known, and the subject was studied quite exhaustively on a laboratory scale. Until 1908, however, the use of hypochlorites in the purification of public water supplies had not received serious consideration.

The first practical demonstration in this country of the usefulness of this germicide in connection with water purification was made at the filter plant of the Chicago Stock Yards, on the recommendation and under the direction of the writer, in the fall of 1908. Immediately following the spectacular results obtained at Chicago came the adoption of this process for the sterilization of the water supply of Jersey City, amounting to 40,000,000 gallons per day. The results obtained at these two places were given wide publicity and a large number of scientific articles have since been written setting forth the results obtained with this germicide in different localities and under varying conditions. At this time (1911) scores of cities are making use of it in the purification of their public water supplies, among which are many of the larger cities in North America, including Brooklyn, N. Y.; Cincinnati, Columbus and Toledo, Ohio; Harrisburg, Philadelphia, Erie, and Pittsburgh, Pa.; Hartford, Conn.; Louisville, Ky.; Minneapolis, Minn.; Indianapolis, Ind.; Montreal, Quebec; Hoboken, Jersey City, and Paterson, N. J.; Nashville, Tenn.; and St. Louis, Mo.

THE JERSEY CITY CASE.

Probably the most extended information regarding the hypochlorite treatment in the sterilization of water was obtained in connection with the litigation surrounding the Boonton plant, where the water supply of Jersey City has been treated with hypochlorite since the latter part of 1908. The water supply of Jersey City is derived from Rockaway River, the waters of which are impounded in a large reservoir at Boonton, about 23 miles west of the city. The reservoir has a storage capacity equal to over 200 days' supply at the present rate of consumption, and the water is conveyed from the point of discharge to Jersey City through an aqueduct of concrete tunnel and steel pipe. The sterilization plant is located in the gatehouse and immediately below the dam.

The works are owned by a private company, and several years ago the city raised the contention that the water supplied was not at all times pure and wholesome for drinking, as it was required to be by the terms of the contract. The opinion of the court, handed down May 1, 1908, was to the effect that, owing to certain combinations of circumstances, occurring perhaps two or three times a year, the water as delivered at Jersey City contained too many bacteria, that sewage bacteria were present, and that on these occasions the water was of doubtful quality. The court did not consider it necessary to filter this water, but held that the company was obliged under the contract to deliver water every day in the year which was free from matter deleterious to health for drinking or for other domestic uses. A sterilization plant was therefore built, being offered as a substitute for sewerage systems and sewage purification works in the communities located on the area tributary to the Boonton reservoir. After many months' operation of this plant, further testimony was heard by the court to determine whether the object sought had been achieved. This testimony, covering about 3,000 pages, was given before a special master in chancery, Hon. William J. Magie, and resulted in the following opinion, rendered May, 1910, which was later confirmed by the chancellor of the State of New Jersey:

> From the proofs taken before me of the constant observations of the effect of this device, I am of the opinion and find that it is an effective process, which destroys in the water the germs the presence of which is deemed to indicate danger, including the pathogenic germs, so that the water after this treatment attains a purity much beyond that attained in water supplies of other municipalities. The reduction and practical elimination of such germs from the water was shown to be substantially continuous.
>
> Upon the proofs before me, I also find that the solution described leaves no deleterious substances in the water. It does produce a slight increase in hardness, but the increase is so slight as in my judgment to be negligible.
>
> I do therefore find and report that this device is capable of rendering the water delivered to Jersey City pure and wholesome for the purposes for which it is intended and is effective in removing from the water those dangerous germs which were deemed by the decree to possibly exist therein at certain times.

HYPOCHLORITE OF LIME.

Hypochlorite of lime, commercially known as bleaching powder, has been and still is extensively used for bleaching in paper mills and many textile industries. It is commonly sold in the form of a white dry powder, and is usually packed in wooden or sheet-iron containers of a capacity ranging from 100 to 750 pounds each. It is manufactured at numerous places in this country as well as abroad, and in large quantities costs about 1¼ cents a pound at the works.

It is the custom to test the strength of the powder as received by taking a representative sample from the container and subjecting it to what is known as the Penot test, described in Sutton's Volumetric Analysis, ninth edition, page 173. Full details, many of which are taken from this publication, are given at the close of this section.

The chemical in the powder form consists of approximately equal amounts of chloride of calcium and hypochlorite of calcium; when added to water the former salt remains inert, whereas the hypochlorite of calcium, acted on by the free and half-bound carbon dioxide, splits up, with formation of hypochlorous acid. The decomposition of the extremely inert and unstable hypochlorous acid results in the liberation of oxygen in a very active state and of the the chlorine radicle. It is the liberation of oxygen in this way that effects the destruction of bacterial life by oxidation in a manner similar to the result effected when ozone is used.

The general result of the application to water of hypochlorite of lime is the destruction of the majority of the nonspore-bearing forms of bacteria, the oxidation of organic matter in general proportion to the amount of the chemical applied, and a slight increase in the total hardness of the water and in the total solid matter. Where the quantity used is no greater than from 5 to 15 pounds of the powder to each million gallons of water, such as is the common practice, the changes in the physical and chemical characteristics are so slight as to be barely noticeable. The important result and greatest change is the virtual destruction of bacterial life in the water, more particularly the germs of disease-producing origin, including the germs of Asiatic cholera, typhoid fever, etc.

HYPOCHLORITE OF SODA.

Hypochlorite of soda is obtained through the electrolysis of common salt, as already stated. A careful study of the relative efficiency of hypochlorite of lime from the bleaching powder and of hypochlorite of soda electrolytically produced shows that unit for unit hypochlorite of soda is slightly more efficient in the destruction of bacterial life. The process of manufacture of hypochlorite of soda is not so well understood in waterworks circles, however, but it is by no means an intricate process nor one which can not readily and cheaply be installed and operated. It appears certain that where electric current can be obtained for 1½ cents or less per kilowatt hour, and salt for one-third cent a pound or less, it will prove to be a somewhat cheaper germicidal agent than hypochlorite of lime.

Hypochlorite of soda has a number of advantages over hypochlorite of lime. Its use does not call forth the esthetic objections sometimes raised against the use of hypochlorite of lime, as there is no lime sludge to be disposed of. This sludge in hypochlorite of lime solutions contains about as much of the active agent as the solution itself, and can not be dumped indiscriminately into running streams or lakes without danger to fish life or without leaving unsightly deposits on the banks. Furthermore, such deposits have a tendency to clog the orifices in the chemical feeding devices, which does not occur with hypochlorite of soda solutions.

ABSENCE OF POISONOUS FEATURES.

It has been asserted that free chlorine is liberated in the hypochlorite process of water sterilization. In this connection it is well to point out that the term "available chlorine" is one of convenience used by analysts to express the strength of hypochlorite solutions, and was adopted years ago by industrial chemists for the reason that in bleaching operations at some places the commercial product was treated with strong acids which did break up the chemical and release free chlorine. There is abundant evidence to show that the weak carbonic acid found in natural water is incapable of releasing appreciable free chlorine from bleaching powder. Instead, hypochlorous acid, which is not a poison, is produced. Efforts have been made in the past by those who did not favor the process, to find a toxicologist who would classify this treatment as a poisonous one, but all such efforts have failed.

In the Jersey City case Prof. G. A. Hulett, of Princeton University, testified that in his examination of the Jersey City water, to which had been added 10 pounds of hypochlorite of lime to the million gallons of water, he was unable to determine the presence of free chlorine. He stated, however, basing his assumption on the theory of electrolytic dissociation, that it was theoretically possible for free chlorine to be present in the water after such treatment to the extent of 6.4 parts in a trillion parts of water. He admitted that he was unable to prove this assertion. It was furthermore pointed out in this case that if Prof. Hulett's theory was correct, in order for an adult to obtain a medicinal dose of free chlorine, such as occasionally administered to typhoid fever patients as an antiferment and germicide, it would be necessary for such a person to drink over 2,500,000 gallons of water so treated.

PREPARATION OF HYPOCHLORITE SOLUTIONS.

It is the more common practice to make up hypochlorite solutions of 0.5 to 2 per cent strength; that is, 1 to 4 pounds of bleaching powder to 200 pounds of water. It is probable that solutions as strong as 5 per cent may be used without material loss of oxidizing power, but the more dilute the solutions are the easier they are to work with.

For solution tanks concrete or iron appear to be the most suitable materials. Iron tanks last well, owing to protective coatings of lime deposited upon the exposed surfaces. Black iron pipes and special bronze pumps have lasted well in many places. Wooden tanks are the least suitable containers for hypochlorite solutions, but cypress seems to be the best wood if such tanks are to be used. White pine is reduced to a pulp in a comparatively short space of time.

When solutions of hypochlorite of lime are used, it is essential that they be thoroughly stirred in the beginning in order to get into solution all of the soluble parts of the chemical. After that stirring is not absolutely essential, but is convenient for keeping the sludge well distributed; otherwise it gives trouble as the last portion of the solution is removed from the tank. Solutions deteriorate but little on standing, perhaps 2 per cent in a day or two.

PERIOD OF CONTACT OF HYPOCHLORITE.

All of the data available indicate clearly that the germicidal action of hypochlorite is exceedingly rapid. As a general proposition it is thought advisable to provide for a period of contact of about one hour before the water is delivered to the consumer, but the actual period required depends largely upon the character of the water itself. It is also highly important that the chemical be quickly and thoroughly mixed with the water at the time of its application.

AMOUNT OF CHEMICAL USED AND POINT OF APPLICATION.

It appears clear that the best point of application of hypochlorite to a water depends largely on the surrounding conditions. In some places where there are filters it has been found advisable to apply it to the raw water, at others to the water as it flows to the filters. As a general proposition the evidence points strongly to the advisability of applying it to the filtered water. It is essential, however, that there should always be a sufficient period of time elapsing before the treated water is finally delivered to the consumer.

Generally from 5 to 10 pounds of the powder to the million gallons are required to effect practical sterilization of a satisfactorily filtered water. If the water is unfiltered or contains abnormally large quantities of organic matter, or contains dissolved iron, or iron in an incompletely oxidized state, considerably larger quantities of the germicide are required to obtain the best results. Some high-grade filtered waters are satisfactorily sterilized with less than 5 pounds of hypochlorite of lime to the million gallons of water treated and some unfiltered waters require as much as 20 pounds to the million gallons. Each problem must be studied in the light of the surrounding conditions and of data obtained in the very beginning bearing on the capacity of the water for absorbing the hypochlorite under the range of conditions usually encountered during an average year, so that the chemical may effect satisfactory sterilization without leaving behind an objectionable taste.

To aim at the complete sterilization of a water is not necessary. The object to be sought is the destruction of all disease-producing germs, such as those of typhoid fever. This can be done without effecting the destruction of all the bacteria in the water, for the reason that the typhoid bacillus is less hardy than most bacteria which naturally predominate in water and which are known to be nonpathogenic, and their removal, therefore, is not a matter of consequence. Hypochlorite is known to have a selective action on such germs as the bacillus of typhoid fever, and owing to their less resistant state in water it destroys them more quickly and completely. It is not uncommon to find that such bacteria as resist the hypochlorite treatment are spore formers and other hardy forms of nonpathogenic bacteria.

After preliminary study has established the amount of hypochlorite which must be added to a water in order to effect satisfactory sterilization under all conditions, it is the common practice to increase this quantity by about 25 per cent in order to guard against any sudden fluctuations in the character of the unfiltered water which may increase the power of absorption of the hypochlorite. Where the germicide is added to a filtered water such fluctuations are much less marked.

PRECAUTIONS AGAINST UNDERDOSING AND OVERDOSING.

It can be readily understood that if too little of the germicide is used unwarranted security may be caused, and also that for months the results may be thoroughly satisfactory from the use of a given amount of the chemical and that then, owing to a sudden change in the character of the water, unsatisfactory results may be obtained. For this reason it is always better to use more of the chemical than is required under all conditions.

Overdosing, on the other hand, is quite as undesirable. If the attempt is made to sterilize the water completely rather than to destroy the pathogenic bacteria, then there is strong probability that at times there will be imparted to the water a taste or odor which has been variously termed by laymen as similar to that of iodoform or carbolic acid. All of the evidence available seems to indicate that within working limits the presence of a small excess of hypochlorite in the water is not deleterious to health, but it is objectionable to the senses if it produces a noticeable taste, and is therefore inadmissible.

ADVANTAGES AND DISADVANTAGES OF THE PROCESS.

In making a complete analysis of the practicability of the hypochlorite treatment in the sterilization of public water supplies, it is necessary to recognize the fact that its field of accomplishment is limited. Its advantages and disadvantages may be set forth as follows:

1. It will not remove or destroy all of the spore-forming bacteria, but such germs are not considered to be pathogenic, at least those which are common in water. It will not remove bacteria which are contained in particles of suspended matter. It will effect the substantially complete destruction of objectionable bacteria, especially those of disease-producing qualities.

2. It will not remove turbidity nor appreciable amounts of color. nor dissolved vegetable stain, organic matter, swampy tastes, or odors. It will not soften water.

3. It can be reliably and easily applied, and it is not necessary under ordinary conditions to vary the dose, except at infrequent intervals. The cost of the chemical and its application are merely nominal and the speed of reaction makes unnecessary any extensive arrangement as to basins other than for storage. It is difficult of application, except with the greatest care, to waters which contain appreciable quantities of reducing agents or compounds capable of oxidation, such as nitrites and unoxidized iron.

4. The use of hypochlorites is attended by a total absence of poisonous features, either in the chemical product as applied to the water or in any of its resulting decomposition products.

5. It is possible with its use to effect a substantial saving in the cost of coagulation of waters that are of sufficiently unsatisfactory appearance to require clarification or filtration.

6. Its use permits rates of filtration materially in excess of those otherwise possible where high bacterial efficiency is required of the filtration process. It reduces the clogging of the filter beds and consequently lengthens the runs between cleanings. Particularly interesting information as to this line is recorded by Joseph W. Ellms, superintendent of filtration of the Cincinnati waterworks.[1]

These statements set forth the advantages and the limitations of this process, the application of which in water purification problems, though comparatively simple, should always be carried out with much care and fidelity. Otherwise, if the dose is not so adjusted as to meet satisfactorily all the local conditions, there is liable to be alternately an underdose of the chemical insufficient to sterilize or an overdose which will result in objectionable tastes and odors readily noticeable to the consumers and due to the chemical itself.

The use of hypochlorites can not be considered as a substitute for filtration. Where waters are uniformly satisfactory in appearance but open to suspicion as regards their content of bacteria, the use of the hypochlorite process alone may commonly prove sufficient. Where waters are unsatisfactory in physical appearance and are also polluted and require filtration, the combined use of filters and the

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[1] Eng. Record, April 8, 1911, p. 388.

hypochlorite process is called for. As an adjunct to filtration processes it has a distinct field of applicability, for at a moderate cost it insures a water above suspicion. Furthermore, there is brought about a considerable decrease in the first cost of the filtration plant. This is made possible by the use of higher rates of filtration, and the required filter area may therefore be reduced. It also effects a substantial economy in the cost of operation.

SOLUTIONS REQUIRED FOR TESTING BLEACHING POWDER.

The following notes may guide the operator in making the simple laboratory tests which are necessary in the hypochlorite treatment:

The solutions required to test the strength of bleaching powder are iodine, alkaline arsenite, with a starch solution used as an indicator.

Tenth-normal iodine solution.—Of chemically pure iodine take 12.7 grams and 18 grams of pure potassium iodide, free from iodate. Dissolve together in about 25 cubic centimeters of distilled water and dilute to a liter. The flask must not be heated in order to promote solution, or iodine vapors would be lost in the operation.

The iodine solution is best preserved in stoppered bottles, kept cool in the dark, and completely filled.

The iodine solution may be verified by titration against a tenth-normal solution of alkaline arsenite.

Tenth-normal alkaline arsenite solution.—The solution of alkaline arsenite is prepared by dissolving 4.95 grams of the purest sublimed arsenious oxide reduced to powder in about 250 cubic centimeters of distilled water in a flask, with about 20 grams of pure sodium carbonate.

The mixture needs warming and shaking for some time in order to complete the solution; when this is accomplished it is diluted somewhat, cooled, then made up to a liter.

In order to test this solution, 20 cubic centimeters are put into a beaker with a little starch indicator, and the iodine solution is allowed to flow in from a burette, graduated to tenths of a cubic centimeter, until the blue color appears. If exactly 20 cubic centimeters are required, the solution is strictly decinormal; if otherwise, the necessary factor must be found for converting it to that strength.

Starch indicator.—One part of clean potato starch or arrowroot is first mixed smoothly with cold water into emulsions and then gradually poured into about 150 or 200 times its weight of boiling water; the boiling is continued for a few minutes; then the solution is allowed to stand and settle thoroughly. Nothing but the clear solution is to be used as the indicator, of which only a few drops are necessary. The solution may be preserved for some time by adding a few drops of chloroform and shaking well in a stoppered bottle, but it is preferable to use a fresh solution each time.

TEST FOR STRENGTH OF BLEACHING POWDER.

The test for strength of the bleaching powder is best made according to the Penot method, as follows: The sample is well and quickly mixed; 7.17 grams are weighed and put into a mortar; a little water is added, and the mixture is rubbed to a smooth cream; more water is then stirred in with the pestle, allowed to settle a little while, and then poured off into a liter flask; the sediment is again rubbed with water, and poured off, and so on repeatedly, until the whole of the sample has been conveyed into the flask without loss, and the mortar has been washed quite clean. The flask is then filled to the mark with water and well shaken; 50 cubic centimeters of the milky liquid are taken out with a pipette and emptied into a beaker; and the N/10 arsenious solution is delivered in from a burette until a drop of the mixture taken out with a glass rod and brought in contact with prepared starch paper gives no blue stain.

The starch paper may be dispensed with by adding arsenious solution in excess and then starch, and then by titrating residually with N/10 iodine till the blue color appears. The number of cubic centimeters of arsenious acid solution used shows the direct percentage of available chlorine.

PREPARATION OF BLEACHING-POWDER SOLUTIONS.

In most of the work done up to this time it has been the custom to prepare solutions of the bleaching powder of about 0.5 to 2 per cent strength, by dissolving 5 to 20 pounds of the dry powder in 1,000 pounds (120 gallons) of water. The solution, after being well stirred, is sampled and this sample is subjected to the Penot test, as follows: Ten cubic centimeters of the solution of bleaching powder are placed in a beaker and N/10 arsenious solution is run in slowly, the contents being stirred continuously with a glass rod. At frequent intervals a drop of the solution is removed on the glass rod and brought into contact with the prepared starch paper. When no blue color is produced on the paper in this way the burette is read and the strength of the solution is figured as follows: On the assumption that—10 cubic centimeters of the solution of bleaching powder are used for titration, that 5 cubic centimeters of N/10 solution of alkaline arsenite solution are used up, and that 1 cubic centimeter of this N/10 alkaline arsenite solution equals 0.003545 gram chlorine; then—

5 cubic centimeters $\times 0.003545 \times 100 = 1.7725$ grams of chlorine per liter.

One liter weighs 1,000 grams, therefore the solution is 0.17725 per cent strong in available chlorine; also each cubic foot of the solution weighs about 28,500 grams, therefore, according to the assumption, 1 cubic foot will contain 50.5 grams (778 grains) of available chlorine. Where 10 pounds of bleaching powder corresponding to 35.45 per cent strength (as above) or 3.545 pounds of available chlorine, are applied to each million gallons of water, it follows that 30.6 cubic feet of such a solution as the above (0.5 per cent in bleaching powder) must be added during each 24 hours, for the reason that 3.545 pounds of available chlorine times 7,000 = 23,815 grains.

Each cubic foot of the solution contains 778 grains, then—

$$\frac{23{,}815}{778} = 30.61 \text{ cubic feet of solution.}$$

Such a dose of the chemical is equal to 10 pounds of the bleaching powder per million gallons; 3.545 pounds of available chlorine per million gallons; 0.788 pound of available oxygen per million gallons; 0.0238 grain per gallon of available chlorine; 0.407 part per million of available chlorine; 0.091 part per million of available oxygen.

The test may also be made by running in an excess of arsenite solution, adding starch, and titrating back with the iodine solution, as described above in the test for the strength of the powder.

MUNICIPAL WATER SOFTENING.

HARD-WATER SUPPLIES.

Hard waters—those containing high quantities of lime and magnesia in a dissolved state—are less desirable for domestic and industrial use than soft waters. Hard water produces scale in boilers, wastes coal, and shortens the life of the boiler. It is ill suited to the needs of many industries, particularly those in which chemicals are used, such as paper mills. Hard water wastes soap in the laundry and frequently makes necessary the use of washing soda or other compounds which have an injurious effect on some fabrics. It almost always affects the skin unpleasantly, and is more or less undesirable and uneconomical in various ways for general household use.

Waters which have a total hardness of over 50 parts per million (3 grains per gallon) are usually classed among the hard waters. Such waters as these are found in scores of cities in this country, particularly in regions where limestone deposits predominate. To illustrate this point a few examples are given of some of the hardest water supplies of this country. This is, of course, a very incomplete list, and could be added to almost indefinitely. The figures given for total hardness are necessarily approximate, for the hardness of a water naturally fluctuates widely during the year, becoming greater during the months of low stream flow and least during high-water periods.

Approximate total hardness of the raw-water supplies of some American cities.

	Parts per million.
Warren, Ohio	580
Shreveport, La	360
McKeesport, Pa	300
Dayton, Ohio	290
Columbus, Ohio	275
Toledo, Ohio	200
Oswego, N. Y	190
Philadelphia, Pa	180
Starke, Fla	165
Vincennes, Ind	165
Minneapolis, Minn	160
St. Paul, Minn	150
Lancaster, Pa	120
Quincy, Ill	105
Washington, D. C	100
New Orleans, La	95

Water softening is not widely practiced in America except by private industries. Among the cities where the public supply is softened may be mentioned Freeport, Ill., Oberlin, Ohio, St. Louis, Mo., McKeesport, Pa., New Orleans, La., and Columbus, Ohio, the municipal water-softening plant at Columbus, first placed in operation in the fall of 1908, being the largest and the most complete. For complete details of the chemistry of the water-softening problem at Columbus, the reader is referred to an article by A. E. Kimberly, published in the supplement to the Journal of Infectious Diseases, May, 1909.

DISSOLVED MINERAL CONSTITUENTS.

In problems of water softening, the most important features requiring thorough and reliable data are particularly the nature and the relative amount of the dissolved mineral constituents to the presence of which the water owes its hardness. Such data indicate, in large measure, the treatment of the water best adapted to its softening. With rare exceptions the hardness of water is due to the presence of calcium and magnesium radicles.

There are two kinds of hardness, temporary and permanent. Waters in which carbonate or bicarbonate radicles are equal or greater in reacting value than the calcium and magnesium may be almost completely softened by boiling and their hardness is known as temporary. Waters in which carbonate and bicarbonate radicles are less in reacting value than the calcium and magnesium can not be effectively softened by boiling. The removal of all the calcium and magnesium from such water can be effected only by the addition of chemicals that will cause the formation of insoluble calcium and magnesium compounds. Hardness corresponding to the excess in reacting value of calcium and magnesium over carbonate and bicarbonate radicles is termed permanent.

LIME AND SODA ASH AS SOFTENING AGENTS.

The process of softening water consists primarily in removing from it the calcium and magnesium radicles. This is accomplished with lime and soda ash by the formation of insoluble compounds of these radicles, but these chemicals also react with other substances in the water. The lime is introduced as calcium hydroxide and the soda ash as sodium carbonate. The effects are:

(1) Hydrogen (acidity) is neutralized, forming water; (2) carbon dioxide is changed to carbonate radicle and water; (3) bicarbonate is changed to carbonate radicle and water; (4) iron, aluminum, and magnesium form their insoluble hydroxides and fall as precipitates; (5) calcium present in the water and added as lime is precipitated as calcium carbonate; (6) the sodium of the added soda ash remains in solution in the water.

From the foregoing it appears that lime must be added in quantity sufficient to provide hydroxyl (OH) to combine with the iron, aluminum, magnesium, bicarbonate, and hydrogen radicles, and carbon dioxide. Moreover, if the carbonate radicle in the water plus that formed by the change of the bicarbonate radicle and carbon dioxide is not sufficient to precipitate the calcium present in the water and added as lime, a larger quantity must be provided by the addition of soda ash in order that all the calcium may be precipitated. This latter consideration determines the amount of soda ash to be added. In terms of pounds of 90 per cent lime (CaO) and 95 per cent soda ash (Na_2CO_3) per 1,000 gallons of water, these statements may be expressed in the following formulas:[1]

1. Lime required:

$$\begin{aligned}&=0.26(rFe+rAl+rMg+rH+rHCO_3+0.0454CO_2)\\&=0.00931\,Fe+0.0288Al+0.0214Mg+0.258H+0.00426HCO_3\\&\qquad+0.0118CO_2.\end{aligned}$$

2. Soda ash required:[2]

$$\begin{aligned}&=0.465(rFe+rAl+rCa+rMg+rH-rCO_3-rHCO_3)\\&=0.0167Fe+0.0515Al+0.0232Ca+0.0382Mg+0.462H-0.0155CO_3\\&\qquad-0.00763HCO_3.\end{aligned}$$

The formulas may usually be simplified for practical use by the omission of iron, aluminum, and hydrogen, for they are not often

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[1] The symbols of the radicles represent the number of parts per million of the various radicles, respectively, found by analysis. The symbol "r" represents the "reaction coefficient." The indicated product represents reacting value in parts per million. Thus, rMg represents the reacting value, in parts per million, of the proportion of magnesium found by analysis. See Stabler, Herman, The industrial application of water analyses: Water-Supply Paper U. S. Geol. Survey No. 274, 1911, p. 167.

[2] A negative value for this formula indicates that the water has no permanent hardness and that the use of soda ash is unnecessary.

present in sufficient quantity to affect the results. Total incrustants in parts per million (as determined by the standard method of the American Public Health Association) multiplied by 0.0093 will be practically equal to the value of formula 2.

MANUFACTURE OF LIME.

The raw material for the manufacture of lime is carbonate of lime, either as a natural limestone or in the form of the shells of mollusks. By subjecting the raw material to a temperature of 900° to 1,000° C., the carbonic acid is driven off and calcium oxide or quicklime is left.

There are two distinct types of furnace in use for the manufacture of lime, namely, periodic and continuous kilns. In the continuous system the kilns, once charged with alternate layers of limestone and fuel, are never allowed to cool down, resulting in great economy of heat. In this country more lime is perhaps burnt in kilns operated periodically. In this system the charged kiln, after the burning, is allowed to cool down, the lime is removed, and the kiln is recharged and reheated for the following run. In comparison with the continuous system, the periodic method of operation is uneconomical, owing to the losses involved in fuel and in time.

As the result of the burning a good limestone is broken into lumps; it suffers no change in volume, its weight and properties only being affected. The loss of weight during the decarbonization is about 50 per cent. Well-burnt and entirely satisfactory lime should be porous, nearly as hard as the original limestone, and should contain little, if any, magnesium and but inappreciable quantities of silica and iron. For softening water, economy and expediency demand that the highest grade of lime obtainable should be used. It is evident that for softening water the value of a given lime is dependent on the amount of available calcium oxide it contains. As lime is bought and sold on this basis for softening water, the chemical analysis should be the standard under all circumstances.

MANUFACTURE OF SODA ASH.

The manufacturing process of soda ash depends on the fact that bicarbonate of soda is insoluble in ammoniacal solutions of common salt. Common salt, ammonia gas, and carbonic acid gas constitute the raw materials. Strong brine saturated with ammonia is pumped to the top of carbonating towers and allowed to descend through iron baffle plates up through which a stream of carbonic acid is constantly flowing. Under these conditions bicarbonate of soda is formed and separates out, falling to the bottom of the tower, whence it is removed. The crude product is subsequently calcined, carbonic acid and water are driven off, and the pure normal carbonate of soda or soda ash is left.

Soda ash of a high degree of purity may be obtained in the market, and such soda ash alone should be used in all water-softening plants. The percentage of soda ash will vary from 95 to 98 per cent.

COST OF LIME AND SODA ASH.

The cost of high-grade lime and soda ash is subject to considerable fluctuation. Speaking generally, a high-grade lime, containing 90 per cent available calcium oxide or more, may be obtained for about $4.50 a ton in bulk in carload lots. Soda ash, containing upward of 95 per cent sodium carbonate, may be obtained in bags of 300 pounds each for about $20, or somewhat less, a ton in carload lots.

PREPARATION OF LIME SOLUTION.

It may be stated, practically without reservation, that it is advisable to use limewater for softening water. The reason for this is that limewater, being a true solution, is much more readily applied in uniform quantities than milk of lime. In water-softening plants which are operated on an intermittent basis it is possible to make use of milk of lime, owing to the fact that the application of the desired amounts of chemical may be kept under strict control. In plants which are operated on a continuous basis it is obvious that the effect of errors relating to the faulty application of lime must in a great measure vary inversely with the amount of water to be treated, or, in other words, with the amount of chemical to be used.

Although it is true that milk of lime is used in a small number of continuously operated water-softening machines of considerable size, the agitation factor is more particularly emphasized in such apparatus than would perhaps be feasible in larger plants. Without adequate mixing of the raw water and the milk of lime there is a marked loss in softening efficiency on the part of concentrated suspensions of lime, owing to the fact that the suspended particles of calcium oxide become coated over with the precipitating carbonate of lime and hydrate of magnesium, and thereby become inactive. With vigorous agitation this vitiating factor—the inactivity of a part of the lime suspensions—is greatly diminished, but doubtless it is still to be considered as important in proportion to the amount of suspended calcium oxide which the milk of lime contains.

From the evidence available it appears to be clear that limewater possesses distinct advantages over milk of lime in continuously operated water-softening plants for two reasons—first, because of the relative ease with which accurate and uniform application of this chemical may be maintained when it is applied in solution, and, second, because the softening efficiency of limewater is relatively higher. This second consideration involves questions of cost, which must be considered.

In a system of water softening operated on the continuous plan the device in which limewater is prepared is an important feature. In practice limewater is generally produced by diverting a portion of the raw water to the bottom of a tank or reservoir, sometimes known as the lime saturator, where it meets a continuous flow of cream of lime in slight excess of the quantity necessary to soften the raw water and to produce a saturated limewater. Thorough mixing of the cream of lime and the raw water is obtained by means of a stirring device situated at the bottom of the lime saturator. The raw water, softened to the fullest extent possible by treatment with cream of lime alone, becomes a saturated solution of lime. In order to obtain limewater which shall be practically free from undissolved lime and the precipitated salts of lime and magnesium the saturator is made sufficiently deep so that, as the water passes upward to the outlet at the top of the tank, the suspended matter will largely subside.

PREPARATION OF SODA-ASH SOLUTION.

Available evidence indicates that a 20 per cent solution of soda ash in hot water should be used. Such a solution has a specific gravity of 1.23. A solution of approximately this composition is made by dissolving 20 pounds of soda ash in 100 pounds of water.

LIMITATIONS IN WATER SOFTENING.

When once raw water, charged with carbon dioxide, has in its course over or through the earth become impregnated with calcium and magnesium there is no practical process applicable to municipal use which can restore the water to its pristine condition. The reactions and the resulting precipitation will vary in completeness with conditions of temperature, mixing, and sedimentation. Furthermore, the precipitates formed are not wholly insoluble. In a water softened under ideal conditions there may remain in solution 5.2 parts per million of calcium and 3.4 parts per million of magnesium, together with equivalent amounts of negative radicles, representing an alkalinity of nearly 30 parts per million. These figures may be increased by the presence of other substances, so that it is apparently certain that a water once hard can not be softened in a practical plant to less than 34 to 37 parts of alkalinity per million.

With regard to the permanent hardness, it is not generally thought economical or advisable to remove all of the incrustants. As soda ash, which is used for the removal of these constituents, constitutes one of the chief items of expense in softening a selenitic water, its use should be restricted to the lowest limit commensurate with the benefits to be derived therefrom.

FACTORS INFLUENCING THE SPEED OF SOFTENING REACTIONS.

The process of softening water requires considerable time for its completion. Chief among the factors that influence the rapidity with which the chemical reactions involved in the softening process may take place are the temperature of the water, the thoroughness of the agitation to which the water is subjected following the addition of the softening chemicals, and the maintenance in suspension of the precipitating salts during the period allowed for the reactions to take place.

It is a well-known and accepted fact that the majority of chemical reactions take place with relatively more rapidity as the temperature is increased. Those chemical reactions which are involved in water softening belong distinctly to this class. Cold weather during softening retards the process to such an extent that considerably more time is required for the completion than when the water is at a higher temperature; in extremely cold weather the maximum softening effect is often not obtained.

Even when the amounts of chemicals theoretically necessary for complete softening are applied to a given water, a satisfactory removal of the dissolved calcium and magnesium salts will not be obtained without thorough agitation. The importance of agitation in softening water has long been recognized, the means for effecting this end constituting an important feature in the design of the majority of proprietary water-softening machines.

It is a well-known fact that the presence in suspension of the precipitate previously formed or of that formed in the initial stages of the reaction generally assists materially the completion of the process, its success depending on the removal of dissolved substances by the formation of a precipitate as the result of chemical reactions. In water softening this matter is of particular moment, owing in large measure to the fact that the chemical changes involved are taking place in solutions of a high degree of dilution. The importance of the presence of the suspended precipitates throughout the course of the softening reaction has been recognized for many years, and many water-softening machines have been designed with the view of retaining these precipitates.

Available information indicates clearly that at the beginning of the softening process it is highly advantageous to apply the entire amount of lime required to the major portion but not to the total amount of the raw water to be softened. Mention has already been made of the fact that the maintenance in suspension of the forming precipitates materially accelerates the softening reactions. By overdosing a major portion of the water to be softened, the initial softening reactions are greatly accelerated. The action is particularly marked in the precipitation of the magnesium, which is much more rapidly and completely removed under the conditions outlined above than would otherwise be the case. Further, the indications are strong that by splitting the flow of water to the reaction chamber, overtreating with lime the major portion at the inlet end of the reaction chamber, and, some time after the application of the soda ash, introducing the minor portion of the raw water, the undesirable factor of residual causticity, true of all water-softening processes, would in a large measure be overcome.

In general, therefore, it may be said that the concentrated action of the total amount of lime on the major portion but not on the total amount of water serves to speed up and to render possible a more complete lime reaction, not only as relates to the removal of magnesium but also to the removal of the calcium.

ELIMINATION OF RESIDUAL CAUSTICITY.

In all processes of softening hard water in which lime or caustic soda are used as softening agents, there is a possibility that the softened product will at times contain an excess of free caustic alkali, owing to the frequent changes in the character of the raw water, or to carelessness or accident in the operation of the plant, or to the method of application of the softening chemicals to the raw water. Another condition instrumental in the production of a caustic effluent is the retarding effect caused by low temperature on the rapidity and completeness of the softening reaction. In systems of water softening where the period allowed for the softening reactions to take place is comparatively short, particularly where such plants are designed to furnish water for drinking, rigid precautions are demanded to overcome the occasional inevitable residual causticity. In some plants the matter is controlled by installing carbonating devices for the purpose of subjecting the softened water to the action of carbon dioxide. If properly distributed in adequate amounts through a water possessing causticity, this gas is effective in overcoming this inadmissible condition.

This process is known as "carbonating," the principle involved being the same in all devices designed to accomplish this end. The features essential to successful carbonating are the uniform rate of application of the gas, and the thoroughness with which it is disseminated through the water. Although the process is without doubt practicable for small water-softening plants, its use in large plants would probably entail too great an expense to justify its installation. Further, aside from the cost, which perhaps might be reduced, it appears that the application of the gas to large volumes of water would cause great uncertainties in this feature of the plant, which must be under perfect control at all times.

Causticity that the raw water can neutralize is obviously equal to the amount of caustic lime (or caustic soda) required to soften the water. As a substitute for the carbonating devices in use in small water-softening plants, the application to the softened water of a small percentage of raw water may be practiced. It is apparent that the percentage of raw water required for each part of free causticity which may remain in the softened water will be one hundred times the reciprocal of the number of parts of lime (CaO), required to soften the water. In other words, all unchanged caustic alkalinity which the softened water may contain will be neutralized by the addition of a small percentage of raw water, the caustic neutralizing power of which is at a maximum.

SEDIMENTATION OF SOFTENED WATER PRIOR TO FILTRATION.

Where river waters are to be softened, filtration usually follows the softening process. The necessity for the sedimentation of the softened water after the reaction period and prior to its filtration refers to the removal of an economical percentage of the precipitated salts of lime and magnesium, together with the suspended mud, silt, and clay carried by the water at flood seasons. It is clear that it would not be practicable or economical to apply to filters the softened water as it leaves the reaction chamber. As the precipitating salts are purposely held in suspension during the reaction period, the major portion of them passes out with the water as it leaves this chamber. The volume of this precipitate will be so great as probably to preclude the direct application to the filter of the water as it leaves the reaction chamber. Furthermore, at times when the river water carries high amounts of sediment, economy in filter operation demands that a period of sedimentation be allowed to intervene before such water is applied to the filter in order that a substantial removal of the mud, silt, and clay may take place in the settling basins.

For still other reasons it appears advisable to provide for several hours' subsidence as a means for compensating irregularities in the operation of a softening plant, namely, to guard against incomplete softening in the reaction period; to overcome uncertain factors introduced by winter weather, producing retardation of the softening action; to avoid the undesirable effect produced by possible after-reactions, which cause deposition of slow-forming precipitates on valves, boiler-water condensers, and the like, and to remove the esthetic objection introduced by the presence in the water, as delivered to the consumer, of small particles of precipitated lime and magnesium compounds.

INDEX.

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