CHAPTER XII

Plain Sedimentation

From time immemorial clarification of turbid water by subsidence has been practiced: first, as a household art; then, though rarely, on gravity water supplies brought down by masonry aqueducts; finally, since about 1800, on near-by turbid river supplies, lifted by pumping machinery. Rain water stored in cisterns has benefited by sedimentation, either incidentally or by design. Subsidence by repose has been aided by coagulation from early times, but until well into the twentieth century only on a small scale; recently its use has been on an increasingly larger scale and now is a concomitant of rapid filtration in thousands of water works of all sizes. During the progress of the art of water treatment, removal of color and bacteria, as well as turbidity, has been the object of sedimentation. This chapter, however, will be devoted chiefly to plain sedimentation.

Laodicea may have been the earliest city to have had settling reservoirs to clarify a turbid water supply brought to a city by an aqueduct. In or soon after 260 B.C., Antiochus Theos built an aqueduct some four miles long from the River Caprus to the city, crossing two shallow valleys on arches and a deeper one by twin inverted siphons of bored stone which at one point were under a pressure of about 60 psi. At the terminus of the aqueduct there were two chambers, one 46 × 46 ft. and the other 15 × 15 ft. in plan. A study, made about 1888, of the ruins led to the conclusion that the chambers were settling reservoirs (1).

Remains at Carthage of two many-chambered vaulted reservoirs have been repeatedly described by travelers who visited the site of ancient Carthage from the twelfth to the twentieth centuries. The date of these structures has been the subject of frequent archaeological discussions, particularly in regard to the "lesser cisterns," built for public use to supplement the innumerable private rain water cisterns. For present purposes it will be assumed that the public rain water cisterns were built by the free Carthaginians, before the Romans carried out their declaration *Carthago delenda est,* consummated in seventeen days of carnage in 146 B.C. With reasonable certainty it may be said that the "greater cisterns" at the lower end of the famous aqueduct were built by the Emperor Hadrian (ruled 117–138 A.D.) to supply the new Carthage built by the Romans in and after 122 A.D. Interest in both reservoirs is heightened by assertions that one or the other was used either for sedimentation or filtration.

The Arabian geographer Idrisi visited the ruins of Carthage in the twelfth century. He reported 24 rain water cisterns, built upon a single line, "the whole disposed geometrically, with great art" (2).

Five hundred years later Thomas Shaw, an English traveler, visited the site of Carthage (3). Besides the cisterns "appertaining to individual houses," he noted "two sets Belonging to the Publick." The smaller of these was at a higher elevation than the larger, "near the Cothon; having been cuntrived to collect the Rain Water which fell upon the Top of It, and upon some adjacent Pavements, made for the Purpose." He added that it "might be repaired with little Expence; the small earthen Pipes through which the Rain Water was conducted, wanting only to be cleaned." Fortunately, Shaw included in his published *Travels* a plan of the rain water cisterns, inserted in a map of ancient Carthage and environs. His plate, with the map curtailed and simplified, is here reproduced, as is also a view of the remains of the cisterns as they stood more than a century later. The general agreement of the plan and view is striking.

Dr. N. Davis, who explored the ruins of Carthage in 1860 and measured and described both sets of cisterns, states in his *Carthage and Her Remains* (4) that the lesser cisterns were beneath the outer walls of the later temple of Aesculapius, were eighteen in number, each $93 \times 19\frac{1}{2}$ ft. in plan, with their water line 17 ft. above their bottom and $10\frac{1}{2}$ ft. below the inner summit of their arched roof. They extended from northwest to southeast. Quoting now:

> On each side there is an arched gallery upward of six feet wide, which communicates with the cisterns, and was probably intended for the convenience of the public in drawing water. Originally there were six circular chambers with cupolas, one at each of the angles, and two in the centre. These may have contained statues, and served, at the same time, as a shelter for those who had charge of the cisterns. Our photographic sketch embraces the ruins of the only cupola still remaining, toward the western angle, as well as that portion of the cisterns upon which the decaying effects of time and the merciless grasp of the barbarian have told least. Near this cupola we obtain a good view of the central division of the whole range of cisterns, the first of which are either partly or entirely filled up, but the remainder are still in

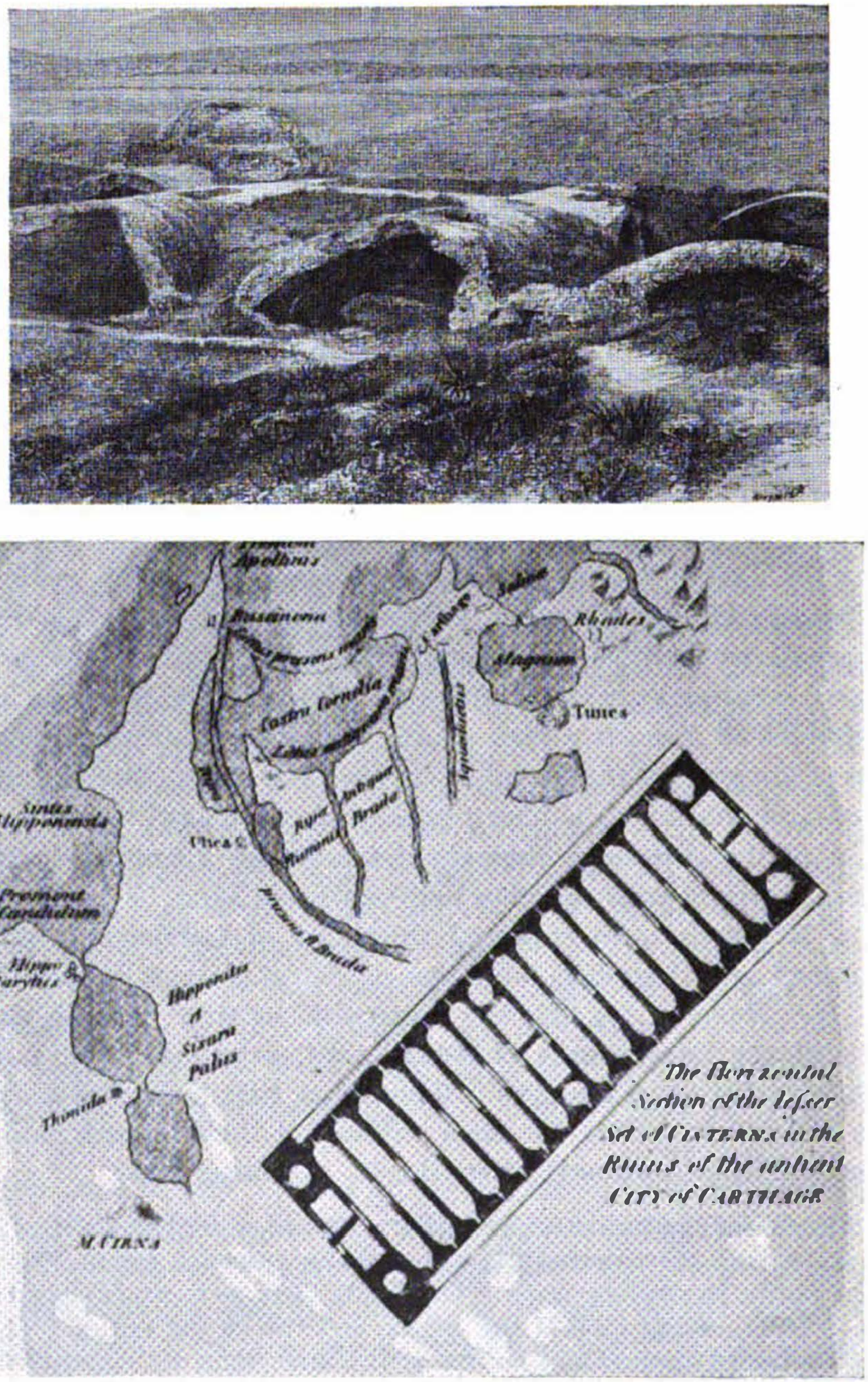

Fig. 59. Rain Water Storage and Settling Reservoirs at Ancient Carthage

Top: Ruins of rain water reservoirs; orientation agrees with plan below
Bottom: Plan, with map of Carthage and vicinity; chief objects on map re-lettered; end of later aqueduct shown
(Top view redrawn by Whymper from photograph in Davis's *Carthage and Her Remains,* New York, 1861; bottom plan from Shaw's *Travels,* Edinburgh, 1738)

excellent preservation, contain water to this day, and might be restored at a small cost. . . .

These cisterns, which appear to have been surrounded by a colonnade, were supplied by a vast terrace above, which collected the rain-water; and, no doubt, some of the edifices within the precincts of Aesculapius, so close by, also contributed toward filling them. (4)

Near by Davis found a subterranean aqueduct running toward the reservoir at the lower end of the aqueduct.

As seen by Thomas Shaw in 1738, "the grand Reservoir for the Aqueduct lay near the western wall of the City and consisted of more than twenty contiguous cisterns," each about 100 ft. long and 30 ft. broad (see more exact figures by Davis below). "Adjoyning these we see the first ruins [lower end] of the ancient and celebrated Aqueduct, which may be traced as far as Zow-wan and Zung-gar, to the distance of at least fifty miles [about 60] . . . two leagues to the Northwest of Tunis several of the arches are entire, which I found to be seventy feet high" (3).

Instead of the twenty cisterns seen by Shaw in 1738 Davis found only fourteen in 1860. Each was about 400×20 ft. in plan. Their depth he did not ascertain as they were filled to the level of the imposts of the arches with an accumulation of earth. Six or seven were entirely available for Arab dwellings, forming the village of Malkah. A fifteenth structure, which may have been a gallery rather than a cistern, abutted the group of cisterns at one end. It was about 18 ft. wide and had an arched roof a little higher than those of the cisterns. Remains of a conduit that once delivered water from the aqueduct to the cisterns were seen. Near by were the "immense ruins" of the aqueduct. Work was in progress for utilizing portions of the aqueduct (filling in gaps with iron pipe) to convey "the delicious water from Zoghwan spring . . . not to magnificent Carthage, but to the filthy, miserable and wretched city of Tunis" (4: pp. 362–63 and 269).

J. J. R. Croes, eminent American water works engineer, during a visit to Tunis in 1880 visited the lower end of the aqueduct and the site of one or both of the many-chambered cisterns or reservoirs. After describing the rain water cisterns he states that

———there is another great reservoir . . . divided into eighteen compartments, two evidently intended for filters or settling basins, and the rest for storage of the settled water. These reservoirs have been restored, and are now used for the water supply of the towns of Goletta and Marsa, water being brought to them from the hills of Zaghouan . . . utilizing for a portion of the way the magnificent aqueduct built 1,670 years ago by the Emperor Hadrian. (5)

Unfortunately Croes did not state his reasons for believing that two of the compartments of the reservoir were used for water clarification, nor whether this dated from their construction or was a modern innovation.

Audollant, writing on Roman Carthage twenty years later, declared, in general terms rather than by naming specific structures, that the Carthaginians built their cisterns in compartments so as to give "progressive filtration" (sedimentation?). He reviewed the statements and opinions of many writers on whether the rain water cisterns were built by pre-Roman Carthaginians or by Romans. Unlike Davis, who argued the subject at length, Audollent concluded that the rain water cisterns were of Roman origin (6). Careful study of all the data the author has seen, including rainfall and topography records and reports from other parts of North Africa, leads to the belief that the rain water cisterns were constructed by the Carthaginians.

Finally, Imbeaux's *Annuaire* of January 1, 1930, states that the aqueduct was constructed in the second century A.D. by the Emperor Hadrian to make up for the deficiency in the ancient cisterns in times of drought, and the report adds that it was cut by the Vandals in the fifth century, re-established after the Arab conquest, and finally plundered anew after the Turkish conquest of 1374. In 1859–64, says the *Annuaire,* the aqueduct was restored by Collin, a French engineer, and in 1886 by the Tunis water administration. Various portions of the aqueduct have been replaced or supplemented by modern types of conduits, including *"ciment armé centrifugé système Hume."* Another up-to-date practice of the Tunis water administration is the sterilization by "javellization" [chlorination] of its water supply (7).

At Rome, a settling reservoir at the head of one of the aqueducts, apparently put into use in 52 B.C., and *piscanae* located on the lower part of each of six of the nine aqueducts, are mentioned by Frontinus (8). His descriptions are the only contemporary engineering records of works built to improve the quality of a public water supply until long after the beginning of the Christian Era. Of the settling reservoirs, Frontinus says:

The intake of New Anio is on the Sublacensian Way, at the forty-second mile-stone . . . from the river; which flows muddy and discolored even without the effect of rainstorms, because it has rich and cultivated lands adjoining, and, as a result, loose banks; for this reason a settling reservoir was built upstream from the intake, so that in it and between the river and the conduit the water might come to rest and clarify itself. But in spite of this construction the water reaches the city in a discolored condition, whenever there are heavy rains. The Herculanean Brook, which has its source on the same way, at the thirty-eighth mile-stone, opposite the springs of Claudia and beyond the river and highway, joins it, being of itself exceeding clear, but losing the charm of its purity by admixture. (8: p. 19)

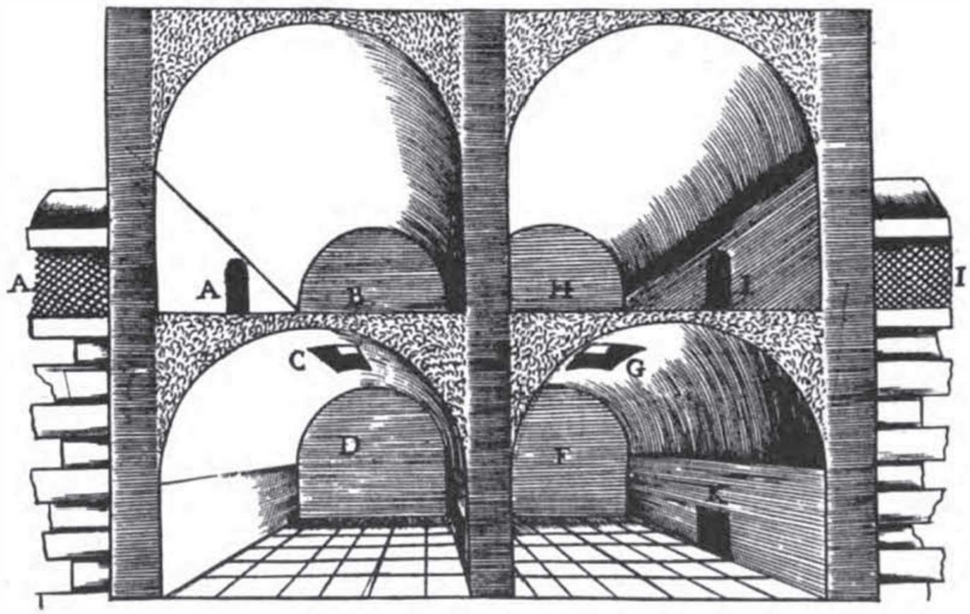

Fig. 60. Piscana on Roman Aqueduct Virgo

Two-story, four-chambered catch-basin; water enters upper left chamber *B* at *A*, drops through *C* to chamber *D*, passes through *E* to chamber *F*, rises through *G* to chamber *H*, returns through *I* to aqueduct; mud or slime passes through flood gate *K* to cloaca built by Tarquinus Piscus

(From Fabretti's *De Aquis et Aquaeductibus Veteris Romae*, Rome, 1680)

Further on Frontinus uses the following graphic language, in speaking of structures on some of the aqueducts:

Of these waters six are drawn into covered catch-basins [*piscanae*] . . . in which, resting as it were from their run and taking a new breath, they deposit their sediment. Their volume is also determined by gauges set up in these basins." (8: p. 21)

Clemens Herschel calls the *piscanae* "covered catch-basins," designed to intercept pebbles that came rattling down the aqueducts which, if not removed, would have plugged the lead service pipes of water consumers. He bases this conclusion, in part, on the fact that in a garden which he visited in Rome, the paths were paved with pebbles said to have been removed from a *piscana*. A model of a *piscana,* in a museum at Rome, was photographed by Herschel and is shown in his book (8: p. 199). It closely resembles the sketch here reproduced from Fabretti.

Vitruvius, writing about 15 B.C., after telling how to wall up wells and cisterns, says:

> If such constructions [cisterns] are in two compartments or in three so as to insure clearing by changing from one to another, they will make the water much more wholesome and sweeter to use. For it will become more limpid, and keep its taste without any smell, if the mud has somewhere to settle; otherwise it will be necessary to *clear it by adding salt* [author's italics]. (10)

Vitruvius seems to have had in mind clarification on the premises of the consumer. It would be interesting to know just what salt he had in mind and what specific examples of its use he could have cited in the first century before Christ.

When Caesar began his successful attack on Alexandria, in 47 B.C., he found the royal area of the city supplied with water brought from the Nile through aqueducts to private cisterns which afforded both storage and clarification. In these cisterns, says Hirtius (11), the water "settles by degrees, and becomes perfectly clear . . . the water of the Nile being exceedingly thick and muddy, is apt to breed many distempers."

At Lugdunum (now Lyons, France), the aqueduct system built by the Romans included three reservoirs with vaulted roofs. These were called settling basins in a lecture delivered by William Corfield, Professor of Hygiene and Public Health, University College, London, in 1873 (12). He states that they were on the hill of Fourvieres. One was 48 ft. long, 44 ft. broad and 20 ft. high. Water was admitted through two conduits. It is said that water was drawn through "several round holes in the roof." A second reservoir was 110 ft. long, 12 ft. broad and 15 ft. high, divided by a wall into two chambers. A third was described by Corfield as "large," and as having five of the supporting arches still in place. There was also a discharge conduit 1½ ft. wide from which lead pipes distributed water to the palaces and gardens. He does not give the date these reservoirs were constructed. It may have been 13 A.D. or later.

Modern Times

No more such settling reservoirs appear to have been constructed until modern times. The first one then recorded is notable because it is the earliest baffled settling reservoir to be described. It was apparently built late in the seventeenth century. Henry C. Engelfield reported in 1804:

> A most excellent arrangement for the purification of river water on a large scale is mentioned in the writings of De Luc or De Saussure, but I cannot turn to the passage in their works.* It was applied with complete success to the stream which supplied a large town in Switzerland (13).

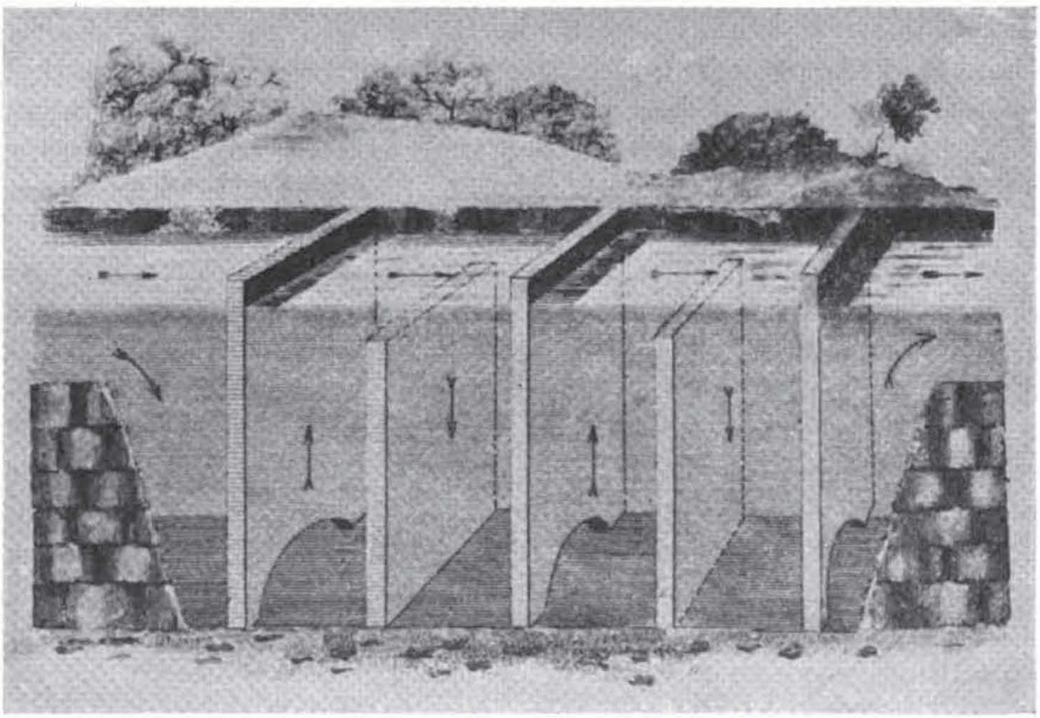

FIG. 61. BAFFLED SETTLING RESERVOIR IN SWISS STREAM
(From *Journal of Philosophy, Chemistry and the Arts*, October 1804)

A sketch of the device, here reproduced, shows a series of under-and-over baffles. By means of these, wrote Engelfield, "all floating

* Engelfield's forgotten source may have been one of the works of either Jean Andre Deluc, F.R.S., a Swiss geologist and meteorologist (1727–1817), or Horace Benedict de Saussure, a Swiss physicist and geologist (1740–99). Such of their works as I have located lack indexes. I have not seen de Saussure's *De Aqua* (1771).—*M. N. B.*

impurities will be left at the top, and the heavier mixtures will subside." To clean the reservoir, the partitions might be removed or a man sent down between the baffles.

The nineteenth century opened with three notable instances of sedimentation in Europe, all to lessen the burden on the earliest-known filters for public water supplies. At Paisley, Scotland, a ring-shaped settling basin surrounded the circular filters—the first known filters for general city supply—completed in 1804 by John Gibb. At Paris, two years later, a series of small settling chambers preceded the filters built by Happey on the Quai des Celestins. At Glasgow, in 1807, Telford built very shallow settling basins ahead of his ill-fated filters for a water company. About this time two proposals for settling reservoirs in Great Britain were made: the earliest, in 1804, by Ralph Dodd, a civil engineer of note, for two projected London supplies, another one, by Dr. Hope, in a report on an additional water supply for Edinburgh. These settling reservoirs were in lieu of filters, for which favorable sites were not available. (See Chap. IV for Paris reservoirs and Chap. V for the other reservoirs mentioned here.)

In the 1820's and 1830's, in Great Britain, sedimentation and filtration each had their supporters, with the former leading for a time and the two soon being joined. James Simpson, in the early stages of his investigations, held that settling reservoirs were inadequate and too costly for water clarification. He included a small one in his experimental plant at Chelsea but none in his pioneer slow sand filter plant in 1829 (see Chap. V). Some of the other London water companies put sole dependence on sedimentation for a time but either voluntarily or by Parliamentary mandate built filters before 1860.

In America, until late in the nineteenth century, reliance was placed on settling reservoirs rather than on filters of proper design and capacity, but most of the reservoirs were too small to do the work needed. The first American settling reservoir on record was a part of water works completed in 1829 for Lynchburg, Va. (14), but it should be remembered that up to 1825 there were only 32 water works in the United States, mostly in small places and supplied from springs or clear upland streams (15). The Lynchburg water works was notable both for its settling reservoir and for the pumping machinery that forced James River water to the reservoir under a 245-ft. head. The works were designed by Albert Stein. He it was who completed water works for Richmond, Va., in 1832, which included the unsuccessful first filter in America. Inadequate sedimentation preceded filtration at Richmond (see Chap. VI).

Turning briefly from America to France, we review some little-known experiments on sedimentation and the notable opinions of a French savant. Arago, reporting in 1837 to the French Academy of Sciences on Fonvielle's rapid pressure filter, mentioned experiments on sedimentation * made at an unstated date by Leupold at Bordeaux. The little that Arago said about the experiments is followed by remarks on the limitations of sedimentation which are as true today as they were when made a century ago. Quoting:

> From the very interesting experiments and calculations made at Bordeaux, by M. Leupold, we learn that after ten days of absolute repose, the water of the Garonne, taken at the time of a freshet, had not returned to its natural limpidity. At the commencement, it is true, the larger particles subside very fast, but the finer go down with a slowness which would put all patience at a stand.
>
> Simple repose then cannot be resorted to as a means of clarifying the water destined for the supply of a large city. Who does not perceive that eight or ten separate basins would be necessary for a day's consumption? Add to this that in certain places and at certain seasons, water exposed in a stagnant condition to the open air during ten consecutive days, would become foul and taste badly, either on account of the putrefaction of innumerable insects which would fall into it from the atmosphere, or in the consequence of the vegetation which would begin to take place on its surface.
>
> Repose, however, may be considered as one valuable means of getting clear of the grosser particles which are held in suspension. It is under this point of view *only*, that basins and reservoirs have been contrived and established in England and France. (16) (See also Chap. XIII.)

At Quebec, Canada, in 1848, a settling reservoir for a proposed water supply from either the St. Charles or the Montmorency River was considered. George R. Baldwin † reported that from what he had seen "waters more highly charged with sediment than either of these streams are very often allowed to enter the pipes of distribution in some of the large cities in England and Scotland. The character of the sediment here is probably a sand, coarser or finer according to the violence of the flood" (17).

* The date and further details of these experiments have not been found. They must, of course, have been prior to Arago's report of 1837.—*M. N. B.*

† Brother of Loammi Baldwin, better-known early American engineer. George had inspected water works in Great Britain prior to 1834 and perhaps subsequently. —*M. N. B.*

A settling reservoir for use only when the stream was muddy was built in 1854 by the borough of West Chester, Pa. It was 125 ft. square and was located at the pumping station on Chester Creek. This was perhaps the first American instance of a settling reservoir designed for occasional use only and one of few anywhere (18).

Two settling basins and a clear-water basin working in series were put into use at Augusta, Ga., on March 6, 1861. They received water from the local power canal leading from the Savannah River several miles above the city. In rainy seasons the water carried much clay in suspension. Water from the canal was admitted to a settling basin 10 ft. deep, passed to a 200 × 200-ft. basin, 15 ft. deep, then through ¼-in. joints in brick paving to a clear-water basin, also 15 ft. deep. The second basin was intended to contain a filter but the Civil War prevented its completion as such (19).

At Kansas City, Mo., a settling reservoir in two long, parallel compartments, with water from the Kaw River flowing lengthwise through one and back through the other, formed a part of water works built in 1874. Each compartment was 350 × 100 ft. in plan and 13 ft. deep. The combined holding capacity was 7 mil.gal. In a description of the reservoir published in 1887, Galen W. Pearson said that it differed from any he knew when he designed it, "in allowing the maintenance of a uniform water level in the subsiding reservoirs"—evidently meaning that it was operated on the flow-through rather than the fill-and-draw plan. He stated that sedimentation gave good results while the consumption did not exceed about 2 mgd. (3½ days' detention or less) with the important exception that in times of high turbidity "the water had really human aversion to settling" (20).

In or about 1887, a group of settling basins of 60-mgd. capacity was completed at Quindaro, on the Missouri River. The group was horseshoe-shaped, with three basins adjoining a smaller basin of similar shape. Water was admitted near the center of the bottom of the smaller basin. It was withdrawn over a weir at the farther end of the basin into a conduit and passed to the bottom of basin No. 2. From this it was withdrawn at the top and introduced into the bottom of No. 3. The process was repeated in No. 4 (21). Pearson was chief engineer of the National City Water Works Co., which built the works and operated them until they were bought by the city in 1895. Under Wynkoop Kiersted, as consulting engineer, the mode of operating the Quindaro settling basins was changed in

1898–99 by cutting long notches in the dividing walls so that the water flowed from basin to basin at the surface. A large additional basin was put into use in 1910, after designs by Kiersted. It was 600 ft. long by 480 ft. wide and had its bottom laid out as six rectangular flat inverted pyramids. A central pocket, with mud valve, was connected with a pipe leading to a main mud discharge pipe. The new basin was fed from the group of old ones through a 48-in. pipe, its center 5.65 ft. below the water surface. Besides, three 30-in. pipes were laid down the slope to permit feeding from the bottom. If desired, it could be used as a clear-water reservoir (22).

Before the additional basin was built, the use of a coagulant was begun. The first record of such use is in the annual report for 1902, which states that 670,000 lb. of alum were added to 5,467 mil.gal. of water during the year.

After having depended on sedimentation, either alone or aided by coagulation, for 54 years, the city put into use in May 1928 a rapid filtration plant, preceded by sedimentation and coagulation. Chlorination has been practiced since January 1911, beginning with hypochlorite of lime (23).

Other large American cities that were supplied from settling reservoirs before the days of coagulation and filtration included Cincinnati and St. Louis (see Chap. VI) and Omaha (see Chap. XIII).

The natural laws governing sedimentation were first studied in 1888 or 1889 by James A. Seddons, at St. Louis, Mo., preliminary to designing a new system of settling basins for that city. With these studies as a basis it was decided to adopt the fill-and-draw system. The general conclusions drawn by Seddons were:

> (A) The basins should not be covered. (B) In the time that could be allowed for settlement there would be no material difference in clearness from the top downward. (C) The time to be occupied in filling the basin could not be counted in the period required for ultimate clearing; for though a considerable quantity of the heavier sediment was deposited during the operation of filling, this filling must stop before the internal currents set up commence to die away. These internal currents were the controlling element in the final clearing of the water. (D) The size and shape of the basin would have little effect in retarding the internal currents. This retardation really depended upon the rate at which the initial motion was consumed by friction between the several interlacing internal currents; the effect of the confining surface upon these currents is simply a factor in the general results. (24)

Fifteen years later Allen Hazen wrote a notable paper on sedimentation. His introduction and final summary follow:

> Since Seddons published his paper on "Cleaning Water by Settlement" (*Jour. Assoc. Eng. Soc.*, 1889, p. 477) there has been but little published discussion on the theory of this subject, but the practice of building and operating sedimentation basins has advanced materially. For example, it has been found in St. Louis that continuous operation, that is to say, a continuous flow of water into, through and out of the basin, gives quite as good results as the intermittent operation which was studied by Seddons, and the new arrangement allows the effluent to be delivered at a higher level, the economic advantage of which is evident. The use of baffles has also been learned, and it has been shown clearly that a well-baffled basin will do as much work as a much larger basin without baffles. A discussion of the subject from a theoretical standpoint, in view of these developments, may lead to a better understanding of it, to the collection of better data, and to improvements in design.
>
> The processes which take place in sedimentation are extremely complex; to discuss them in their entirety seems hopeless. . . .
>
> The fundamental propositions may be very concisely expressed. They are: first, that the results obtained are dependent upon the area of bottom surface exposed to receive sedimentation, and that they are entirely independent of the depth of the basin; and second, that the best results are obtained when the basins are arranged so that the incoming water containing the maximum quantity of sediment is kept from mixing with water which is partially clarified. In other words . . . practically accomplished by dividing the basins into consecutive apartments by baffling or otherwise. (25)

A few other studies of sedimentation, more or less theoretical in character, together with hundreds of references to descriptions of plants, are listed in a bibliography published in 1938 (26). Many references to papers in the journals of the American and New England Water Works Associations may be found in their general indexes.

Chapter XI

Natural Filters: Basins and Galleries

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Chapter XII

Plain Sedimentation

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