2

Historical aspects of wastewater treatment

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2.1 INTRODUCTION

This chapter does not attempt to give a detailed history of wastewater treatment but instead to give an overview, point to the most significant developments and describe why we are where we are in the treatment of sewage. The paper is written from the viewpoint of a practising wastewater process engineer rather than that of an academic historian. It is assumed that the majority of readers are from a similar area of experience and so detailed explanations of the wastewater treatment unit processes are not included. A great deal of reference is made to history of developments in the UK, particularly to those in London. This is largely because the UK was one of the first industrialised countries and hence

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experienced the problems which result from very densely populated cities before many other countries. Mention is made of potable water supply and sewerage systems since they are intimately associated with the development of wastewater treatment, but they are not discussed in detail.

2.2 EARLY HISTORIC TIMES

The use of sewers is not new. In the Mesopotamian empire (3500 to 2500 BC) some homes were connected to a stormwater drain system to carry away wastes. In Babylon there were latrines which were connected to 18 inch (450 mm) diameter vertical shafts lined with perforated clay pipes leading to cesspools. However most people in Babylon threw debris including garbage and excrement on to the unpaved streets. The streets were periodically covered with clay, eventually raising the street levels to the extent that stairs had to be built down into houses.

In the Indus city of Mohenjo-daro (located in Pakistan) the wealthy as well as some of the peasants used latrines and cesspools. These were connected to drainage systems in the streets from whence the liquid flowed to cesspools or through drains to the nearest river. In some cases terracotta pipes were used to connect second-floor bathrooms to street sewers.

Archaeologists have found four separate drainage systems at King Minos' Royal Palace at Knossos (Crete), which dates from 1700 BC. The wastewater drained through terracotta pipes which were joined with cement into stone sewers. Rainwater-fed cisterns and stone aqueducts tapped available water sources to deliver a continuous flow of water through the bathrooms and latrines which eventually discharged to the Kairatos River. From 2000 BC the island of Crete had a drainage system made up of terracotta pipes with bell and spigot joints sealed with cement. The system conveyed mainly stormwater but also some human waste. Water stored in large jars was used to fill the system periodically. Wolfe (1999) states that many of the drains are still in use today.

There was a recent discovery of a stone lavatory with running water in a royal tomb from the Western Han dynasty (206 BC to AD 24) in the central province of Henan, China (Rennie 2000).

The Ancient Greeks (300 BC to 500 AD) tackled the problem of waste in a different way. They had public latrines which drained into sewers which conveyed the sewage and stormwater to a collection basin outside the city. From there brick-lined conduits took the wastewater to agricultural fields which used the wastewater for irrigation and to fertilise crops and orchards. The sewers were periodically flushed with wastewater.

A good review of the very earliest uses of sewers and waste disposal is given by Wolfe (1999) in the special issue of *World of Water 2000*. The reader is referred to that review for more detailed information.

2.3 ROMAN TIMES: 800 BC TO 450 AD

In about 800 BC the Romans constructed the Cloaca Maxima*,* the central sewer system, to drain the marsh upon which Rome was later built. The system took surface water to the River Tiber. By 100 AD the system was almost complete and connections had been made to some houses. The streets were still open sewers and, although many Romans used the public latrines, human wastes were still thrown into the streets. Water was supplied by an aqueduct system which carried away sewage and wastewater from the public baths and latrines thence to the sewers beneath the city and finally into the Tiber. The streets were regularly washed with water from the aqueduct system and the waste washed into the sewers (Wolfe 1999).

The Romans knew of the need for clean water and the need to dispose of wastewater away from the source of drinking water. In the UK they built their villas on the sides of hills where springs emerged from the hillside, and disposed of their wastewater to streams away from their villas. It has long been known that the Romans built brick-lined sewers in London (which they called Londinium). However, it has recently been discovered that these were preceded by wood-lined sewers which drained the water from the city to the River Thames. Pieces of the brick-lined sewers still exist.

2.4 THE SANITARY DARK AGES: 450 TO 1750

When the Roman empire collapsed their sanitary approach collapsed with it, since it depended upon far-reaching aqueducts and these needed effective government and the protection of a powerful army (Wolfe 1999).

During this period the main form of waste disposal (solid or liquid) in European cities such as Paris and London was simply to dispose of it in the streets. The terms ‘Tout a la rue’ (Paris), ‘All in the road’, ‘Gare de l’eau’ (Edinburgh) and ‘Gardyloo’ (Glasgow) come from that period. Often it was just thrown from windows and God help anyone who happened to be passing. This is the basis of the custom for the gentleman to walk on the side of the pavement closest to the road so that he could shield the lady from the splashing of passing carts and coaches and chamber pots of human waste which were flung from the second-storey windows which overhung the pavement.

Paris was founded upon the ruins of the Roman city Lutece in 360 AD (Wolfe 1999). Waste went into the streets where rainfall and heavy traffic helped it to decompose and it was picked over by pigs and wild dogs or collected by scavengers for fertiliser. In the thirteenth century King Phillipe Augustus ordered the city's roads to be paved to reduce the stench of the mixed garbage and sewage. However, once paved, the wastes could not break down to mud and in 1348 King Phillipe VI formed the first corps of sanitation workers to clean the streets. He also issued an ordinance that required all citizens to sweep in front of their houses and dispose of garbage to dumps. The first covered sewer was built in 1370 which dumped sewage into the River Seine near the Louvre. The French monarchy only took action over the sewers if affected by the smell. King Francois I moved his mother to the Tuilleries to escape the stench. In 1539, when plagues swept Europe, King Francois I ordered houseowners to build cesspools (indoor pit toilets) for sewage collection in new houses. These were constructed so that they leaked and did not have to be emptied often. These continued to be used until the late 1700s.

In London cesspools were in existence in 1189. The first Mayor of London, Henry Fitzalwyn, ruled that they be located no less than 2.5 feet (75 cm) from neighbouring buildings if made of stone or 3.5 feet (105 cm) if constructed of other materials (Wolfe 1999). Cistercian monks in the south of Scotland built stone-lined sewers to drain latrines in the monks' cells to the nearby watercourse. The clay pipes and brick-lined sewers put in place by the Romans in London were still in use but they were originally intended to take surface waters. Stephen Halliday, in his recently published book *The Stink of London* details the work done by Sir Joseph Bazalgette in providing sewers to cleanse Victorian London in the second half of the 1800s. In this he quotes a statement from *The Builder* journal written in 1884 which pointed out that as late as 1800 it was a penal offence to discharge sewage or any noxious matter to sewers that were meant for surface drainage only. The sewage of the city was to be collected in cesspools and their contents conveyed into the countryside for application to land. This was done in medieval times by 'rakers' or 'gong-fermors' who removed the foul sewage from the cesspools and sold it to farmers just outside the city walls. By the 1300s the city of Norwich, at that time the second largest city in England after London, was selling 'night soil' to farmers outside the walls of the city as fertiliser (Campbell 2000). Cesspools were built to drain into the street by a crude culvert, but when these became blocked the sewage spread under buildings and contaminated shallow wells and waterways that supplied drinking water. Several hundred thousand Londoners died from cholera, typhoid, plague and pestilence before the city realised that its own waste was causing the problems (Wolfe 1999). Overflowing cesspools could drain into neighbouring dwellings, causing poor families to live in houses saturated by their neighbours' excrement. Entire families were killed by asphyxiation from hydrogen sulphide coming from sewage collecting in or below their cellars.

In 1596 Sir John Harington had designed two water closets (called The Necessary) for Queen Elizabeth I but these did not achieve popularity until adopted by Londoners late in the 1700s. (Thomas Crapper in 1861 achieved long-standing fame for inventing a better flushing mechanism than his predecessors.)

2.5 THE AGE OF SANITARY ENLIGHTENMENT AND THE INDUSTRIAL REVOLUTION: 1750 TO 1950

2.5.1 The age of miasmas, disease, a shortage of safe water and development

This period is characterised by a high population growth in the new industrial cities, leading to high population densities (see Figures 2.1 and 2.2 and Table 2.1). The growth rate in London was extremely high, increasing from just under 1 million in 1801 to 2.8 million in 1861 (see Figure 2.2 and Halliday 1999) and to 6.5 million by 1900 (Lee 1997). The increasing death rates (Table 2.2) are now known to be related to water and waste-borne disease.

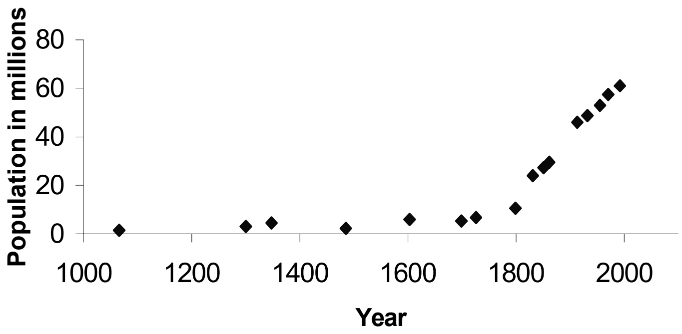

Figure 2.1. Increase in population of the British Isles over the last millennium (Lee 1997, 1999).

Table 2.1. Growth of population in new industrial towns. Yorkshire Wool Industry Towns (Stanbridge 1976)

	1801	**1831**
Huddersfield	15000	34000
Bradford	29000	77000
Halifax	63000	110000
Leeds	53000	123000

Table 2.2. Disease in the Industrial Revolution in Great Britain. Deaths per 1000 people (Stanbridge 1976)

	1811	**1841**
Birmingham	15	27
Leeds	20	27
Bristol	17	31
Manchester	30	34
Liverpool	21	35

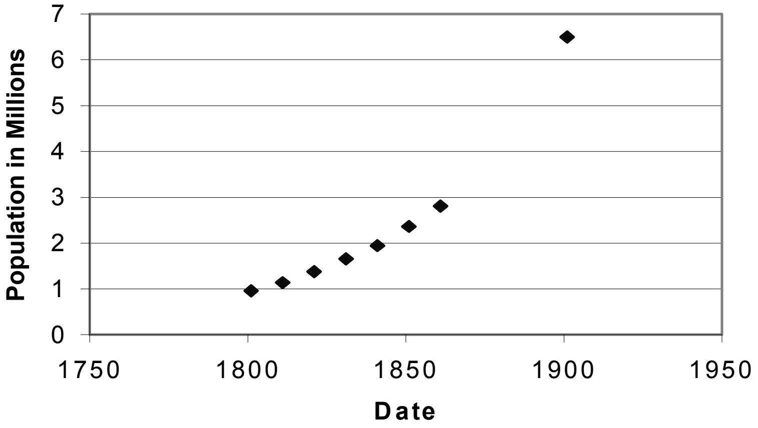

Figure 2.2. Growth of population in London in the 19th century (Halliday 1999; Lee 1997).

The early part of the nineteenth century (1820 to 1850) saw great debate as to how diseases like cholera and typhus was spread and what could be done to prevent it in the rapidly expanding cities and towns as the Industrial Revolution gathered pace. Outbreaks of cholera took place in other large European cities. This was the era of Miasmas. The belief was that that miasmas (noxious gaseous emanations and infections derived from the rotting waste which abounded in streets and public places) led to disease. In other words people were made ill as a result of poisoned air. This idea was put forward by the “Miasmatists”, who included Florence Nightingale and Edwin Chadwick. Another rival group, the “Contagionists” believed that disease was passed by physical contact, whether from human to human, or through the consumption of infected food or water. Drs John Snow and William Budd were amongst those who saw that infected drinking water seemed to be the likeliest source of disease and particularly cholera (Chartered Institute of Environmental Health 1998). The link was not established until later in the century but the developments in Europe and most particularly in the US were influenced by the English ‘Sanitary Idea’ in the 1840s (Melosi 2000) Filth and foul smells were thought to be responsible for epidemics. Whilst the miasmatic theory did not show the cause of disease, it did place a great deal of emphasis on the need for sanitation to combat the disease.

Melosi (2000) pays fulsome tribute to ‘the nineteenth century English civil engineers and sanitarians who became leaders in setting standards for water and wastewater systems throughout Europe and north America’. In particular he pays considerable attention to the work of Sir Edwin Chadwick (1800-1890), referring to the period up to 1830 as ‘Pre-Chadwickian’. Chadwick was a lawyer and journalist who was associated with Jeremy Bentham and other Philosophical Radicals known as ‘Utilitarians’ in the 1820s. He developed an interest in the condition of the London slums and whilst doing this contacted typhus, from which he recovered. He was appointed to the commission enquiring into the state of the Poor Law, which resulted in the 1834 Poor Law report. Chadwick took on the role of Secretary to the Commission and in 1842 produced the *Report on the Sanitary Conditions of the Labouring Population of Great Britain*. The report made the following recommendations:

- Provision of water supply to every house
- Use of water-closets over older systems (earth closets and privies)
- Discharge of domestic wastewater direct to sewer rather than to cesspools
- Sewers to also take solid refuse from streets
- Sewers, instead of discharging to watercourse, to convey sewage to an agricultural area away from town where its manurial value could be utilised. (This is now called land treatment.)

The report contained much background material and thinking. Here are a few snippets:

- It was ‘not customary to provide sanitary accommodation in poor areas and very few privies existed in crowded courts (yards)’
- 33 privies for 7905 persons in Liverpool
- 2 privies for 80 persons in Manchester
- waste in yards 6 inches (15 cm) deep

One major result that came from this report was the 1848 Public Health Act which set up Local Boards of Health and gave them the power to construct sewers.

Despite the success of the measures that he advocated, Chadwick was not a popular man. He was very determined and this meant that he created friction. One of the main reasons for his unpopularity was that he was the Secretary to the new Poor Law Commission, which had been set up to make the Poor Law Amendment Act 1834 work (Chartered Institute of Environmental Health 1998). The Poor Law was the first official form of social welfare provision in the UK but it was extremely unpopular. As an assistant commissioner, Chadwick had been instrumental in writing the report on which the act was based and hence it was natural that people should regard him as the architect of the monolithic, all-purpose workhouses designed to deter people from entering them. He had been against these huge establishments which could house up to 2,000 miserable people. He had wanted specialised workhouses for different needs and was concerned that children should be properly looked after. Charles Dickens was one of his chief critics and attacked him in newspaper articles and in *Oliver Twist*. Later in 1851 Dickens became a supporter of the Chadwickian reforms since his brother-in law, Henry Austin, a public health engineer and Secretary of the General Board of Health, was able to show the benefits of the Chadwick recommendations.

Chadwick proposed a hydraulic (or arterial-venous) system that would bring potable water into homes equipped with water closets and then carry effluent out to public sewer lines to be deposited as ‘liquid manures’ on to neighbouring agricultural fields (Melosi 2000). He also proposed the ‘backyard tubular drainage’ system in which sewage was drained from the backs (where the privies, latrines and water closets were placed) of back-to-back houses (being built in the poorer areas in the rapidly expanding cities) rather than putting the sewer connection through the fronts of the houses as was usual (General Board of Health 1852). He claimed that it would reduce the cost of sewer runs by two-thirds to four-fifths and allow the use of smaller sewers. This idea was taken up successfully 130 years later in Brazil (Mara 1999).

The water closet which began to be adopted by Londoners in the late 1700s gained tremendous popularity in the 1800s because of its ability, once connected to the sewer, to immediately remove human waste from the house, thus making cesspools no longer necessary. This improved the living conditions in homes but transformed the River Thames, from which most of the city's water supply was drawn, into a virtual cesspool. The water volume in the London drainage system almost doubled in the six years from 1850 to 1856 as a result of increased use of water closets (Halliday 1999).

Chadwick did not get everything his own way. In 1855, after another cholera epidemic, Parliament passed an act that established the Metropolitan Board Of Works to develop an adequate sewerage system for London. Joseph Bazalgette became the chief engineer. He was opposed to the Chadwickian idea of collecting sewage and using it on farm land. Instead he proposed a series of main intercepting sewers running east–west which collected discharge before it got to the Thames. He proposed that the discharge should all go to outfalls downriver from the city. His original proposal in 1856 was rejected because of the outfall location. Two years later the government reversed their decision as a result of the Great Stink of 1858 (Halliday 1999; Melosi 2000). Hot weather and the use of thousands of water closets created an ungodly stench lasting two years, caused by the putrefaction of sewage caught in the tidal reach of the river. Sessions of Parliament (located at the riverside) were only made bearable by hanging sheets soaked with lime of chlorine from each open window (Melosi 2000). The construction of the Bazalgette sewer system started in 1858 and was essentially complete by 1865. A total of 83 miles (133 km) of sewers were laid to drain an area of about 100 square miles (256 km^2). This was one of the examples of the principle 'the solution to pollution is dilution' which had been applied by the Greeks and Romans, but it was not until later in the 1800s that it was realised that it was not good enough to dilute and disperse, and that something would have to be done to remove the pollutants.

The Chadwickian ideas greatly influenced thinking in the US, especially in the east coast cities, including New York, which were growing at similar rates to some of the European cities. In 1845 Dr John Griscom, the New York City Inspector, produced a study, *The sanitary conditions of the laboring population of New York*. Over the next century there was a free exchange of ideas between the east coast cities and the large European cities.

Another major contribution at this time was made by Dr John Snow who was able to provide the link between disease and sanitary conditions, the solution to the link with miasmas. In 1849 he wrote an article 'On the mode of Transmission of Cholera'. He believed that it was transmitted by water contaminated by the vomit and faecal matter of cholera patients. He was able to prove the theory in 1854 when a severe bout of cholera occurred in London (Binnie 1999). He carefully documented the number of cholera deaths occurring in houses served by two of the city's water companies (which served a total of about 300,000 people (BBC 2001)). The two companies supplied water to people in the same areas of the city but derived their water from different sources. He showed that there were 315 deaths per 10,000 houses in the area served by the Southwark Water Company which drew its water from the heavily contaminated lower reaches of the River Thames. In the same period there were only 37 deaths per 10,000 houses served by the Lambeth Water Company which took its water from the upper reaches of the Thames. In particular he showed that in one area near the intersection of Cambridge and Broad Streets more than 500 people died of cholera in 10 days in 1854. After investigation he concluded that these were linked with water taken from the Broad Street pump. He had the handle removed from the pump and the epidemic was contained. In this study he also made use of microscopy and the work of Dr Arthur Hill Hassall (Bingham 1999). Figure 2.3 shows the course of the Broad Street outbreak. In fact it is clear from this figure that the epidemic was almost over. Dr Snow was well aware of this and the real significance of the removal of the pump handle was to prevent a second epidemic because there was a new cholera case in the house (which was later found to have been the source of the contamination of the pump) on the day that the handle was removed (BBC 2001). It is now known that cholera is caused by the bacillus *Vibrio cholerae* which thrives in warm and humid conditions. The whole progress of the disease can take as little as 5 to 12 hours but is usually 3 to 4 days. The incubation period is thought to be a minimum of 24 hours and a maximum of 5 days (Evans 1987).

At this period industrialisation was gathering pace in mainland Europe, in particular in the German states. Epidemics of cholera had periodically caused heavy loss of life in the large European cities for the same reasons as in London (Evans 1987). The first comprehensive sewer network in Europe was begun in Hamburg in 1848 by the English engineer William Lindley (Melosi 2000; Evans 1987). Lindley had gone to Germany in 1838 to construct a railway and then stayed to construct public bath- and wash-houses and then later the sewer network. He was a disciple of both Isambard Kingdom Brunel (railways and civil engineering, such as bridges) and Edwin Chadwick. Lindley was involved in the reconstruction of the city following the Great Fire of Hamburg and this allowed him to get agreement on the construction of a centralised sewer network. In November 1842 he travelled to London to discuss the latest ideas with Chadwick and to examine the progress made. He proposed a sewerage network for the central city of Hamburg in 1843 and this was finally accepted, with construction starting in 1848. The system came into operation in 1853 and the district of St Pauli was connected in 1859. By 1860 there were 48 km of sewers in the city but this network did not cover the new suburbs (Evans 1987). It was not until the 1890s that the municipal authorities could claim that all of the city was completely sewered. The last cholera epidemic was in 1893.

Lindley had included that the idea of wastes being sold to farmers as fertiliser was impractical. This system allowed tidal flow to flush out the main sewers once a week. It made a big impact and was the model for other European cities where English engineers were employed and in the US where it was the model for the New York and Chicago sewerage systems. Lindley was also involved in potable water supply and sanitation projects in Budapest, Warsaw, St Petersburg, Basle and Frankfurt, amongst others.

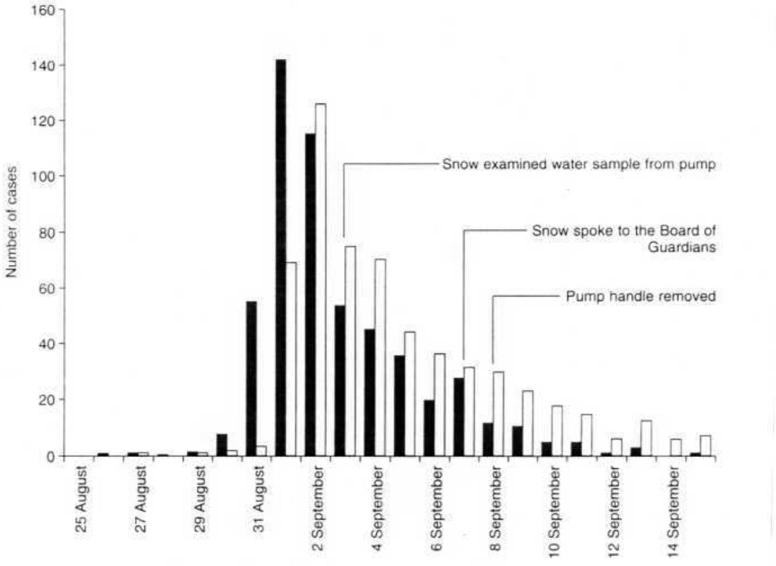

Figure 2.3. Onset of fatal cases of and numbers of deaths in the Broad Street outbreak.

2.5.3 Land treatment

Following the rapid expansion of the cities and towns the first treatment process applied was land treatment, a process which went back to Roman times and even into pre-historic times (Wolfe 1999). One of the first organised users was James Smith, a Stirlingshire cotton mill owner. He found that taking the excrement from his factory privies to his farm improved crop yields (Stanbridge 1976). In 1842 he moved to London and adopted the ideas of James Vetch for distributing sewage on the land by hoses and jets. These ideas were enthusiastically followed by Edwin Chadwick. He was greatly encouraged by Justus von Liebig, the eminent German chemist, who argued that the fertiliser value (particularly the phosphate content) should be used on agricultural land (Stanbridge 1976). Smith was appointed to the Commission on Health of Towns. A whole range of ideas modifications and process designs were used over the next fifty years. The large towns and cities bought more and more land for their sewage ‘farms’. To this day many sewage treatment works are referred to in common parlance as sewage farms. The use of land treatment continued into the twentieth century and the last system in the UK continued to be used until the 1980s. The systems were gradually abandoned because:

(1) They used large areas of land which became more difficult and hence expensive to purchase around the expanding towns and cities.
(2) The land suffered from clogging and waterlogging.
(3) They were unable to achieve the higher hygiene standards required.

2.5.4 Chemical treatment

Chemical treatment of sewage discharges had been used in Paris in 1740 using lime as the precipitant (Wardle 1893).

Between 1850 and 1910 there were several hundred patent applications for recipes for treating sewage. The purpose was twofold: (a) to treat the sewage to remove enough of the pollutant concentration to get it to the point at which the effluent could be safely disposed, and (b) to produce artificial guano. In the early 1800s the UK imported large quantities of the bird droppings from South America and the Galapagos Islands to fertilise farmland and improve cropping yields. It had been shown that sewage could improve fertility but the sewage was diluted and it needed large areas to apply. By using chemicals to enhance the settlement rate and recover more of the solids in a much smaller volume the sludge produced could provide the concentrated fertiliser. Hence it was thought that two problems could potentially be solved at once.

Chemical treatment was helpful in removing some of the polluting load but it had two main disadvantages: it could only remove suspended pollutants and this left about one third of the total pollutant load present in the treated sewage, and it produced a much larger quantity of sludge, which was difficult to dispose of.

When the biological processes (which removed dissolved pollutants as well as the suspended matter) came along at the end of the 1800s then chemical treatment gradually went out of use. It underwent a revival in the 1970s for the removal of phosphates, and continues in this role today (Culp and Culp 1971).

2.6 DEVELOPING THE BASIC TREATMENT PROCESSES: 1870 TO 1914

2.6.1 Primary settlement

When it first became practice to use farm land to treat sewage, trenches or pits were sometimes dug to remove the heavier solids prior to application, thereby reducing the load on the land. When they were filled they were covered over (Stanbridge 1976) and others dug. Possibly the first use of this was at Craigentinny Meadows in Edinburgh in 1829.

The next development consisted of flat-bottomed tanks which were sometimes clay-lined. It seems that these were operated on a fill-and-draw basis, with the removal of water by siphoning. In his patent of 1846 for lime as a precipitant William Higgs mentioned 'tanks or reservoirs in which the contents of sewers and drains from cities, towns and villages are to be collected and the solid animal or vegetable matters therein contained, solidified and dried' (Stanbridge 1976). Horizontal-flow tanks seem to have been invented in the 1850s and radial-flow tanks in 1905. Many of these systems had to be manually desludged with scrapers and squeegees. There were some bucket-and-winch operated systems for desludging in the 1850s and 1860s but true power-operated mechanical systems did not make an appearance until the 1900s.

In 1860, L.H. Mouras of Vesoul in France designed a cesspool in which the inlet and outlet pipes dipped below the water surface thus forming a water seal. This so-called 'fosses Mouras' was described by the Abbe Moigno in 'Cosmos les Mondes' in 1881 as it had been found that liquefaction of the solids took place, which was attributed to anaerobic action (Stanbridge 1976). This is a precursor of modern septic tanks. In 1895 Donald Cameron, the city Surveyor of Exeter, and F.J. Cummins patented a similar, but improved, system and Cameron called it a 'septic tank'. The process gained great popularity and one observer commented, 'Since the septic tank idea gained favour every designer of sewage tank has used the name septic for his tank, and apparently with good reason, for originally the word septic meant simply bacterial, just as the word anti-septic means anti-bacterial' (Melosi 2000).

The Imhoff tank, designed in 1906 by Karl Imhoff of the Emscher Drainage Board in Germany, was a further advance. This improved upon the design of septic tanks by using two chambers which allowed the separation of the settlement and sludge digestion processes. The system was so successful that Imhoff tanks comprised nearly half the total treatment works in the US by the end of the 1930s (Wolfe 1999), and it is still in worldwide use.

2.6.2 Biological filters

Up to 1900 virtually all the sewage treatment, where it existed, was carried out by land treatment. The farms were not always successful, as waterlogging was a major problem (Nicoll 1988). As the population continued to expand it became more and more difficult to find sufficient areas of land on the fringes of the towns and cities. The idea that there might be better ways, using ‘organisms’, gradually began to emerge. In 1870 Sir Edward Frankland established the fundamental principles of filtration through soil on which much of future developments depended (Second Royal Commission on Rivers Pollution 1870). In one of his experimental filters containing coarse porous gravel at Beddington Sewage Farm in Croydon, south of London, it was found that a rate of application of 0.045 m^3/m^3 of bed per day produced a well-nitrified effluent and that the ‘filter’ showed no signs of clogging after four months of operation (Stanbridge 1976). In 1882 Warington wrote that, ‘sewage contains the organisms for its own destruction, and these may be so cultivated as to effect the purpose.’ He went on to suggest the first idea of a filter bed which would have ‘a greater oxidising power than would be possessed by an ordinary soil’ (Nicoll 1988). He also suggested the use of a filter containing a more porous medium than natural soil (Stanbridge 1976). In 1887 William Dibdin (the chief chemist of the London Metropolitan Board of Works and later the London County Council from 1882 to 1897) stated that,

> …in all probability the true way of purifying sewage…will be first to separate the sludge, and then turn into neutral effluent a charge of the proper organism, whatever that may be, specially cultivated for the purpose; retain it for a sufficient period, during which time it should be fully aerated, and finally discharge it into the stream in a purified condition. This is indeed what is aimed at and imperfectly accomplished on a sewage farm.

This is probably the first statement of what is achieved by modern primary and secondary treatment. The idea that there might be a way of biologically treating sewage was revolutionary at the time, but the sewage farm did demonstrate that if sewage was passed through a sandy, gravelly soil it became less polluting and from this came the idea of ‘artificial ground’ which led on to the ‘contact bed’, and eventually to the modern biological filter (Nicoll 1988). After Warington’s suggestion (Warington 1882), Baldwin Latham installed ‘artificial filters’ at Merton, south of London, that contained alternating layers of burnt clay and soil (Stanbridge 1976). Between 1885 and 1891, various artificial filters were constructed across the UK.

The dramatic breakthrough in biological filter design for more reliable performance was made in the US at the Lawrence Experimental Station of the

Massachusetts State Board of Health (MSBH) which had been established in 1886. Local Boards of Health were set up in the US in the 1880s along similar lines as in the UK twenty years earlier. They were set up to combat disease in the rapidly growing cities.

Table 2.3 shows the very rapid rate of growth in population in the USA and the population served by sewage treatment in the period 1880 to 1920.

Table 2.3. Urban population in the USA 1880 to 1920 (from Melosi 2000)

Year	US population (million)	Urban population (million)	Population with sewage treatment (million)
1880	50.15	14.13	0.005
1890	62.95	22.11	0.100
1900	75.99	30.16	1.000
1910	91.97	41.99	4.450
1920	105.71	54.16	9.500

When it was set up, the Lawrence experimental station had been intended to conduct chemical analysis, but the association of drinking water with typhoid led the station to concentrate upon bacteriology (Melosi 2000) and then carry out tests on sewage treatment. They were evaluating the suitability of Massachusetts soil for oxidising organic matter in sewage. They confirmed Frankland’s finding that gravel was the best filtering medium and in November 1890 the first ‘trickling filter’ was commissioned (Stanbridge 1976). Following on from this breakthrough, there was rapid progress in the US and the UK. At first the systems installed were intermittent filtration and contact beds but soon they developed as continuous flow filters as we know them today. The contact beds developed in the 1890s were:

> …essentially tanks containing broken stones, slate or other coarse inert substances which provided a relatively large specific surface area for microbial growth. They were operated on a “fill-and-draw” basis, and bacteria on the filter bed decomposed the organic matter in the sewage. When the filter was empty, bacterial growth would be stimulated by the flow of air through the voids in between filter material’ (Wolfe 1999; American Public Works Association 1976).

One of the earliest biological filters was used at Salford near Manchester in the UK, in 1893 whilst the first in the US was used at Madison, Wisconsin in 1901. Between 1895 and 1920 many were installed to treat sewage from towns and cities in the UK. This rapid application had a negative effect upon the later implementation of the activated sludge process in the UK after it was invented in 1913. City and town councillors were reluctant to spend money on another new-fangled process when they had already committed taxpayers' money to the biological filter process !

From that time on it was a case of gradual development of the biological filter process which does not look too different today than it did in 1900. Many of the early 20th century systems are in operation throughout the world.

2.6.3 The Royal Commission on Sewage Disposal

In 1898 an important event occurred in the formation of the Royal (Iddesleigh) Commission on Sewage Disposal by the UK government. This commission was to write a series of ten reports between 1901 and 1915. The Royal Commission's eighth report in 1912 (Royal Commission on Sewage Disposal 1912) had significant effects since it was concerned with the standards (and testing methods) to be applied to the sewage and effluent being discharged to rivers. It recommended the so-called '20:30 standard', 'Royal Commission Standard' or 'general standard', which was copied by many other countries. This is a general standard of 20mg BOD_5/litre, 30 mg suspended solids/litre for effluent discharges from sewage treatment works. What is often forgotten is that this standard is specific to a dilution of at least eight-fold being achieved in the receiving water !

2.7 THE AGE OF PROCESS DEVELOPMENT: 1914 TO 1965

2.7.1 Activated sludge

Since about 1882 experiments had been carried out on the aeration of settled sewage but in the last two decades of the nineteenth century research efforts had concentrated on treatment by the promising biological filtration theories. In November 1912 Dr Gilbert Fowler of the University of Manchester visited the US in connection with the pollution of New York harbour (Cooper and Downing 1997, 1998). He was also employed as the consultant chemist to Manchester Corporation. On his return he described to his colleagues, Edward Ardern and William Lockett, some experiments that he had seen at the Lawrence Experimental Station of the Massachusetts State Board of Health, in which sewage was aerated in a bottle which had been internally coated with green algae. Tests had also been carried out in an aerated tank containing slabs of slate spaced 25mm apart. Fowler suggested to his colleagues that similar tests should be carried out in Manchester. He was keen on finding a clotting mechanism and had in 1913 worked with Mumford on the M7 mechanism (Ardern and Lockett 1914; Coombs 1992). This was a bacterium found in colliery workings which could help to precipitate organic matter in the presence of low concentrations of iron salts. During 1913 and 1914 they aerated sewage continuously for several weeks and achieved complete nitrification. Lockett allowed the treated liquid to settle and decanted off the supernatant liquid leaving behind the first activated sludge. The bottles were covered with brown paper to cut out light and prevent the growth of algae. Whereas other workers undertaking similar work had discarded the sewage in its entirety after the aeration, the Manchester workers then added further portions of sewage and aerated this in contact with the original settled solids. They found that after each of these aeration periods the amount of solids, now called sludge, had increased and that the period needed for oxidation of the matter in the sewage reduced until it was eventually possible to achieve complete oxidation in 24 hours (Institute of Water Pollution Control 1987). These tests were all done at the Davyhulme Sewage Works in Manchester using sewage from four different districts of Manchester plus a sample from Macclesfield. The results were discussed in the classic paper by Ardern and Lockett which was presented to the society of the Chemical Industry at the Grand Hotel, Manchester on 3 April 1914. During 1914 the process was scaled up to pilot plant scale at Davyhulme Sewage Works. Some of the tests were continuous-flow experiments and some used the fill-and-draw technique (which was a precursor of the modern sequencing batch reactors). The initial Davyhulme work was done with coarse-bubble aeration and later with fine-bubble aeration. Two years later the first full-scale continuous-flow was installed at Worcester (Coombs 1992; Institute of Water Pollution Control 1987).

In 1914 a large-scale test had been carried out at Salford using the fill-and-draw technique. It is interesting to note that these fill-and-draw plants achieved full nitrification and there was no problem with sludge settlement or bulking. By the time that the first book was written on the activated sludge process (Martin 1927) the process was being used in the US, Denmark, Germany, Canada, the Netherlands and India (Professor Fowler had gone to work at the Indian Institute of Technology).

The first British city to fully apply the activated sludge process was Sheffield in 1920. By contrast, its application in the US was far more rapid. The reason for this was because following the First World War capital for investment was very limited in the UK and because all the major cities had already invested in sewage works based on the biological filter process in the period between 1890 and 1910. Hence the major activated sludge works at Mogden in London (which served 1.25 million people), Davyhulme in Manchester and Coleshill in Birmingham were not built until 1934 or 1935. In the US, by contrast, many of the activated sludge plants were the first form of sewage treatment ever used.

Large-scale tests (500m^3/day) took place at San Marcos in Texas in 1916. This was followed by full-scale tests at Houston, Texas (40,000m^3/day) in 1917, Des Plaines, Illinois (20,000m^3/day) in 1922, Milwaukee (170,000m^3/day) and Indianapolis (190,000m^3/day) in 1925 and then in Chicago North (660,000m^3/day) in 1927.

The process was first applied in Europe in Denmark in the Soelleroed Municipality in 1922 (Henze *et al*. 1997). Work commenced in Germany in 1924 when the first experimental plant was built at Essen by Imhoff (von der Emde 1964, 1997). This was followed by the first full-scale system in Germany at Essen-Rellinghausen in 1926. In 1927 Kessener treated an abattoir effluent at Apeldoorn, in the Netherlands (Institute of Water Pollution Control 1987) using an activated sludge process equipped with a brush aerator.

In 1938 Mohlman, reviewing the first twenty-five years of the activated sludge process for the Federation of Sewage Works Association in the US, wrote:

> In 1913, activated sludge was discovered and recognised by W.T. Lockett in the course of some bottle experiments in the laboratory of the Manchester sewage treatment works. In 1938, the activated sludge process is in operation in hundreds of full-scale sewage treatment works and more than a billion gallons of sewage are treated every day. Activated sludge plants are now operated all over the world, extending from Helsinki, Finland to Bangalore, India; from Flin Flon, Manitoba, Canada to Glenelg, Australia; and from Golden Gate Park, San Francisco to Johannesburg, South Africa. Huge plants are in operation at London, New York, Chicago, Cleveland and Milwaukee. This astounding growth in the past twenty-five years is unparalleled in the history of sewage treatment, and must be ascribed to the fact that the activated sludge process is in harmony with the speed of and science of modern life. Sewage treatment works in our modern cities can no longer be obnoxious or inefficient. They must be free from odour, occupy limited area, and be amenable to scientific control.

The Second World War held up development of the process until about 1948 when the search for a way to better control plant performance began. This search was to occupy many workers over the next forty years in many different countries.

The activated sludge process and its many variants is now the main engine of secondary sewage treatment and has probably had the biggest impact of all processes upon environmental improvement in the past century.

Progress in the rest of Europe had not been as rapid as in the UK and the US. In Finland, progress was delayed by the Russian War and occupation, and in 1910 Finand only had three sewage treatment works. This rose to seven by 1950 (Katko 1997) and grew quickly in the 1960s after the Water Act had been passed. The effect of this upon the health of the population in contrast with Sweden, Switzerland and England and Wales is seen in Table 2.4. There are now 110 modern sewage treatment works in Finland (Katko 1997).

Table 2.4. Mortality rates from typhus and paratyphoid fever in selected European countries from 1930 to 1959 (from Katko 1997)

Country	Period	Mortality rate per million people per year
England and Wales	1941–1950	1.5
Sweden	1941–1947	4.0
Switzerland	1941–1949	5.3
Finland	1931–1940	25.0
Finland	1941–1950	43.0

2.8 PROCESS REFINEMENT TOWARDS STANDARDS DICTATED BY ENVIRONMENTAL PROTECTION: 1965 TO 2000

In this period the emphasis has been on:

- more widespread application of known techniques for BOD and TSS removal;
- environmental protection and improvement by the removal of nitrate, phosphate and ammoniacal nitrogen; and
- disinfection.

More fixed film process variants of the original biological filters have gradually been developed. Examples of these such as submerged aerated biological filters and plastic media biological filter systems are now common.

2.8.1 Nutrient removal

Nutrient removal processes to help prevent eutrophication and to protect water sources from high nitrate concentrations have developed rapidly in this period.

By the 1960s the main engine of secondary treatment was the activated sludge process. One of the major problems with activated sludge systems in the period up to the early 1960s was that the oxidation of ammoniacal nitrogen (nitrification) was not reliable or predictable. The solution to this was discovered by an investigation by Downing *et al.* (1964) at WPRL (later part of WRc) at Stevenage. The results of that work are now incorporated into design methods and computer models. Biological denitrification had been known about since the late 1800s but denitrification first took place in sewage treatment in the late 1930s (Edmondson and Goodrich 1947). They used the nitrate as a source of oxygen for an overloaded biological filter. In 1962, in the US, Ludzack and Ettinger put forward the use of anoxic zones to achieve biological denitrification in an activated sludge process. This concept is now standard practice in all AS processes and some fixed film processes.

The problem of how to remove phosphorus in activated sludge processes was solved by James Barnard (1974) and his colleagues in South Africa. This technique is now applied worldwide. In the second half of the twentieth century the South African water industry has protected its water resources very carefully and developed recycling processes because of a water shortage and a rapidly growing population. As a result, some of the most advanced sewage treatment processes have been developed here.

2.8.2 Standards

In the 1970s, a move started to raise standards and improve environmental protection, to some extent driven by public opinion and greater public awareness. The first step in this direction was the Clean Water Act in the US in 1972. As the European Union expanded from the original five states to the present fifteen there have been a series of directives aimed at the prevention of water pollution and protection of cross-border water resources. This began with the Surface Water Directive in 1975 followed by the Bathing Water Directive in 1976, the Fishing Waters Directive in 1978, the Shellfish Water Directive in 1979 and the Drinking Water Directive in 1980. The Urban Waste Water Treatment Directive (CEC 1991) has had a very significant impact upon operators in the last five years since it provides European-wide standards and introduces more stringent standards for nitrogen and phosphorus levels.

2.8.3 Sludge treatment and disposal

Little has been said about sludge treatment and disposal in the earlier periods. It has become a more significant problem in the last twenty years as easy disposal routes have been gradually closed. It is no longer permissible in Europe to discharge sewage sludge to sea; a common practice until the 1990s. Standards for disposal on agricultural land have also become tighter. Many new processes have been proposed and developed. The most common use in the UK is still on agricultural land but incineration and drying/pelletisation are becoming more popular. The sludge treatment and disposal route should be considered at the earliest stage in any process design.

2.8.4 Computer modelling and control

The advent of industrial electronic computers (and electrically controlled valves) in the late 1970s made automatic control of process units a possibility for the first time, and this has progressed apace since that time. In the late 1980s when the first affordable personal computers (PCs) became available, there was another change with respect to the development of computer models of the treatment processes, in particular the activated sludge process, which had previously required powerful mainframe computers. The IAWPRC model (based on COD) (Olsson and Newell 1999) and the WRc STOAT model (based on BOD) (Smith and Dudley 1998) have led the way. They are particularly helpful in allowing a 'dry run' of weather conditions and checking how outside factors, such as storm conditions, will affect the treatment process (Smith *et al.* 1998).

2.8.5 Reed beds/constructed wetlands

Over the past twenty years there has been a rise in interest in less sophisticated drainage and treatment systems such as pond and wetland treatment systems. This has been driven in Europe by the desire to provide safe treatment at a lower cost.

The use of reed beds (also known as constructed wetlands) came in the 1980s (Cooper and Findlater 1990; Cooper *et al.* 1996). These systems are particularly useful for small rural decentralised wastewater treatment systems. There are tales which indicate their use long ago in Italy, even that the Romans may have known of their use.

2.8.6 Anaerobic treatment of wastewaters

Over the past fifty years a number of attempts have been made to apply anaerobic processes to the treatment of wastewaters. There has been considerable success in treatment of agricultural and industrial wastewaters largely based upon the UASB (upflow anaerobic sludge blanket) reactors pioneered in the Netherlands in the 1970s (Zeeman *et al.* 2001). These process systems have been successful because these agricultural and industrial wastewaters are usually warm or concentrated (or both) organic wastes. Municipal domestic sewage is usually cold and weak and so efforts to apply anaerobic treatment have not yet been successful. Recently, considerable research effort has been devoted to the anaerobic treatment of the concentrated wastewaters that result from the separation of 'grey' and 'black' waters in domestic homes (Zeeman *et al.* 2001). This looks to be a promising possibility for localised decentralised treatment, but will not be the solution to treatment of the present weak domestic sewage.

2.8.7 Membrane systems

One of the most important developments relates to the use of membranes. This is possibly the most novel process of the past forty years. Tertiary or quaternary treatment using membranes for removing bacteria is already carried out in Europe, Australia and the US. The potential for use of membranes in reverse osmosis (RO), micro-filtration (MF) and ultra-filtration (UF) has been known since the 1960s (they were used in the American missions to the moon) but research and development has only recently resulted in membranes that are cheap enough to allow for their use with concentrated wastes such as sewage. Total operating costs have dropped four-fold, that is, by 75 per cent since 1992 (and are probably around a hundred times cheaper than they were in the early 1970s). Probably the most exciting application is in membrane biological reactors (MBRs) such as the Kubota system from Japan. In this the membrane panels are inserted directly into the activated sludge aeration tank. This has several advantages:

(1) It allows for operation without a settlement stage (always the most unreliable part of any AS process).
(2) It eliminates a substantial amount of piping.
(3) A tertiary treated effluent is produced in two stages or even one stage.
(4) A disinfected effluent with no TSS is produced, which could be reused for a secondary purpose.
(5) An automated AS process unit could be operated as a package unit for much smaller populations. In the past, poor sludge settlement has hindered this application.
(6) It is possible in this system to allow the biomass concentration to increase to more than 15,000 mg/litre which means that the size of the aeration reactor can be dramatically reduced.

Kubota systems are already being used for small populations in Japan and the UK (Yates 2000). Two village/town systems for 4,000 and 23,000 people have been installed in the UK but it should be noted that the system was developed in the Kubota business group which had responsibility for populations up to 50 people. It may thus be a system that has great potential for a small decentralised sewerage system and for some reuse of treated effluent. A membrane system is also in use at the Millennium Dome at Greenwich, London for grey-water recycling to provide water for toilet flushing.

2.9 CONCLUDING REMARKS

History shows that change comes in cycles and that ideas and processes come back into use when developments in other fields make the improvements needed to allow them to succeed. A good example of this is the sequencing batch reactor (SBR). This was the original form of activated sludge process, the fill-and-draw process. It made a comeback in the 1990s because there is a need for a process which avoids bulking sludge. Interest in it began to revive in the 1970s but has developed strongly in recent years because the invention of computers and electronically controlled valves allows SBRs to operate automatically whereas, in the 1920s, everything had to be done by manual labour.

Another example of this cyclic situation is the current interest in Brazil in backyard drainage/condominial sewerage, a process originally proposed in the 1850s. Yet another example is the widespread use of chemicals which are now used for phosphorus removal rather than enhanced suspended solids removal, as in the previous century.

International cooperation and the free exchange of ideas has been very influential in accelerating development, particularly between 1850 and 1950. At this time there was a considerable exchange of ideas between London and east coast cities in the US such as New York and Boston which were experiencing rapid growth and problems in controlling sewage-linked diseases. A similar exchange of ideas has been seen within Europe and continues to this day.

The water-carriage system is very old. It began in around 2000 BC in Greece and then took hold in the UK as a result of the work of Edwin Chadwick in the 1840s. It is of course now the main form of sewage treatment in developed countries. Care will need to be taken in designing systems to treat sewage from low water use or vacuum systems since the high concentrations of ammoniacal nitrogen in these concentrated wastes may be toxic to the nitrifiers. I find it difficult to see this being usurped as the main form of sewerage system but I can also see the benefit of decentralised systems for small populations and rural areas far from large treatment works. The treatment of sewage from these systems is already being carried out in pond systems and reed beds/constructed wetland systems worldwide. These systems have huge potential for developing countries since they are cheap and can be constructed by local people using simple techniques and equipment (Cooper and Pearce 2000; Mara 2000).

The trend in Europe over the last thirty years has been to organise water and wastewater treatment on a river basin basis by using river basin authorities rather than by municipal councils, as happened in earlier times. This has benefited the areas and population by improving environmental protection and possibly also by lowering costs.

2.10 TIMELINE FOR WASTEWATER TREATMENT

3500-2500 BC	Mesopotamian empire stormwater drainage system. In Babylon clay pipes led to cesspools.
1700 BC	Four separate drainage systems in King Minos' palace. In Knossos, Crete, terracotta pipes drained to stone sewers.
c. 800 BC	Cloaca Maxima central sewer system built in Rome.
c. 100 AD	Sewer network in Rome connected to houses.
c. 400 AD	Brick sewers in London.
c 1100	Cistercian monasteries in Scotland locate next to watercourses and flush latrines via sewers to watercourse.
1189	Regulations in London on placement of cesspools.
1370	First covered sewer in Paris dumps sewage into the River Seine near the Louvre.
1531	Commission on Sewers in London.
1596	Sir John Harington builds two water closets for Queen Elizabeth I. Called the 'Necessary', this is the first water closet flushed by a valve system.
1740	First recorded mention of chemical treatment of sewage. Lime used in Paris.
1776	Magistrate John Shortbridge requires Glasgow tenants to drain water from kitchens via lead pipes, and excreta to be taken to middens.
1790	First sewer built in Glasgow.
1793	First water closet in Glasgow, 200 years after its invention. Edwin Chadwick publishes the landmark report to the Poor Law Commissioners, Report on the Sanitary Condition of the Labouring Population of the Great Britain. Health of Towns Association formed.
1844	Commission on Health of Towns adopted Chadwick's Proposals.
1846	First British patent on chemical treatment is granted to W. Higgs for the use of lime.
1848	Public Health Act in the UK masterminded by Edwin Chadwick. Set up local Boards of Health and gave them rights to construct sewers.
1849	Metropolitan Commission of sewers for London.
1848-54	Dr John Snow proves link between cholera outbreak and water supply polluted by sewage.

1853	First comprehensive sewerage system completed in Hamburg, Germany. System designed by William Lindley serves as model for US and European cities.
1850-1910	Many patents applied for in the UK and US for chemical treatment of sewage. Four hundred and seventeen patents granted in the UK between 1856 and 1876.
1860	Overflowing cesspool (precursor of septic tank) designed in France by L.H. Mouras.
1862-65	More soldiers die from typhoid and cholera than combat in US Civil war.
1866	Medical Officer of the Privy Council (advisers to Queen Victoria) reported that death rates had dropped considerably where the Chadwick report recommendations were followed.
1868-70	Frankland's tests on filtration of sewage through soil and gravel (an extension of land treatment). Nitrification achieved.
1870-90	Many tests in the UK and US on filtration of sewage through various media.
1887	Dibdin suggests basis for biological treatment by organisms and describes modern primary and secondary treatment
1890	First true biological filter at Lawrence Experimental Station, Massachusetts State Board of Health, US.
1890-1900	Many tests and designs in the UK follow up American work on biological filters.
1895	Cameron and Cummins (Exeter) patent septic tank.
1898	1st Royal Commission on Sewage Disposal in the UK.
1906	Imhoff tank designed in Germany.
1912	8th Royal Commission on Sewage Disposal defines the 20 mg BOD/litre; 30 mg SS/litre 'Royal Commission Standard'.
1913	First laboratory experiments on activated sludge by Fowler, Ardern and Lockett at University of Manchester, UK.
1916	First full-scale activated sludge plant at Worcester. Large-scale tests in the US. First full-scale AS plant in US at Houston, Texas.
1922	Activated sludge plant built at Soelleroed, Denmark.
1924	Pilot AS plant in Germany at Essen.
1926	Full-scale AS plant at Rellinghausen, Germany.
1927	Kessener brush aeration, Apeldoorn, the Netherlands.
1936	Denitrification used in Sheffield.
1964	Development of basis for consistent nitrification by Downing, Painter and Knowles, WPRL, Stevenage, UK.

1972	Biological phosphorus removal described by Barnard in South Africa.
1970s	Development of dynamic process computer models by WRc and IAWPRC.
1990s	Membrane biological reactors developed in Japan.

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