1 Historical Development of Wastewater Collection and Treatment

1.1 Water Supply and Wastewater Management in Antiquity

One of the most ancient systems of wastewater management was constructed in Mohenjo-Daro near the river Indus (Pakistan) at about 1500 BC. Some centuries later, the river moved its course and obviously the town was given up and covered by sand during the following decades. In the 1930s and 1940s, this early high civilization was newly discovered. Private and public houses were equipped with toilets. Water used for washing and bathing as well as rain water flowed through special grooves into canals which were built with the necessary slope to transport the water into the river Indus. These installations demonstrate a high hygienic standard of an early culture.

The main wastewater collector, the Cloaca Maxima, in Rome presumably follows the course of an old ditch which was used at about 500 BC as a collector for wastewater. But soon it was insufficient to handle the flow of wastewater. Therefore, it was enlarged in the following centuries, extended and roofed over (Lamprecht 1988). Archaeological studies presented a nearly complete picture of its line starting from near the Forum Augustum and flowing into the Tiber near the Ponto Palatino. During the time of the emperors (31 BC to 193 AD), the canal could be traveled by boat and could be entered via manholes. The canal has a breadth up to 3.2 m and a height of up to 4.2 m (Fig. 1.1).

In Hellenistic and Roman times, several water supply systems were constructed for Pergamon castle, which is situated on a rock with an 800 m long plateau, at a height of nearly 300 m over the town situated below it. We are here only interested in one of these systems: the Madradag pipe 2 constructed during the rule of Eumenas II (197–159 BC; Garbrecht 1987). This pipe had a length of 42 km and started in the Madradag mountains at a height of 1230 m, that is 900 m higher than the rock of Pergamon. Three valleys had to be crossed and afterwards the Pergamon rock had to be climbed. Therefore, the pipe had to be operated under pressure. This was an extremely demanding requirement for the quality of pipe manufacturing, laying and sealing. The difference in the height of 900 m (from source to castle) corresponding to a pressure drop of 90 bar (9 MPa) alone for the nonflowing water column. Therefore, very stringent requirements had to be met. The pipes

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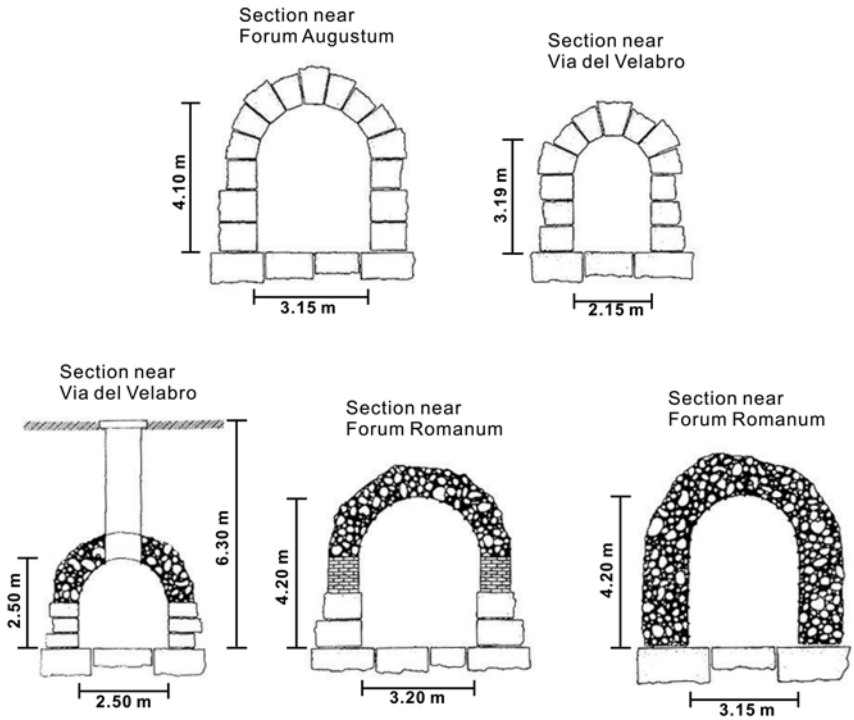

Fig. 1.1 Cloaca Maxima in Rome, sections of the wastewater collector (Lamprecht 1988).

Fig. 1.2 Main street with main wastewater collector below the town at the top of the castle of Pergamon (Garbrecht 1987).

were manufactured from fired clay and had a diameter of 16–19 cm. A mean flow rate 15 L s^{-1} can be assumed. Initially, only one pipe was needed, but later on, two further pipes of nearly the same diameter were laid in parallel. This made possible an increase in the flow rate to nearly 45 L s^{-1} or 162 m^3 h^{-1}.

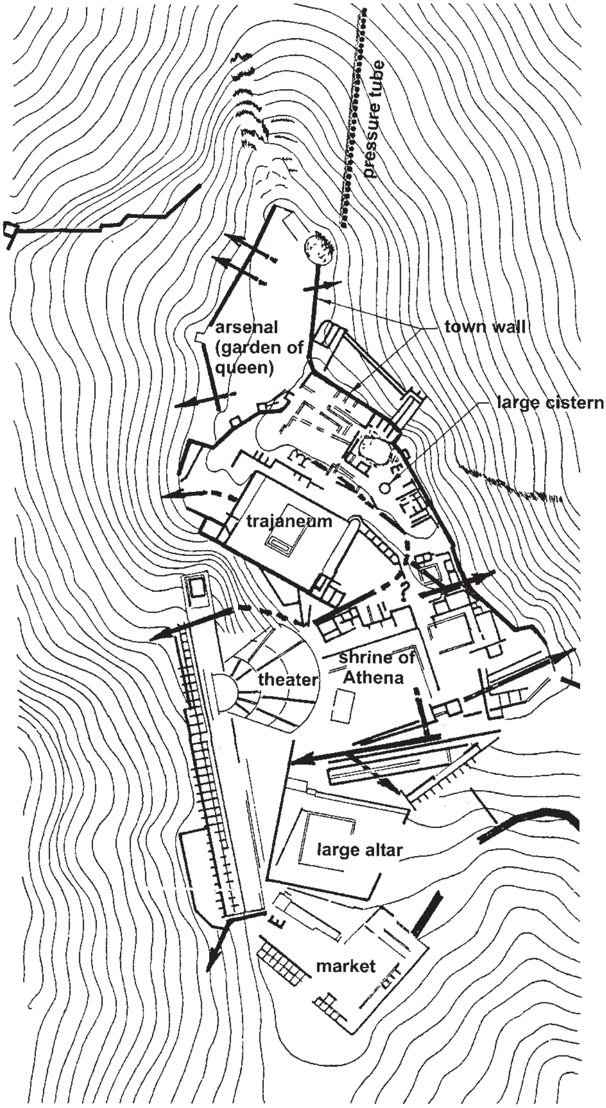

Fig. 1.3 Main wastewater collector with pipes for wastewater discharge at the castle of Pergamon (Garbrecht 1987).

A system for wastewater management was needed for such a high flow rate of fresh water. The resulting wastewater was collected in carefully masoned collectors laid below a main street covered by rectangular stone plates (Fig. 1.2).

The wastewater flowed from different palaces, temples, public buildings and private houses through clay pipes or open ditches. As a result of the growing flow rate, the cross-section had to be increased from 0.45–0.90 m^2 to 1.05–1.70 m^2 in places (Garbrecht 1987).

To keep the water from draining away at only one place at the end of the collector, discharge pipes took up the wastewater at various points and conducted it to the edge of the rock. From these points it fell below (Fig. 1.3).

1.2
Water Supply and Wastewater Management in the Medieval Age

Monasteries founded by Cistercians, Premonstratensians and Benedictines in Europe during the 12th and 13th centuries were exemplary business undertakings for that time. Besides the monks and the abbot, numerous lay persons worked and prayed there, all requiring a reliable source of water. Frequently, a monastery was placed near a river and a ditch was dug, which was laid with a necessary gradient through the area of the monastery. Figure 1.4 presents a system for water supply and wastewater discharge as a fundamental concept (Bond 1991).

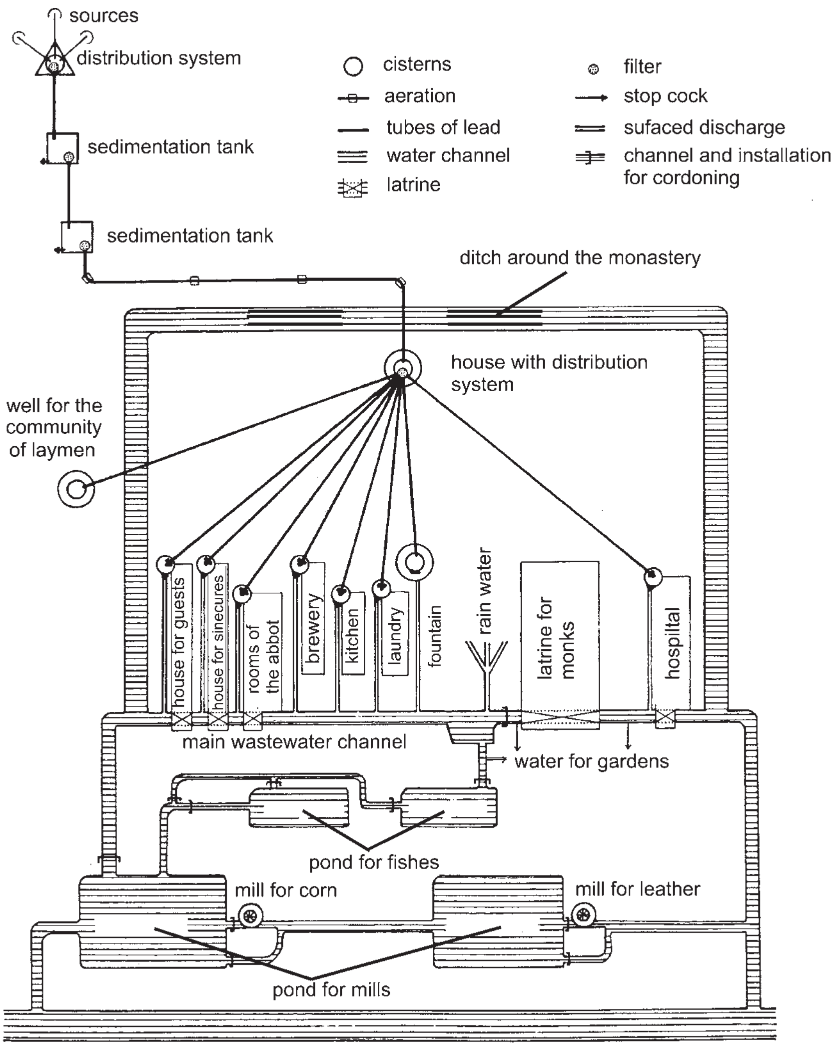

Fig. 1.4 Fresh water supply and wastewater discharge in monasteries (Bond 1991).

First, the water flowed slowly through two sedimentation basins to a distribution house crossing the main ditch of the monastery. Pipes made either from tree trunks, ceramic material or lead were used for this purpose. From the distribution house, the water flowed to the different consumers, where it was polluted to different degrees; and afterwards it flowed into a wastewater canal, which was divided at two adjustable weirs into two different parts: the smaller one discharging into fish ponds and the larger one flowing below the latrines near the dormitories and afterwards into the river. The not very polluted main ditch was connected with ponds as water reservoirs to drive different mills. For such a demanding water supply, distribution and wastewater discharge, the location of the monastery had to be selected carefully and prepared at great expense.

Figure 1.5 shows an outline of the Cistercian monastery Arnsburg in the Wetterau region of Germany, established there in 1197. There are some differences to the

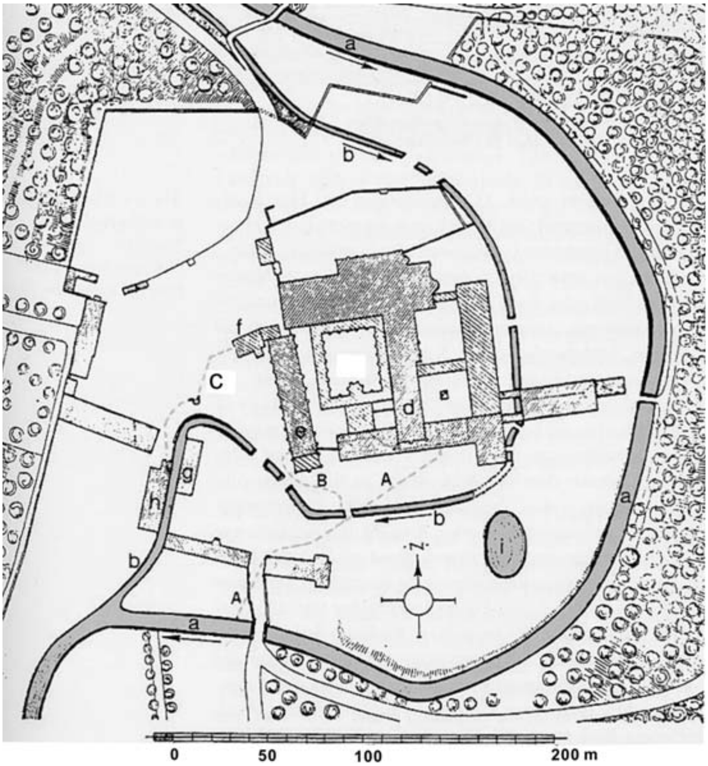

Fig. 1.5 Cistercian Abbey in Arnsburg (Germany), plan of a medieval system for water use and wastewater discharge (Grewe, 1991). (a) Course of the river Wetter; (b) Branch canal; (c) Courtyard of the cloister with well; (d) Dormitory for the monks; (e) Dormitory for the lay brothers; (f) Rooms for the abbot; (g) Mill; (h) Brewery; (i) Fishpond. Broken lines indicate underground medieval sewers: (A) From the latrine of the monks to the sewer below the canal to the Wetter River; (B) From the lay brothers' latrine to the sewer; (C) From the abbot's rooms to the branch canal downstream from the mill.

fundamental pattern of water supply, but principally we can recognize several elements that correspond. The mill ditch branching off from the Wetter River first went immediately past a building, presumable the kitchen, and then the water drove a mill (g) and was obviously used for brewing beer (h). Starting from the dormitories of the monks and from the wards, pipes crossed the ditch and flowed into the Wetter River. The brewery was connected by a pipe with the rooms of the abbot and we shall leave unanswered whether the pipe was used for the transport of beer or wastewater. Large parts of the monastery are now completely destroyed, but the location of the cloister, the enclosures and the house of the fountain could be reconstructed after excavations. The mill ditch flowed higher than the Wetter River and supplied the water to drive the mills.

The water supply and wastewater management in the castles of that time were simpler, although in the courtyard a deep well was dug to reach the groundwater. The latrines were constructed so that the waste could fall down upon the sloping rock. For palaces, castles and upper chambers lying next to a river, the wastes could be discharged using an underground canal or an open ditch. Figure 1.6 shows such a canal belonging to a palace from the 12th century in Frankfurt near the river Main, Germany (Grewe 1991).

However, inside the towns there was often no system for waste management up to the middle of the 19th century. Frequently, refuse was discarded directly at the streets and paths where swine and chickens then foraged for usable foods and increased the wastes even further. Only after the installation of a water supply, the use of water toilets and the construction of open (Fig. 1.7) and closed wastewater ditches in the middle of the 19th century did the situation improve.

Fig. 1.6 Wastewater canal of a castle in Frankfurt from the 12th century, with direct discharge into the river Main (Grewe 1991).

Fig. 1.7 "Freiburger Bächle", initially operated as a wastewater channel, used since the 12th century (Grewe 1991).

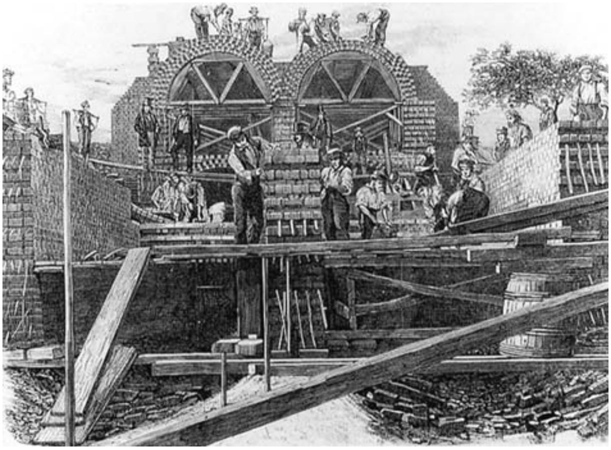

Fig. 1.8 Construction of main sewage collectors along the river Thames in London (three at the northern and two at the southern bank) in 1865–1868 (Föhl and Hamm 1985).

However, during this period the number of inhabitants in the cities increased considerably. This made it necessary to find a fundamental solution to the problems. In London, for example, they first looked for an interim solution. A large canal was constructed in 1865–1868 along the river Thames (Fig. 1.8), which received most of the countless wastewater streams which were previously disposed directly into the river.

East of London, all the wastes in the canal were again discharged into the Thames. Because of the height difference needed to transport the water, wastewater pumping stations were built at Crossners and Abbey Mills. Fundamentally, this was the same method used in Rome 2000 years earlier: collecting, diverting and discharging.

1.3 First Studies in Microbiology

Antoni van Leeuwenhoek (1632–1723) was the first person able to grind simple lenses and who built the first microscopes (Fig. 1.9). The biconvex lens (L) was fastened between two thin metal plates and the object was mounted up on the pin at (P), which was adjustable by moving two screws. He constructed many of these microscopes and all the necessary lenses he ground himself. The best of them magnified about 200 times (Burdon and Williams 1969). With these instruments, he patiently examined numerous natural objects.

Van Leeuwenhoek grew up in Delft, attended school in Leyden, learned the cloth merchants' trade in Amsterdam and subsequently settled in Delft as a cloth merchant. At the age of 28 (1660), he learned to grind lenses and began to study differ-

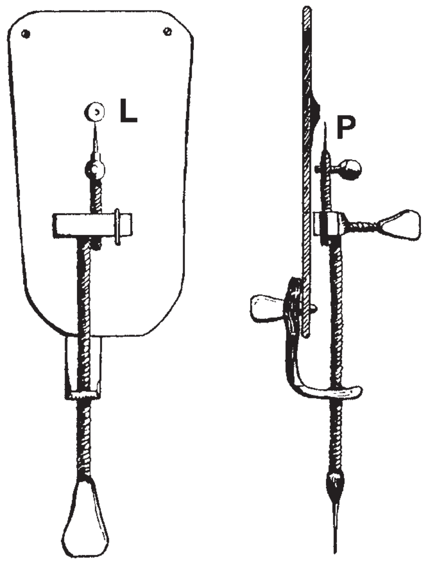

Fig. 1.9 Front and side views of one of van Leeuwenhoek's microscopes. A lens was fastened between two thin plates at L, and the object was fixed upon the adjustable pin at P. The microscope must be held very close to the eye (Burdon and Williams 1969).

ent small things he found in water droplets. Later on, he started to draw all the things he observed. In 1673, he sent a first letter with some new drawings and descriptions to the Royal Society of London. On 7 September 1674, he reported for the first time about "small animals" (animalcules, protozoa) and small globules (green algae). In his 18th letter, written 9 October 1676, we find the first observations of bacteria, "very small animals", the young of the other animals, as van Leeuwenhoeck assumed (Mockmann and Köhler 1996). In his 39th letter, from 17 September 1683, van Leeuwenhoek enclosed an engraved figure (Fig. 1.10) showing a slide prepared from the film on his own teeth. We recognize cocci, rods and helical bacteria. The Royal Society accepted van Leeuwenhoek as a member in 1680. When he died in 1723, nobody had learned his method for grinding lenses and in

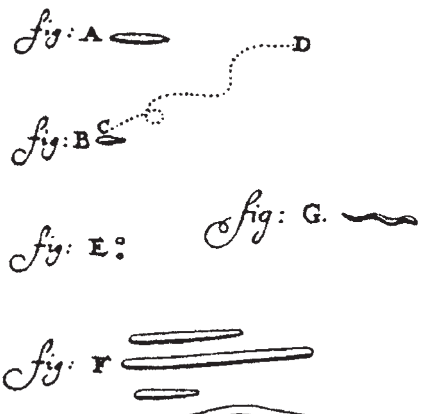

Fig. 1.10 Van Leeuwenhoek's drawing of bacteria in a letter of 1683 to the Royal Society of London (Mockmann and Köhler 1996).

the following decades only a few microscopes similar to that of Fig. 1.9 were available.

In 1720, an important book was published in London with the title “A new theory of consumption: more specifically on a Phthisis, or consumption of the lungs”, written by Benjamin Marten. In contrast to numerous other hypotheses, the cause of the consumption (tuberculosis) was attributed by Marten to small animalcules (microorganisms), which may come in the lungs by the circulation of blood. They may be contained in the air, can be breathed in and can grow in the blood and the lungs.

However, the scholars of that time believed in a phenomenon which was called abiogenesis. This theory of abiogenesis, or “generatio spontanea” (spontaneous generation of living organisms), is an old hypothesis and was not limited to animalcules. The famous alchemist Johann Babtist von Helmont (1577–1644) thought that animals like the mouse, worms and insects could be created by abiogenesis (Helmont 1652).

This period was concluded in part by experiments, carried out by Franceso Redi (Redi 1667), who worked as a personal physician of Ferdinand II de Medici (the grand duke of Toscana). He distributed a snake, some fish, eels and plates of veal into four bottles and closed them with fine porous gauze. The same remains of these animals were placed into open vessels, in which maggots were living after short time, having developed from eggs which were deposited by flies. In the covered bottles no maggots developed.

The abiogenesis of insects had already been refuted and scholars did not perpetuate this idea, but the discussion of abiogenesis started again in connection with animalcules. In their opinion, they must have been produced by abiogenesis.

In 1711, Louse Joblot studied the development of animalcules in hay and water suspensions (Joblot 1718). First, it was boiled for 15 min and distributed into two vessels. One of them was left open and, after some days, many animalcules had grown. The second vessel was closed with moist, oil-impregnated paper. No life could be observed in this vessel. Only after opening the vessel and waiting for some days did the same effect of growing life present itself, probably observed by using van Leeuwenhoek’s microscope. But we can assume that he was not able to observe bacteria.

After these experiments, Joblot was convinced that the observed animalcules were descended from small animals living in the air.

The English priest Father John Turberville Needham (1713–1781) tried to refute this opinion experimentally. He was a resolute advocate of abiogenesis. In order to support this hypothesis, he boiled a suspension of mutton meat, bottled it and sealed the flask from the air with a cork. After some days, the suspension was full of living things. Needham and many other scientists were sure that the theory of preformation was conclusively refuted (Needham 1749, 1750).

Charles Bonnet (1720–1793) was one of the first who questioned whether the flasks were really impenetrable for small animal, or whether there were living creatures or eggs which would be able to survive the heating (Bonnet 1762). The Italian priest Abbate Lazzaro Spallanzani (1729–1799) filled different boiled infusions

(1 h) into vessels, which were closed carefully afterwards (Spallanzani 1765). All mixtures remained sterile.

Needham revised this theory: during a heating time of 1 h, a "vegetative power" would be destroyed, which was now introduced into this discussion instead of a biogenesis.

Spallanzani (1776) carried out further experiments in 1776 to test the existence of a "vegetative power". He boiled different infusions, filled them into vessels, closed them and boiled them again for 0.5, 1.0, 1.5 and 2.0 h. Half of them were opened, half of them remained closed. Only in the opened vessels were animalcules observed to be growing. Therefore, a "vegetative power" which could be destroyed after boiling for 1 h could not exist.

Nevertheless, the idea of abiogenesis or generatio spontanea (heterogenesis) as a model for the origin of life from nonliving organics remained a popular theory until 1830. At this point in time, it was shaken more and more by further experiments.

Franz Schulze filled water, meat and vegetables into a glass. At both ends of the glass, vessels were attached which were filled with sulfuric acid (Schulze 1836). From time to time, air was blown into the system (Fig. 1.11a), but all animalcules were restrained and killed off by the strong acid. The organics remained unchanged, no organism was alive. Only after the vessels filled with H_2SO_4 were removed did the animalcules penetrate from the air into the flask. Schulze proved with this experiment that germs (molecules or particles) distributed in the air of his breath were retained by washing in H_2SO_4, but that they started to digest the organics after entering the open glass.

One year later, Theodor Schwann (1837a) demonstrated that germs could be destroyed by heat. The left bottle in Fig. 1.11b was filled with a heated infusion and connected with a large spherical bottle and a helical tube. Both were heated and the right tube was closed by melting. The organics remained sterile. Obviously, the germs (molecules or particles) could be destroyed by higher temperature.

Schröder and von Dusch (1854) successfully used a layer of cotton as a filter for sterilization (Fig. 1.11c). First, the organic substance in the middle glass was heated and after that a flow of air was adjusted by opening the tap and emptying the left, large bottle slowly. Since then, layers of cotton have been used frequently to sterilize air in microbiology and biotechnology.

Schwann had shown already in 1837 that yeasts are living organisms and that if they grow in aqueous sugar solution and in the absence of oxygen, the sugar is converted to ethanol (Schwann 1837b). This interpretation of fermentation was doubted by scientists over the next 20 years: the conversion of sugar into ethanol must be a purely chemical process!

Nobody was able to describe these germs at this time, but it was known that they grow, that they change organic material and that they multiply. Louis Pasteur (1822–1895) was the first who understood that some germs need oxygen for growing, others do not. If they do not get oxygen, some of them are able to produce lactic acid (Pasteur 1857), ethanol (Pasteur 1860), butyric acid (Pasteur 1861a) and acetic acid (Pasteur 1861b). Pasteur created the foundation of modern *biotechnolo-*

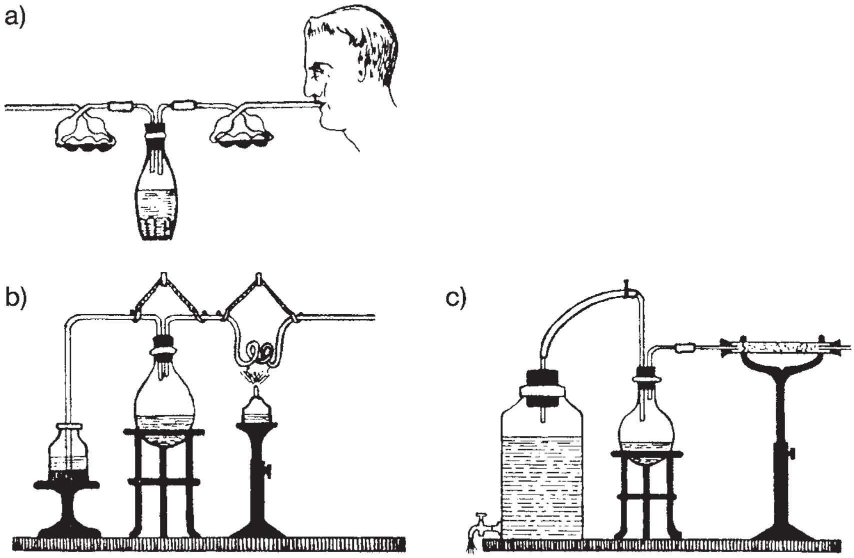

Fig. 1.11 Early experiments showing activities of microorganisms. (a) Franz Schulze's experiment with a heated suspension of meat and vegetables in the bottle and H_2SO_4 in both glasses (Schulze 1836). (b) Theodor Schwann's experiment with a heated glass spiral (Schwann 1837a, b). (c) The Schröder and von Dusch experiment with a glass tube filled with cotton (Schröder and von Dusch 1854).

gy, which gained considerably in importance during the following decades. In the next years, Pasteur studied the causes of "wine and beer diseases" (Pasteur 1876) as well as poultry pestilence (Pasteur 1880a), anthrax (Pasteur 1880 b) and rabies (Pasteur 1885). All these works laid the foundation for *medical bacteriology*.

1.4 Wastewater Management by Direct Discharge into Soil and Bodies of Water – The First Studies

In the middle of the 19th century, wastewater produced in the fast-growing industrial regions and cities was discharged directly into rivers and canals, as well as into the soil below the toilets at the courtyards of tenement blocks. Frequently, the drinking water pump was located directly next to the toilets. Therefore, it was no wonder that cholera illnesses often occurred, especially in large cities.

Drinking water drawn with these pumps occasionally smelled of H_2S; and Rudolf Virchow was the first who assumed that it must be a product of anaerobic reduction of $CaSO_4$ (gypsum) by "microscopic algae" (Virchow 1868).

The situation in English rivers and canals was characterized by Fig. 1.12, a drawing in the satirical journal "Punch" from 1858 (Föhl and Hamm 1985).

Fig. 1.12 Drawing from the satirical journal *Punch*, demonstrating the extremely polluted river Thames in 1858 with the title "The silent highway man" (Föhl and Hamm 1985).

The first step in solving the problem of river pollution was to describe it by taking samples and making measurements.

Frankland was instructed by the administration of London to present a monthly report about the water supply. In 1868, on the occasion of a meeting of the Royal Institution of Great Britain, he pointed out that the drinking water coming to London from the Cader Idris and Plyalimmon mountains (northern Wales) was polluted by "unhealthy germs" and chemicals (Frankland 1869a). In the same year, Frankland proposed ten analyses of water to characterize the river water quality (Frankland 1869b), but it took a long time to establish regular sampling and measuring.

A similar report and a description of measuring methods and results were published by Finkener and Zinreck, concerning the lakes and rivers in and around Berlin (Finkener 1871; Zinreck 1871). The results cannot be compared with those of today because of the different methods for sampling and measuring. Therefore, we will not report them here.

In 1871, the results of the River Pollution Commission led by Frankland were made available. Of special interest was the condition of the river Irwell and its tributaries. Over a length of 56 km there were 285 factories discharging their effluents into the small river, which was extremely polluted (Reich 1871).

At this time, it was discussed whether the concentration of pollutants could be reduced by chemical oxidation during its transport in a river. Eduard Wiebe, for example, was convinced that all the wastewater of Berlin discharged into the river Spree between Charlottenburg and Spandau was cleaned by "self-purification", a natural chemical process which can be used beneficially (Wiebe 1873).

1.5
Mineralization of Organics in Rivers, Soils or by Experiment – A Chemical or Biological Process?

The process of "self-purification" had to be studied experimentally. A commission presumably led by Frankland obtained the order to investigate the problem. Wastewater from the channel was mixed with river water and filled automatically from one vessel to another after short interruptions. In the course of this filling process, oxygen must be transferred from air if it was necessary for the reaction. But the concentration of the organics was not considerably reduced, even after several weeks. Therefore, the "self-purification" observed was no simple chemical process. Alexander Müller was probably the first who suspected, in 1869, that the degradation of organics must be a microbiological process (Roechling 1899).[1)]

An initial answer resulted from experiments by J. König. A wire mesh was sprayed with wastewater for some weeks and it was observed that a biofilm had formed and that dissolved organics had been removed (König 1883). In this light, the experiments of Wolffhügel and Thiemann are also important, being the first to study the growth of bacteria on culture medium after adding drinking and process water. In these experiments, they were advised by Robert Koch (Wolffhügel and Thiemann 1883).

Between 1885 and 1890, several further studies were published proving that microbiological processes must be responsible for the production of H_2CO_3 and HNO_3 by the oxidation of organic compounds and NH_4^+ (Emich 1885; König 1886; Knauff 1887; Weigmann 1888; Winogradsky 1890).

Nevertheless, another group of chemists could not be convinced by the results of these experiments. Dunbar, the famous director of the Staatliche Hygiene Institut in Hamburg cited Travis in his paper in 1912 (Dunbar 1912), who strongly denied the microbial degradation of organics. Travis presented experimental results on the occasion of the seventh International Congress of Chemists in London in 1907, which should have proved pure chemical oxidation instead of biodegradation by microorganisms. However, Dunbar criticized Travis's methods in his last paper (Dunbar 1912), and obviously the idea of the pure chemical mechanisms was no longer supported in scientific meetings and journals.

We should not conclude this brief description of the birth of environmental microbiology without emphasizing the work of Winogradsky (1890), who carried out fundamental and most important studies on nitrification. In contrast to all the bacteria which use organic compounds as a source of energy and/or carbon, nitrifying bacteria are chemolitho-autotrophs, obtaining energy by the oxidation of NH_4^+ and NO_2^- and obtaining carbon from the reduction of CO_2 (Chapter 10). He discovered all these facts and much more about this kind of bacteria, catabolism and anabolism during the years prior to 1890; and it is astonishing that the dispute about the oxidation of organic and inorganic compounds as a result of chemical or biological processes was not concluded for several further years.

In 1891, the first textbook on hygiene, "Grundriss der Hygiene" by C. Flügge, was published in its second edition (Flügge 1891). Rightfully, the reader could expect that the very important dictions of the past decade would have been mentioned. But the book, with its 560 pages, did not give any references to the topic. Should we conclude that the papers published in the journal "Gesundheits-Ingenieur", for example, were not noticed by doctors working in the field of hygiene?

1) A. Müller is mentioned in several other papers. But until now, the original publication has not been found.

1.6 Early Biological Wastewater Treatment Processes

The collection of wastewater in canal systems served a purpose, but its discharge into rivers was no solution of the problem, if the amount of wastewater discharged was too great in comparison with the river flow rate. In Berlin, Hobrecht proposed and built a wastewater collecting system consisting of 12 radial arms – five to the south and seven to the north of the river Spree. In each radial system, rainwater and wastewater flowed to a central lowest point by gravity (and the system is still in use today), from where it was pumped in pipes to an irrigation field outside the city. In the middle of each irrigation field, the water exited through a standpipe and gate valves through irrigation ditches in the irrigation fields. The water seeped through the ground and was collected by porous ceramic pipes and flowed into drainage channels and finally into canals or rivers (Hobrecht 1884). Similar irrigation fields were built in the surroundings of several other cities. Data for concentrations measured in the influent and effluent are very rare. Table 1.1 shows some data from 14 April 1891 for the irrigation field in Breslau (Uffelmann 1893). If we compare the values for dissolved organics of 155.9 mg L^{-1} (influent) and 53.2 mg L^{-1} (effluent), we can conclude that about 66% was removed. Nitrification was nearly complete (ammonia 105→7 mg L^{-1}).

The cleaning effect of irrigation fields had already been proven in the late 1870s, but in the first decade of operation, the scientific basis for the reduction of organics, which was being monitored by smell (often) and/or by taste (seldom), was largely unclear. During the 1890s, it became more and more certain: it was not a chemical but a biological process performed by aerobic and anaerobic bacteria. Nevertheless, the dispute was not resolved until the beginning of the 20th century (Dunbar 1912).

Table 1.1 Concentration of samples from the influent and effluent of an irrigation field in Breslau (14 April 1891; Uffelmann 1893, extract).

Substance	Concentration (mg L^{-1})	
	Influent[a)]	Effluent[b)]
Suspended material	295.2	54.0
Organics	246.0	–
Inorganics	49.2	–
Dissolved material	687.3	478.4
Organics	155.9	53.2
Inorganics	531.4	425.2
$KMnO_4$ consumption	118.1	9.7
Ammonia ($NH_3 + NH_4^+$)	105.0	7.0
Nitric acid	–	17.5
Phosphoric acid	22.4	–

a) Pump station. b) Mean dewatering ditch.

Experiments in ways to increase the specific wastewater load (in m^3 (ha day)$^{-1}$) compared with that of irrigation fields resulted in the development of intermittent soil filtration. The following operational conditions had to be met for the first sites: (a) the groundwater level must be low enough, (b) the percolating water must be collected in lateral ditches for recycling and (c) the application of wastewater must be intermittent, so that water levels in the ground recede and allow the simultaneous flow of air downwards to provide oxygen for bacterial growth, respiration and degradation of organics. Although this biological process was not completely understood, it was tested with increasing success.

One of the first of this kind was operated successfully in Lawrence, Massachusetts, USA, in 1888. These first experiments were very successful, showing nearly complete removal of organics and complete NH_4^+ oxidation (Dunbar 1899). In London and its surroundings, similar experiments with intermittent soil filtration were carried out by Dibdin in 1894–1896 (Roeckling 1899). In Barking Creek, London, near the river Thames, an area of 4047 m^2 was built up with soil that had walls 1 m high, supported by laid bricks. Several solid materials were tested as a contact bed. This filter was periodically filled with wastewater over 2 h, stopped for 1 h and emptied slowly over 5 h; and the cycle was repeated every 8 h. About 70–75% of the dissolved organics were removed. The plants in Sutton and Exeter were different from that of Barking only in one point: the wastewater was biologically pretreated for 24 h – in Sutton apparently aerobically in an open vessel and in Exeter anaerobically in a closed vessel. In both plants, the results were somewhat better than in Barking (Dibdin 1898). Similarly, very early pilot plants for the study of biodegradation went into operation in 1897 in Hamburg (Eppendorfer hospital; Dunbar 1899), in Groß-lichterfelde near Berlin, in 1898/1899 (Schweder 1901) and in Tempelhof near Berlin in 1900 (Thumm and Pritzkow 1902). After the foundation of the “Königliche Prüfanstalt für Wasserversorgung und Abwasserbeseitigung” in Berlin, pilot experiments were carried out systematically to study intermittent soil filtration, in order to find the best type of contact beds and to improve the process in Tempelhof (Thumm and Pritzkow 1902; Zahn 1902). All these experiments and developments led finally to the development of continuously operated trickling filters (Table 1.2). One of the first large-scale plants was built in the form of contact beds using large pieces of coke and operated with intermittent filtration, in Stahnsdorf near Berlin (Müller 1907).

Table 1.2 Development of irrigation fields and trickling filters – increase in specific load.

Year	Process	Specific load [m^3 (ha h)$^{-1}$]
1860	Irrigation fields prepared on suitable soil and level area	0.24–0.36
1878	Irrigation fields with drain trenches and soil fields	4–8
1884	Irrigation fields and preliminary sedimentation	8–10
1886–1900	Intermittant soil filtration	30–40
1890	Intermittant filtration with contact beds	120
1903	Trickling filter	500–2000
1960	High-load trickling filter	8000

1.7
The Cholera Epidemics – Were They Caused by Bacteria Living in the Soil or Water?

In the rapidly growing European cities of the 19th century, cholera epidemics claimed many thousands of lives. In the time before 1860, nobody had a realistic idea about the cause of these epidemics. It was not until 1883, when Robert Koch discovered the bacteria which caused the illness (Brown 1935) that physicians were able to look for the natural reason of these bacteria. Two different hypotheses characterized the dispute of the following 10 years. Max von Pettenkofer and his followers were convinced that the cholera bacteria lived and grew in the soil and that the infections were caused by contact with soil and dust particles (von Pettenkofer 1882). Robert Koch and his followers supported the opinion that infection by cholera bacteria resulted from surface waters which were often used as sources of drinking water without any processing (Brown 1935).

In 1892, cholera appeared in Hamburg. All the victims of this disease had been supplied with drinking water which came directly from the river Elbe without sand filtration. The central prison and the Attendorfer lunatic asylum with its own groundwater supplies remained completely unaffected by cholera (Kluge and Schramm 1986). In the neighboring town of Altona, the morbidity was significantly lower, although water from the Elbe was used there as well. Was the rate of infection so much lower because the water was sand-filtered in the Altona waterworks? After some months, the number of illnesses was about 18 000 and the number of deaths 7600. But up to this point, the cholera bacillus was only found in the bodies and excrement of those taken ill. But just one year later, the cholera bacillus was also detected in the water of the river Elbe and most notably also in the pumps. After the source of the cholera infection had been identified, an effective solution to the problem had been found: sand filtration in waterworks and wastewater discharge into the river as before (Flügge 1893) or groundwater withdrawal as shore filtrate and wastewater treatment by irrigation fields (Virchow 1868; Hobrecht 1884). Both methods were employed, the first in Hamburg, the second in Berlin. The idea that a river can be loaded with untreated wastewater and then be cleaned by “self-purification” was upheld for the next 80 years. Only in the 1960s did we realize that wastewater must be treated in plants before being discharged into surface waters!

1.8
Early Experiments with the Activated Sludge Process

Obviously, nobody before 1913 had the idea to increase the concentration of aerobic bacteria by sludge sedimentation after aerating the sewage in a bottle for several hours, to remove the solids-free water carefully and then add sewage again. The first persons to observe an increase in sludge by repeating this process several times were Edward Arden and William T. Lockett from the River Committee of the Manchester Corporation in 1914. They presented their results on the occasion of a meeting at the Grand Hotel in Manchester on 3 April 1914 (Arden and Lockett 1914). It was of high importance that the glass bottles filled with 2.27 L of sewage were protected from light for the first time, so that algae could not grow. They filled their bottle with sewage from the Sewage Works at Davyhulme. If the sludge had a volume of 25% after sedimentation, "carbonaceous fermentation" and nitrification could be completed to a high degree within 24 h. It was very important that the sludge was mixed with the sewage and that sufficient air was added. The pH must be controlled by adding a small quantity of alkali. These published results are presented in Fig. 1.13.

In this figure, concentrations are given in "parts per million", which means approximately $200/10^6 = 200$ mg L^{-1}. The organics were measured as "Oxygen Abs.". The authors probably used $KMnO_4$ as an oxidizing agent. The nitrification rate was slow compared to the removal rate for organics over the first 8 h. After this time, the situation changed.

Over the following years, this batch process was converted to a continuous process using an aeration tank, a sedimentation tank and sludge recycle system. After several experiments were performed in the UK and in the USA using pilot plants to study the process (Mohajeri 2002), the first technical-scale activated sludge plant was constructed in Sheffield, UK, in 1920 (Haworth 1922). The water flowed in open meandering channels and was aerated, moved and circulated by paddle stirrers. In Indianapolis, USA, compressed air flowed through perforated tubes arranged near the bottom at one side of a long channel, producing a spiral flow of air bubbles (Hurd 1923). The first surface aerator with a vertical shaft was constructed by Bolton. A conducting tube forced the two-phase flow near the bottom, resulting

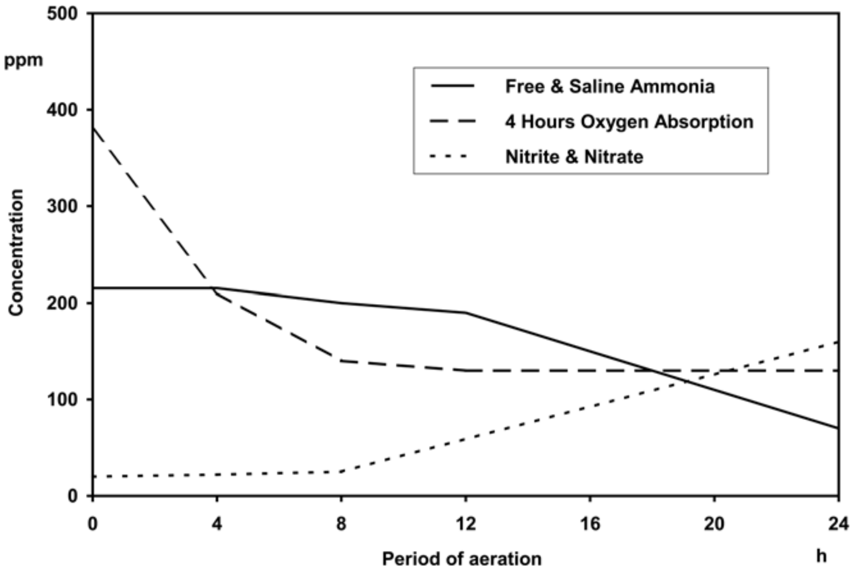

Fig. 1.13 First batch sewage aeration experiment with enriched activated sludge (Arden and Lockett 1914).

in sufficient oxygen transfer and mixing of the water and sludge (Bolton 1921; Imhoff 1979). In Germany, the first large plants were built in Essen-Rellinghausen in 1926 (Kuhn 1927) and in Stahnsdorf near Berlin in 1929–1931 (Langbein 1930), the latter of which was designed and operated as an experimental plant for the study of different sedimentation tank designs (Mohajeri 2002).

1.9
Taking Samples and Measuring Pollutants

There are some important questions which must be answered when studying water technology and pollution control:

- How dirty is the wastewater with respect to specific compounds or total parameters; and how can I measure these parameters or the concentration of these specific compounds?
- What is the best point to take a sample for analysis from a river or treatment plant?
- What is the best method for taking samples (sampling by drawing within a short time, sampling and mixing within a given time period of 1–2 h)?
- How frequently should samples be taken, once per hour, per day, per week or per year?

One of the first methods developed was the measurement of potassium permanganate ($KMnO_4$) consumption for the oxidation of organic compounds dissolved in water (Marqueritte 1846). It took 23 years until Frankland proposed to the Royal Commission of England what else should be measured and how this can be done (Frankland 1869b). Malz in 1999 divided the time which followed into three periods. During the first period (1870–1920), wastewater was mostly characterized by colour and smell, although many methods were available for measuring different compounds. The ability of the wastewater to digest and to form gases (CH_4, CO_2) was of interest as well as the concentrations of potassium, magnesium and nitrogen to characterize the value for use as fertilizer (Mohajeri 2002). Not until the second period (1920–1970) were some simple methods used for measuring specific compounds (BOD_5, COD, dissolved oxygen, pH, conductivity, solid concentration, etc.). The most important problem was that standard methods did not exist. Frequently, one water sample investigated in two different laboratories gave two different results lying considerably beyond the range of confidence. The third period since 1970 is the time of using more and more methods controlled by computers with automatic sampling (COD, DOC, AOX) and the analysis of individual organic and inorganic compounds (different detectors after separation by GC, HPLC, etc.; Malz 1998; Mohajeri 2002). It was very important to standardize the methods of sample-taking, storage and measurement. Often, national standards were agreed upon only after drawn-out discussions. As a result of the development of political and economical confederations, further agreements on standards had to be developed (EU guidelines for prevention of water pollution; Pöppinghaus et al. 1994).

1.10 Early Regulations for the Control of Wastewater Discharge

Initially, solid and liquid wastes were disposed and poured out onto the streets and in the courtyards of medieval towns and villages. The unpaved streets and paths were filled with mud, particularly after a strong rainfall. Since domestic animals also lived in these areas, the mud was mixed with solid and liquid faeces. This situation went unchanged until the first regulations were issued by local authorities (Hösel 1990).

In the 16th and 17th centuries in Berlin, regulations by the Elector and the town council were mostly limited to the sweeping of solid wastes and the formation of heaps. In the 18th century, many tenants who had no toilets in the courtyards still emptied their chamber pots onto the streets. The town council of Berlin forbade this by levying a fine and defining a list of places on the river Spree where chamber pots could be emptied at a certain time of day. After 1830, more and more wastewater channels were constructed, some of them laid underground, some of them as open channels directly near the sidewalks. These were frequently clogged and wastewater could not flow, especially during and after rain or snowfall. In the 19th century, it was forbidden to empty chamber pots into the Spree. Obviously, this law was difficult to enforce (Fig. 1.14; Hösel 1990).

Until the second half of the 19th century, it was common practice to discharge wastewater into the rivers; and it was normal for the communities downstream to have to put up with the polluted water (Driewer 1999). These problems increased dramatically as industrial development took off in the fast-growing cities. In order to avoid epidemics such as cholera and typhus, laws had to be issued for the treatment and discharge of wastewater.

Until 1945 in Germany, water regulations were only issued by the states, some of them even only in the last 32 years of the 19th century (e.g. Oldenburgische Wasserordnung, 10 November 1868; Braunschweigisches Wassergesetz, 20 June 1878). In Prussia, the largest and most highly industrially developed region of Germany, the regulation of water was first established in 1913 (Schlegelberger 1927,

Fig. 1.14 Berlin: secret emptying of chamber pots into the river Spree. The gases of anaerobic processes (mainly CH_4) were used to provide light for the woman during her nightly job. Caricature by Doebeck, dated 1830 (Hösel 1990).

1931), because about 80 single regulations had to be unified which were each valid for only one of the 80 regions of Prussia. This fulminous work of about 1600 pages addressed such problems as ownership rights to waterways and lakes, usufructs, duties for the maintenance of the waterways and the banks as well as flood protection. Limits to volume or concentration of wastewater discharged into surface waters were not fixed. Similar laws were in effect in all German states and were not fundamentally changed until 1945.

Four points were important for the new laws:
- They were passed separately under different conditions in the Federal Republic of Germany (FRG) and in the German Democratic Republic (GDR).
- On 1 March 1960, the Water Resources Policy Act (WRPA) was issued in the FRG; and on 7 April 1963, the Water Act (WA) was issued in the GDR.
- The WRPA was a legal framework in the FRG, supplemented by the legislation of the individual states.
- The WA was a uniform regulation valid in all states.

An important development of the legislation of the FRG was the structure of the "Law governing the payment of fees for disposing of wastewater in surface waters" ("Gesetz über Abgaben für das Einleiten von Abwasser in Gewässer", Abwasserabgabengesetz [AbwAG], from 13 September 1976), which took effect on 1 January 1978. The levying of fees began on 1 January 1981 and only covered the direct discharge of wastewater into surface waters (Direkteinleiter). So-called load equivalents (Schadeinheiten) are calculated according to the yearly disposal load of particular substances (Berendes and Winters 1981). One load equivalent (the untreated domestic wastewater produced by one person in one year) was valued in 1986 at DM 12 (≈ 6 €) and in 1986 at DM 40. Further developments of the AbwAG are described in the appropriate literature.

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