Comenius University Bratislava, Faculty of Natural Sciences
Department of Environmental Ecology and Landscape Management

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History and presence of water sanitation

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Content

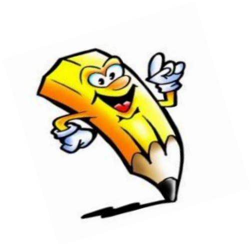
Foreword

The textbook „History and presence of water sanitation“ was prepared in effort to enable the students of Comenius University, Faculty of Natural Sciences, in the specialization of Environmental Studies better to understand all the processes of water and wastewater treatment, which the mankind accompanies since the long time ago, during the historical development of our civilization. By individual study of this subject in English language, using above textbook, the students may better understand as well as complete their knowledges obtained from lectures.

1.1. History of water supply and sanitation

In this section you will learn about

- ✓ History of water supply and sanitation since prehistoric time to the WWI in 1914 in Indus Valley and Hellenic civilizations, China and Asia Minor, ancient Rome as well as Middle Age Europe.
- ✓ Inventors of biological treatment and activated sludge process in United Kingdom.



Key words:

Water supply systems, aqueducts
Cloaca Maxima
Sewage farms, indoor plumbing
Biological treatment and activated sludge process

Major human settlements could initially develop only where fresh surface water was plentiful, such as near rivers or natural springs. Throughout history, people have devised systems to make getting water into their communities. Early human habitations were often built next to water sources. Rivers would often serve as a crude form of natural sewage disposal.

During the Neolithic era, humans dug the first permanent water wells, from where vessels could be filled and carried by hand. The size of human settlements was largely dependent on nearby available water.

1.1.1. Wastewater reuse activities and drinking water supply since prehistoric time

Reuse of untreated municipal wastewater has been practiced for many centuries with the objective of diverting human waste outside of urban settlements. Likewise, land application of domestic wastewater is an old and common practice, which has gone through different stages of development.

Domestic wastewater was used for irrigation by prehistoric civilizations (e.g. Mesopotamian, Indus valley) since the Bronze Age (ca. 3200-1100 BC). Thereafter, wastewater was used for disposal, irrigation, and fertilization purposes by Hellenic civilizations and later by Romans in areas surrounding cities (e.g. Athens and Rome).

The ca. 2400 BCE, Pyramid of Sahure, and adjoining temple complex at Abusir, was discovered to have a network of copper drainage pipes.

Some of the earliest evidence of water wells are located in China. The Neolithic Chinese discovered and made extensive use of deep drilled groundwater for drinking. Archaeological evidence and old Chinese documents reveal that the prehistoric and ancient Chinese had the aptitude and skills for digging deep water wells for drinking water as early as 6000 to 7000 years ago.

Devices such as shadoofs were used to lift water to ground level. Ruins from the Indus Valley Civilization had settlements with some of the ancient world's most sophisticated sewage systems. They included drainage channels, rainwater harvesting, and street ducts.

The ancient Greek civilization of Crete was the first civilization to use underground clay pipes for sanitation and water supply. Their capital had a well-organized water system for bringing in clean water, taking out waste water and storm sewage canals for overflow when there was heavy rain. It was also one of the first uses of a flush toilet, dating back to the 18th century BC. In addition to sophisticated water and sewer systems they devised elaborate heating systems. The Ancient Greeks of Athens and Asia Minor also used an indoor plumbing system, used for pressurized showers. The Greek inventor Heron used pressurized piping for fire fighting purposes in the City of Alexandria.The Mayans were the third earliest civilization to have employed a system of indoor plumbing using pressurized water.

An inverted siphon system, along with glass covered clay pipes, was used for the first time in the palaces of Crete, Greece. It is still in working condition, after about 3000 years.

Fig.1.1.1. Pont du Gard, a Roman aqueduct in France.

In ancient Rome, the Cloaca Maxima, considered a marvel of engineering, discharged into the Tiber. Public latrines were built over the Cloaca Maxima.

Fig.1.1.2. Ancient Rome factual approximation

Beginning in the Roman era a water wheel device known as a noria supplied water to aqueducts (Fig.1.1.1.) and other water distribution systems in major cities in Europe and the Middle East.

The Roman Empire had indoor plumbing, meaning a system of aqueducts and pipes that terminated in homes and at public wells and fountains for people to use (Fig.1.1.2.). Rome and other nations used lead pipes; while commonly thought to be the cause of lead poisoning in the Roman Empire, the combination of running water which did not stay in contact with the pipe for long and the deposition of precipitation scale actually mitigated the risk from lead pipes.

Roman towns and garrisons in the United Kingdom between 46 BC and 400 AD had complex sewer networks sometimes constructed out of hollowed-out elm logs, which were shaped so that they butted together with the down-stream pipe providing a socket for the upstream pipe.

There is little record of other sanitation systems (apart of sanitation in ancient Rome) in most of Europe until the High Middle Ages. Unsanitary conditions and overcrowding were widespread throughout Europe and Asia during the Middle Ages. This resulted in pandemics which killed tens of millions of people. Very high infant and child mortality prevailed in Europe throughout medieval times, due partly to deficiencies in sanitation.

In medieval European cities, small natural waterways used for carrying off wastewater were eventually covered over and functioned as sewers. London's River Fleet is such a system. Open drains, or gutters, for waste water run-off ran along the center of some streets. These were known as canals, channels and in Paris were sometimes known as “split streets,” as the waste water running along the middle physically split the streets into two halves. The first closed sewer constructed in Paris was designed by Hugues Aubird in 1370 on Montmartre Street and was 300 meters long. The original purpose of designing and constructing a closed sewer in Paris was less-so for waste management as much as it was to hold back the stench coming from the odorous waste water. In Dubrovnik, then known as Ragusa (Latin name), the Statute of 1272 set out the parameters for the construction of septic tanks and channels for the removal of dirty water. Throughout the 14th and 15th century the sewage system was built, and it is still operational today, with minor changes and repairs done in recent centuries. Pail closets, outhouses, and cesspits were used to collect human waste. The use of human waste as fertilizer was especially important in China and Japan, where cattle manure was less available. However, most cities did not have a functioning sewer system before the Industrial era, relying instead on nearby rivers or occasional rain showers to wash away the sewage from the streets. In some places, waste water simply ran down the streets, which had stepping stones to keep pedestrians out of the muck, and eventually drained as runoff into the local watershed.

In the 16th century, Sir John Harington invented a flush toilet as a device for Queen Elizabeth I (his godmother) that released wastes into cesspools. After the adoption of gunpowder, municipal outhouses became an important source of raw material for the making of saltpeter in European countries. In London, the contents of the city's outhouses were collected every night by commissioned wagons and delivered to the nitrite beds where it was laid into specially designed soil beds to produce earth rich in mineral nitrates. The nitrate rich-earth would be then further processed to produce saltpeter, or potassium nitrate, an important ingredient in black powder that played a part in the making of gunpowder.

Sewage farms (i.e. wastewater application to the land for disposal and agricultural use) were operated in Silesia in 1531, in Scotland in 1650, in Paris in 1868, in Berlin in 1876 and in different parts of the USA since 1871, where wastewater was used for beneficial crop production. In the 16th and 18th centuries in many rapidly growing countries/cities of Europe (e.g. Germany, France) and the United States, “sewage farms” were increasingly seen as a solution for the disposal of large volumes of the wastewater, some of which are still in operation today. Irrigation with sewage and other wastewater effluents has a long history also in China and India; while also a large “sewage farm” was established in Australia in 1897.

1.1.2. Modern age

1.1.2.1. Sewer systems

A significant development was the construction of a network of sewers to collect wastewater. In some cities, including Rome, Istanbul (Constantinople) networked ancient sewer systems continue to function today as collection systems for those cities modernized sewer systems. Instead of flowing to a river or the sea, the pipes have been re-routed to modern sewer treatment facilities.

Basic sewer systems were used for waste removal in ancient Mesopotamia, where vertical shafts carried the waste away into cesspools. Similar systems existed in the Indus Valley civilization in modern-day India and in Ancient Crete and Greece. In the Middle Ages the sewer systems built by the Romans fell into disuse and waste was collected into cesspools that were periodically emptied by workers known as 'rakers' who would often sell it as fertilizer to farmers outside the city.

The tremendous growth of cities in Europe and North America during the Industrial Revolution quickly led to crowding, which acted as a constant source for the outbreak of disease. As cities grew in the 19th century concerns were raised about public health.As part of a trend of municipal sanitation programs in the late 19th and 20th centuries, many cities constructed extensive gravity sewer systems to help control outbreaks of disease such as typhoid and cholera. Storm and sanitary sewers were necessarily developed along with the growth of cities. By the 1840s the luxury of indoor plumbing, which mixes human waste with water and flushes it away, eliminated the need for cesspools.

Modern sewerage systems were first built in the mid-nineteenth century as a reaction to the exacerbation of sanitary conditions brought on by heavy industrialization and urbanization. Baldwin Latham, a British civil engineer contributed to the rationalization of sewerage and house drainage systems and was a pioneer in sanitary engineering. He developed the concept of oval sewage pipe to facilitate sewer drainage and to prevent sludge deposition and flooding. Due to the contaminated water supply, cholera outbreaks occurred in 1832, 1849 and 1855 in London, killing tens of thousands of people. This, combined with the Great Stink of 1858, when the smell of untreated human waste in the River Thames became overpowering, and the report into sanitation reform of the Royal Commissioner Edwin Chadwick, led to the Metropolitan Commission of Sewers appointing Joseph Bazalgette to construct a vast underground sewage system for the safe removal of waste. Contrary to Chadwick's recommendations, Bazalgette's system, and others later built in Continental Europe, did not pump the sewage onto farm land for use as fertilizer; it was simply piped to a natural waterway away from population centres, and pumped back into the environment.

From as early as 1535 there were efforts to stop polluting the River Thames in London. Beginning with an Act passed that year that was to prohibit the dumping of excrement into the river. Leading up to the Industrial Revolution the River Thames was identified as being thick and black due to sewage, and it was even said that the river “smells like death.” As Britain was the first country to industrialize, it was also the first to experience the disastrous consequences of major urbanization and was the first to construct a modern sewerage system to mitigate the resultant unsanitary conditions. During the early 19th century, the River Thames was effectively an open sewer, leading to frequent outbreaks of cholera epidemics. Proposals to modernize the sewerage system had been made during 1856 but were neglected due to lack of funds. However, after the *Great Stink* of 1858, Parliament realized the urgency of the problem and resolved to create a modern sewerage system.

Joseph Bazalgette, a civil engineer and Chief Engineer of the Metropolitan Board of Works, was given responsibility for the work. He designed an extensive underground sewerage system that diverted waste to the Thames Estuary, downstream of the main center of population. Six main interceptor sewers, totaling almost 160 km in length, were constructed, some incorporating stretches of London's 'lost' rivers. Three of these sewers were north of the river, the southernmost, low-level one being incorporated in the Thames Embankment. The Embankment also allowed new roads, new public gardens, and the Circle Line of the London Underground.

The intercepting sewers, constructed between 1859 and 1865, were fed by 720 km of main sewers that, in turn, conveyed the contents of some 21000 km of smaller local sewers. Construction of the interceptor system required 318 million bricks, 2.7 million cubic metres of excavated earth and 670000 cubic metres of concrete. With only minor modifications, Bazalgette's engineering achievement remains the basis for sewerage design up into the present day.

In 1802, Napoleon built the Ourcq canal which brought 70 000 cubic meters of water a day to Paris, while the Seine river received up to 100 000 cubic meters of wastewater per day. The Paris cholera epidemic of 1832 sharpened the public awareness of the necessity for some sort of drainage system to deal with sewage and wastewater in a better and healthier way. Between 1865 and 1920 Eugene Belgrand lead the development of a large scale system for water supply and wastewater management. Between these years approximately 600 kilometers of aqueducts were built to bring in potable spring water, which freed the poor quality water to be used for flushing streets and sewers. By 1894 laws were passed which made drainage mandatory. The treatment of Paris sewage was left to natural devices as 5000 hectares of land were used to spread the waste out to be naturally purified.

The first comprehensive sewer system in a German city was built in Hamburg_ in the mid-19th century. In 1863, work began on the construction of a modern sewerage system for the rapidly growing city of Frankfurt am Main, based on design work by William Lindley. 20 years after the system's completion, the death rate from typhoid had fallen from 80 to 10 per 100 000 inhabitants.

The first sewer systems in the United States were built in the late 1850s in Chicago and Brooklyn. Initially the gravity sewer systems discharged sewage directly to surface waters without treatment. Later, cities attempted to treat the sewage before discharge in order to prevent water pollution and waterborne diseases. During the half-century around 1900, these public health interventions succeeded in drastically reducing the incidence of water-borne diseases among the urban population, and were an important cause in the increases of life expectancy experienced at the time.

Early techniques for sewage treatment involved land application of sewage on agricultural land. One of the first attempts at diverting sewage for use as a fertilizer in the farm was made by the cotton mill owner James Smith in the 1840s. He experimented with a piped distribution system initially proposed by James Vetch that collected sewage from his factory and pumped it into the outlying farms, and his success was enthusiastically followed by Edwin Chadwick and supported by organic chemist Justus von Liebig.

The idea was officially adopted by the Health of Towns Commission, and various schemes (known as sewage farms) were trialled by different municipalities over the next 50 years. At first, the heavier solids were channeled into ditches on the side of the farm and were covered over when full, but soon flat-bottomed tanks were employed as reservoirs for the sewage; the earliest patent was taken out by William Higgs in 1846 for 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. Improvements to the design of the tanks included the introduction of the horizontal-flow tank in the 1850s and the radial-flow tank in 1905. These tanks had to be manually de-sludged periodically, until the introduction of automatic mechanical de-sludgers in the early 1900s.

Fig. 1.1.3. A Chinese ceramic model of a well with a water pulley system, excavated from a tomb of the Han Dynasty (202 BC - 220 AD) period (left) and typical old medieval water wells (right).

1.1.2.2. Chemical treatment and sedimentation

As pollution of water bodies became a concern, cities attempted to treat the sewage before discharge. In the late 19th century some cities began to add chemical treatment and sedimentation systems to their sewers. In the United States, the first sewage treatment plant using chemical precipitation was built in Massachusetts in 1890. During the half-century around 1900, these public health interventions succeeded in drastically reducing the incidence of water-borne diseases among the urban population, and were an important cause in the increases of life expectancy experienced at the time.

Odor was considered the big problem in waste disposal and to address it, sewage could be drained to a lagoon, or "settled" and the solids removed, to be disposed of separately. This process is now called "primary treatment" and the settled solids are called "sludge." At the end of the 19th century, since primary treatment still left odor problems, it was discovered that bad odors could be prevented by introducing oxygen into the decomposing sewage. This was the beginning of the biological aerobic and anaerobic treatments which are fundamental to wastewater processes.

The precursor to the modern septic tank was the cesspool in which the water was sealed off to prevent contamination and the solid waste was slowly liquified due to anaerobic action; it was invented by L.H Mouras in France in the 1860s. Donald Cameron, as City Surveyor for Exeter patented an improved version in 1895, which he called a 'septic tank'; septic having the meaning of 'bacterial'. These are still in worldwide use, especially in rural areas unconnected to large-scale sewage systems.

1.1.2.3. Biological treatment

It was not until the late 19th century that it became possible to treat the sewage by biologically decomposing the organic components through the use of microorganisms and removing the pollutants. Land treatment was also steadily becoming less feasible, as cities grew and the volume of sewage produced could no longer be absorbed by the farmland on the outskirts.

Edward Frankland conducted experiments at the sewage farm in England, during the 1870s and was able to demonstrate that filtration of sewage through porous gravel produced a nitrified effluent (the ammonia was converted into nitrate) and that the filter remained unclogged over long periods of time.This established the revolutionary possibility of biological treatment of sewage using a contact bed to oxidize the waste.

From 1885 to 1891 filters working on this principle were constructed throughout the UK and the idea was also taken up in the US at the Lawrence Experiment Station in Massachusetts, where Frankland's work was confirmed. Contact beds were tanks containing an inert substance, such as stones or slate, that maximized the surface area available for the microbial growth to break down the sewage. The sewage was held in the tank until it was fully decomposed and it was then filtered out into the ground.

1.1.2.4. Activated sludge process

Most cities in the Western world added more expensive systems for sewage treatment in the early 20th century, after scientists at the University of Manchester discovered the sewage treatment process of activated sludge in 1912.

The activated sludge process was discovered in 1913 in the United Kingdom by two engineers, Edward Ardern and W.T. Lockett, who were conducting research for the Manchester Corporation Rivers Department. In 1912, Dr. Gilbert Fowler, a scientist at the University of Manchester, observed experiments being conducted at the Lawrence Experiment Station at Massachusetts involving the aeration of sewage in a bottle that had been coated with algae. Fowler's engineering colleagues, Ardern and Lockett, experimented on treating sewage in a draw-and-fill reactor, which produced a highly treated effluent. They aerated the waste-water continuously for about a month and were able to achieve a complete nitrification of the sample material. Believing that the sludge had been activated the process was named *activated sludge*. Not until much later was it realized that what had actually occurred was a means to concentrate biological organisms, decoupling the liquid retention time from the solids retention time.Their results were published in their seminal 1914 paper, and the first full-scale continuous-flow system was installed at Worcester two years later.

1.1.2.5. Water treatment

The first documented use of sand filters to purify the water supply dates to 1804, when the owner of a bleachery in Scotland, John Gibb, installed an experimental filter, selling his unwanted surplus to the public. This method was refined in the following two decades by engineers working for private water companies, and it culminated in the first treated public water supply in the world, installed by engineer James Simpson for the Waterworks Company in London in 1829. This installation provided filtered water for every resident of the area, and the network design was widely copied throughout the United Kingdom in the ensuing decades. Early attempts at implementing water chlorination at a water treatment plant were made in 1893 in Germany, and in 1897 in England, was the first to have its entire water supply treated with chlorine. Permanent water chlorination began in 1905, when a faulty slow sand filter and a contaminated water supply led to a serious typhoid fever epidemic in England. Founders of microscopy, Antonie van Leeuwenhoek and Robert Hooke, used the newly invented microscope to observe for the first time small material particles that were suspended in the water, laying the groundwork for the future understanding of waterborne pathogens and waterborne diseases.

1.1.2.6. Water supply and sanitation in medieval Pressburg (Bratislava)

Fig. 1.1.4. The first digged well on the Sihoť Island for Pressburg (upper left), Water Works at the Sihoť(upper right), Inventor of drinking water pumping to the castle of Pressburg Wolfgang von Kempelen (lower left) and Company which constructed the first 4.1 km of sewerage for the city of Pressburg (lower right).

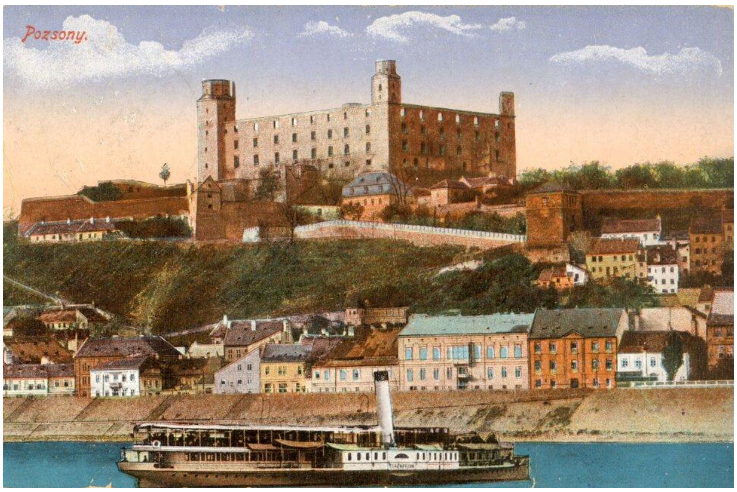


Fig. 1.1.5. Prešporok (Bratislava), Pressburg, Pozson in the middle-age time.

During the 16th century Pressburg (Bratislava) inhabitants used plenty wells, such as on the streets Hlavné námestie, Zámocká, Kapitulská, Michalská brána and the others (Fig.1.3.). Drinking water was supplied also from surrounded Malé Karpaty mountains using for transportation firstly stone and wooden and later on copper pipes and troughs. Around the year 1760 there was digged some well on the Danube river embankment which supplied with drinking water and horse drive the castle reservoir. Construction of the first objects of the city plumbing was started on the August 25, 1884 by C. Corte Company which managed Bernard Salbach. Since the February 1886 started the operation of the first city plumbing for 50 000 inhabitants with the capacity of 1059 m^3/d (20 liter/d/inhabitant) using the steam pump.

The first water pumping station was constructed on the left bank of the Danube River in Karlova Ves in 1886. Together with the well on the island of Sihoť and the water reservoir near Bratislava Castle, the pumping station forms the base of the waterworks for Bratislava.
Drinking water was supplied from underground sources on the island of Sihoť.These sources have been rich in naturally filtered water from the Danube. Water was supplied from the water well on Sihoť to the main pumping station in Karlova Ves via a 1.7 km pipeline. From there, water was distributed by steam pumps to the entire city and then into the main water reservoir near Bratislava Castle. Designed and engineered by Bernhard Salbach and Zdenko Ritter von Wessely, Bratislava's waterworks use a pressure-gravity system and were the first of their kind in Slovakia. The island's first water well from 1886 is surrounded by a high bank and lined with granite to protect it from floods (Fig.1.1.4.). In the past, 3000 m^3 of water could be pumped from this well. The first pumping station with electric pumps was built on the island in 1912. Leading from here is a 100 meter concrete tunnel with water pipes, located beneath the arm of the Danube river. The Karloveské rameno is one of the few free-flowing arms of the Danube along the entire section of the Danube flowing through Slovakia. Its total length is 4 800 m and it flows around the island of Sihoť, one of the most important sources of drinking water in Bratislava. The original vegetation of the floodplain forest and natural willow-poplar forests which complement it are preserved in the surroundings of the Karloveské rameno. It is the home of many rare plant and animal species.

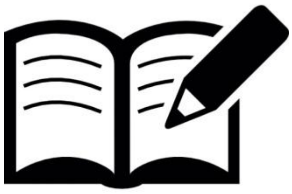
The first 4.1 km long sewerage system was constructed in Pressburg (old Bratislava) during the years 1897 – 1900 by Pittel & Brausenwetter Company (Fig.1.1.4. and 1.1.5.).

Conclusions

Early human habitations were often built next to water sources. Rivers would often serve as a crude form of natural sewage disposal. Some of the earliest evidence of water wells are located in China. The Roman Empire had indoor plumbing, meaning a system of aqueducts and pipes that terminated in homes and at public wells and fountains for people to use. Rome and other nations used lead pipes; while commonly thought to be the cause of lead poisoningin the Roman Empire, the combination of running water which did not stay in contact with the pipe for long and the deposition of precipitation scale actually mitigated the risk from lead pipes. In the 16th and 18th centuries in many rapidly growing countries/cities of Europe (e.g. Germany, France) and the United States, “sewage farms” were increasingly seen as a solution for the disposal of large volumes of the wastewater, some of which are still in operation today. Irrigation with sewage and other wastewater effluents has a long history also in China and India; while also a large “sewage farm” was established in Australia in 1897. It was not until the late 19th century that it became possible to treat the sewage by biologically decomposing the organic components through the use of microorganisms and removing the pollutants. The activated sludge process was discovered in 1913 in the United Kingdom by two engineers, Edward Ardern and W.T. Lockett, who were conducting research for the Manchester Corporation Rivers Department.

Questions for self-control

1. How can you characterize history of water supply and sanitation?
2. What do you understand under the Cloaca Maxima?
3. How can you define sewage farms and how cesspool?
4. Who are inventors of activated sludge process?



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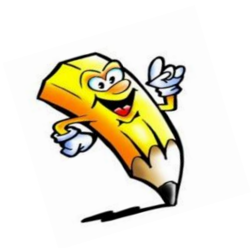
1.2. Water purification

In this section you will learn about

- ✓ Pretreatment of surface water
- ✓ Sedimentation
- ✓ Coagulation and flocculation
- ✓ Water softening
- ✓ pH adjustment
- ✓ Disinfection.

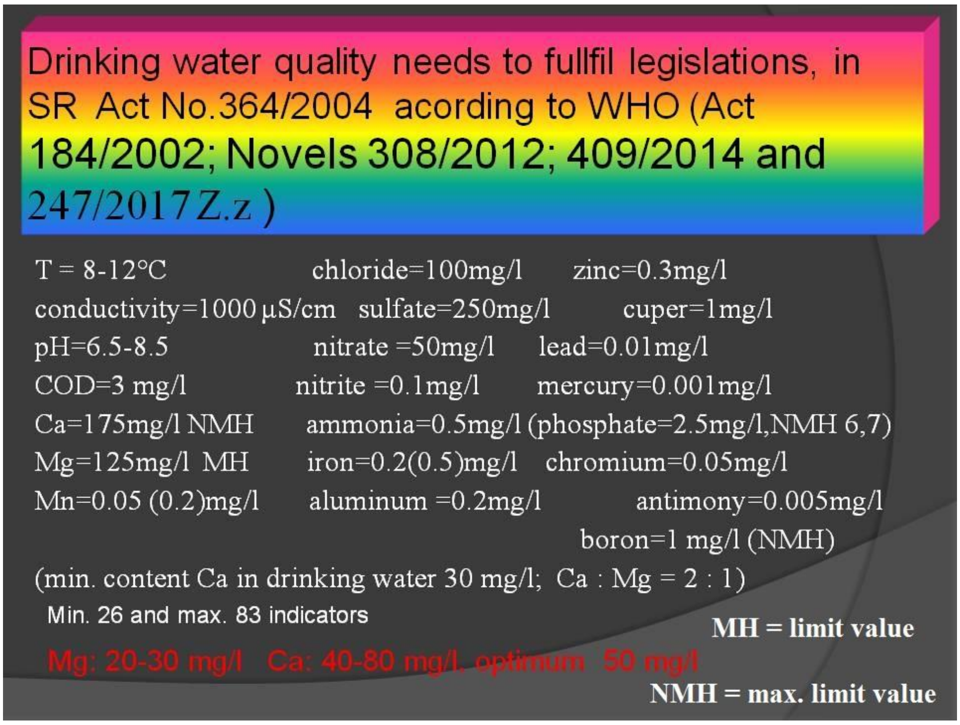


Key words:

Water purification, underground and surface waters
Water pretreatment, sedimentation, coagulation and flocculation
Water softening, pH adjustment, disinfection, drinking water quality
Solids, microorganisms, dissolved inorganic and organic substances

Water purification means the process of removing undesirable chemicals, biological contaminants, suspended solids, and gases from water. The goal is to produce water that is fit for specific purposes. The history of water purification includes a wide variety of methods. The methods used include physical processes such as filtration, sedimentation, and distillation and chemical processes such as slow sand filters or active carbon, flocculation and the use of electromagnetic radiation such as ultraviolet light. Water purification may reduce the concentration of particulate matter including suspended particles, parasites, bacteria, algae, viruses, and fungi as well as reduce the concentration of a range of dissolved and particulate matter. Simple procedures such as boiling or the use of a household activated carbon filter are not sufficient for treating all possible contaminants that may be present in water from an unknown source. Even natural spring water, considered safe for all practical purposes in the 19th century, must now be tested before determining what kind of treatment, if any, is needed. Chemical and microbiological analysis, while expensive, are the only way to obtain the information necessary for deciding on the appropriate method of purification.

The standards for drinking water quality are typically set by governments or by international standards. These standards usually include minimum and maximum concentrations of contaminants, depending on the intended use of the water. Table 1.2.1 illustrates individual element concentrations valid according to Slovak Water Act in drinking water.



Tab. 1.2.1. Drinking water quality indicators (physico-chemical) according to Slovak Water Act.

Widely varied techniques are available to remove contaminants like fine solids, micro-organisms and some dissolved inorganic and organic materials, or environmental persistent pharmaceutical pollutants. The choice of method will depend on the quality of the water being treated, the cost of the treatment process and the quality standards expected of the processed water. The processes below are the ones commonly used in water purification plants.

1.2.1. Pretreatment of water

The majority of water must be pumped from its source or directed into pipes or holding tanks. To avoid adding contaminants to the water, this physical infrastructure must be made from appropriate materials and constructed so that accidental contamination does not occur. The first step in purifying surface water is to remove large debris such as sticks, leaves, rubbish and other large particles which may interfere with subsequent purification steps. Most deep groundwater does not need screening before other purification steps.

1.2.1.1. Sedimentation

Waters exiting the flocculation basin may enter the sedimentation basin, also called a clarifier or settling basin (Fig. 1.2.1). It is a large tank with low water velocities, allowing floc to settle to the bottom. The sedimentation basin is best located close to the flocculation basin so the

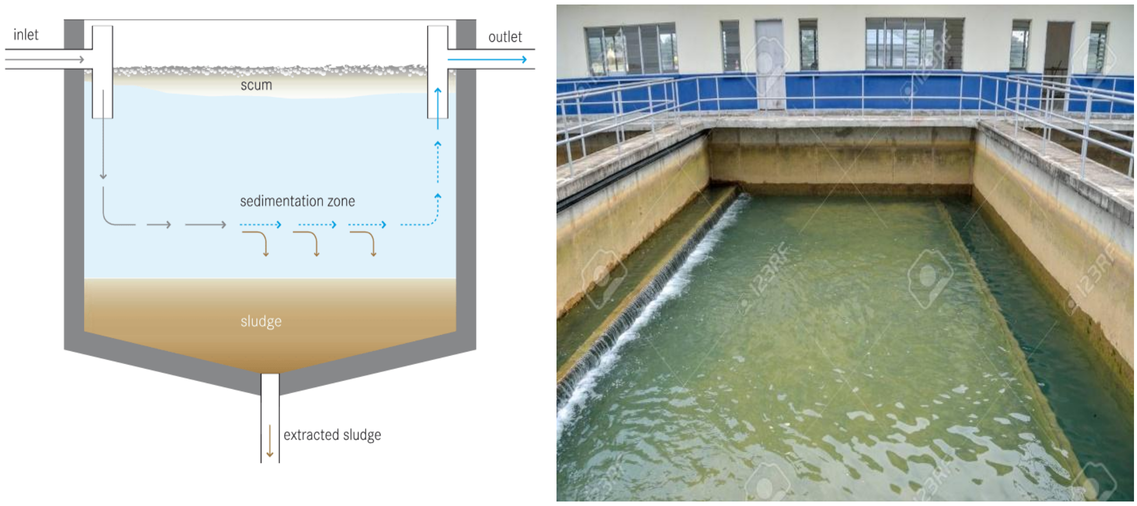


Fig. 1.2.1. Sketch of sedimentation tank (left) and sedimentation basin in real waterworks (right).

transit between the two processes does not permit settlement or floc break up. Sedimentation basins may be rectangular, where water flows from end to end, or circular where flow is from the centre outward. Sedimentation basin outflow is typically over a weir so only a thin top layer of water - that furthest from the sludge - exits. In general, sedimentation basin efficiency is not a function of detention time or depth of the basin. Although, basin depth must be sufficient so that water currents do not disturb the sludge and settled particle interactions are promoted. As particle concentrations in the settled water increase near the sludge surface on the bottom of the tank, settling velocities can increase due to collisions and agglomeration of particles. Typical detention times for sedimentation vary from 1.5 to 4 hours. As particles settle to the bottom of a sedimentation basin, a layer of sludge is formed on the floor of the tank which must be removed and treated. The amount of sludge generated is significant, often 3 to 5 percent of the total volume of water to be treated. The cost of treating and disposing of the sludge can impact the operating cost of a water treatment plant. The sedimentation basin may be equipped with mechanical cleaning devices that continually clean its bottom, or the basin can be periodically taken out of service and cleaned manually.

1.2.1.2. Sand filtration

The most common type of filter is a rapid sand filter. Water moves vertically through sand which often has a layer of activated carbon or anthracite coal above the sand. The top layer removes organic compounds, which contribute to taste and odour. The space between sand particles is larger than the smallest suspended particles, so simple filtration is not enough. Most particles pass through surface layers but are trapped in pore spaces or adhere to sand particles. Effective filtration extends into the depth of the filter. This property of the filter is key to its operation. If the top layer of sand were to block all the particles, the filter would quickly clog (Fig.1.2.2.).

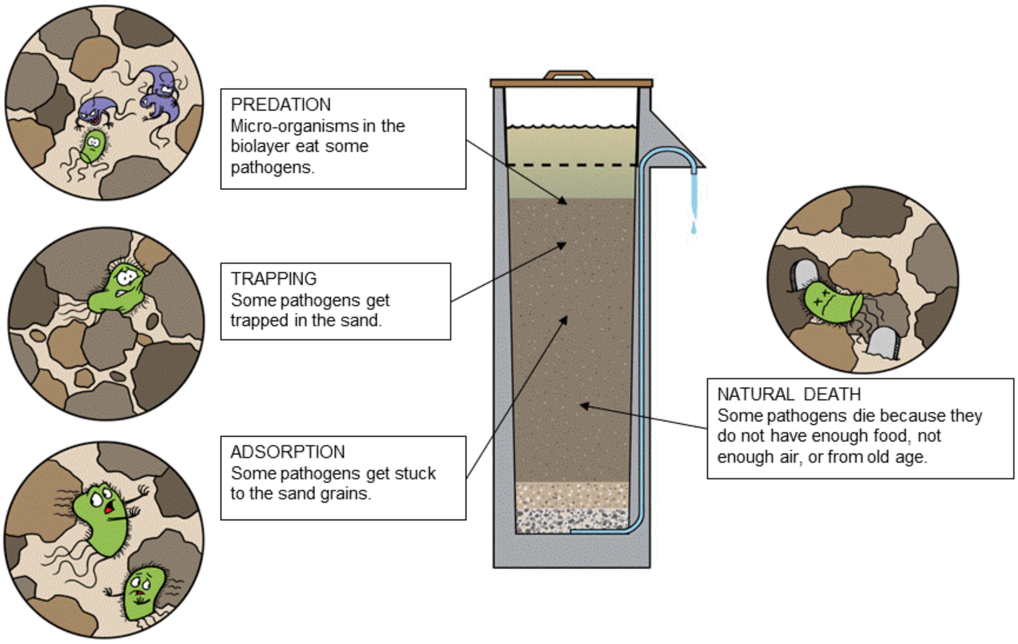


Fig. 1.2.2. Principle of mechanical sand filtration.

To clean the filter, water is passed quickly upward through the filter, opposite the normal direction (called *backwashing*) to remove embedded or unwanted particles. Prior to this step, compressed air may be blown up through the bottom of the filter to break up the compacted filter media to aid the backwashing process; this is known as *air scouring*. This contaminated water can be disposed of, along with the sludge from the sedimentation basin, or it can be recycled by mixing with the raw water entering the plant although this is often considered poor practice since it re-introduces an elevated concentration of bacteria into the raw water. Slow sand filters may be used where there is sufficient land and space, as the water flows very slowly through the filters. An effective slow sand filter may remain in service for many weeks or even months, if the pretreatment is well designed, and produces water with a very low available nutrient level which physical methods of treatment rarely achieve. Some water treatment plants employ pressure filters (Fig.1.2.3.). These work on the same principle as rapid gravity filters, differing in that the filter medium is enclosed in a steel vessel and the water is forced through it under pressure.

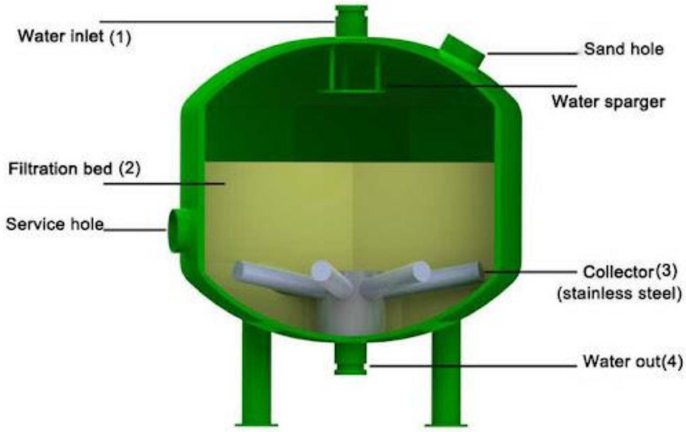


Fig. 1.2.3. Commercial steel pressure filter composition.

1.2.1.3. Coagulation and flocculation

One of the first steps in most conventional water purification processes is the addition of chemicals to assist in the removal of particles suspended in water. Particles can be inorganic such as clay and silt or organic such as algae, bacteria, viruses, protozoa and natural organic matter. Inorganic and organic particles contribute to the turbidity and color of water.

The addition of inorganic coagulants such as aluminum sulfate (or alum) or iron (III) salts such as iron(III) chloride cause several simultaneous chemical and physical interactions on and among the particles. Within seconds, negative charges on the particles are neutralized by inorganic coagulants. Also within seconds, metal hydroxide precipitates of the iron and aluminium ions begin to form (Fig.1.2.4.).

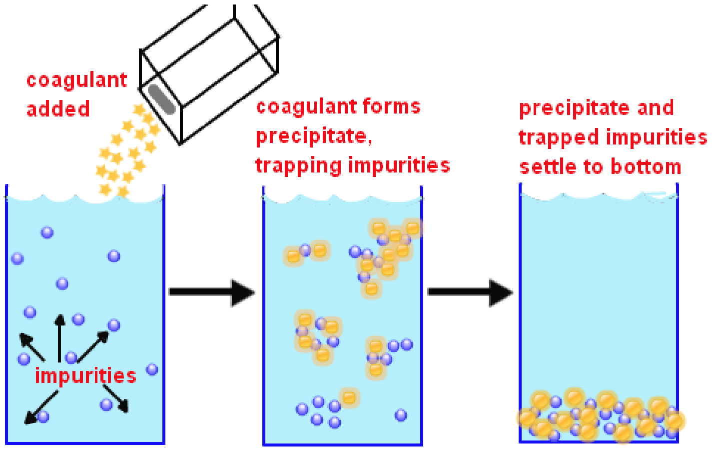


Fig. 1.2.4. Basic process explanation for coagulation and flocculation.

These precipitates combine into larger particles under natural processes such as Brownian motion and through induced mixing which is sometimes referred to as flocculation. Amorphous metal hydroxides are known as "floc". Large, amorphous aluminum and iron (III) hydroxides adsorb and enmesh particles in suspension and facilitate the removal of particles by subsequent processes of sedimentation and filtration. Aluminum hydroxides are formed within a fairly narrow pH range, typically: 5.5 to about 7.7. Iron (III) hydroxides can form over a larger pH range including pH levels lower than are effective for alum, typically 5.0 to 8.5. In water purification plants, there is usually a high energy, rapid mix unit process (detention time in seconds) whereby the coagulant chemicals are added followed by flocculation basins (detention times range from 15 to 45 minutes) where low energy inputs turn large paddles or other gentle mixing devices to enhance the formation of floc. In fact, coagulation and flocculation processes are ongoing once the metal salt coagulants are added (Fig.1.2.5. and Fig. 1.2.6.).

Organic polymers were developed in the 1960s as aids to coagulants and, in some cases, as replacements for the inorganic metal salt coagulants. Synthetic organic polymers are high molecular weight compounds that carry negative, positive or neutral charges. When organic polymers are added to water with particulates, the high molecular weight compounds adsorb onto particle surfaces and through interparticle bridging coalesce with other particles to form floc.

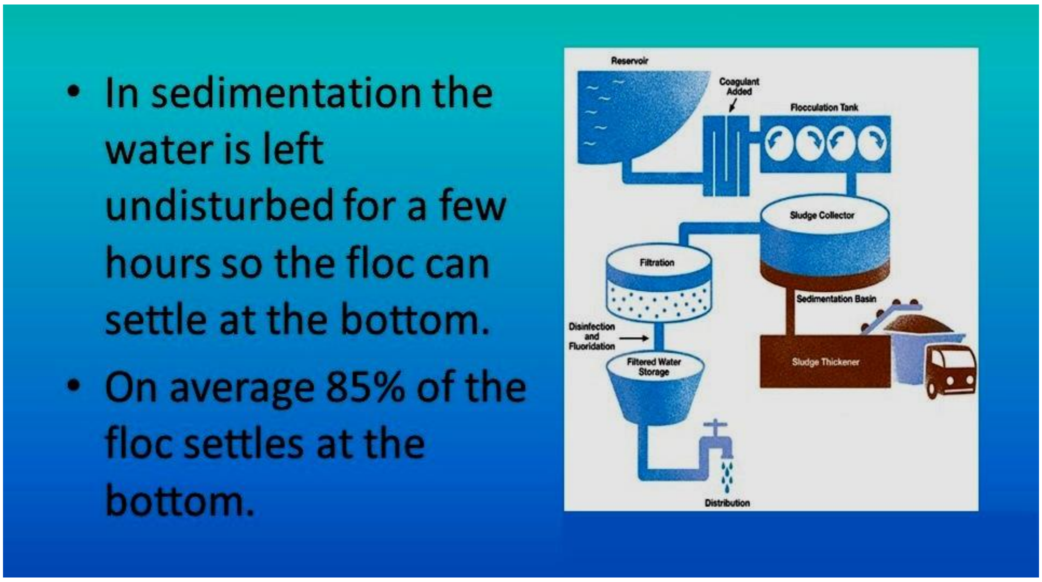


Fig. 1.2.5. Sketch of surface water purification incl. coagulation and flocculation.

Fig. 1.2.6. View of coagulation & flocculation process in real waterworks.

1.2.1.4. Water softening

Water softening is the removal of calcium, magnesium, and certain other metal cations in hard water. The resulting soft water requires less soap for the same cleaning effort, as soap is not wasted bonding with calcium ions. Soft water also extends the lifetime of plumbing by reducing or eliminating scale build-up in pipes and fittings. Water softening is usually achieved using lime softening or ion-exchange resins but is increasingly being accomplished using nanofiltration or reverse osmosis membranes. Hard water contains calcium or magnesium ions that form insoluble salts upon reacting with soap, leaving a coating of insoluble stearates on tub and shower surfaces, commonly called soap scum (Fig.1.2.7.).

Fig.1.2.7. Limescale in a PVC pipe.

Fig. 1.2.8. Ion exchange resin in the form of beads.

Water rich in hardness (calcium and magnesium ions) is treated with lime (calcium oxide) and/or soda-ash (sodium carbonate) to precipitate calcium carbonate out of solution utilizing the common-ion effect. Lime softening is the process in which lime is added to hard water to make it softer. It has several advantages over the ion-exchange method but is mainly suited to commercial treatment applications. In this method, water is treated with a calculated amount of washing soda (Na_2CO_3), which converts the chlorides and sulfates of calcium and magnesium into their respective carbonates, which get precipitated:

$CaCl_2 + Na_2CO_3 \dashrightarrow CaCO_3 + 2NaCl$
$MgSO_4 + Na_2CO_3 \dashrightarrow MgCO_3 + Na_2SO_4$

Ion exchange resins in the form of beads **(**Fig.1.2.8.) are organic polymers containing anionic functional groups to which the divalent cations (Ca^{2+}) bind more strongly than monovalent cations (Na^+). Inorganic materials called zeolites also exhibit ion-exchange properties (Fig. 1.2.9.). These minerals are widely used in laundry detergents. Resins are also available to remove the carbonate, bicarbonate, and sulfate ions that are absorbed and hydroxide ions that are released from the resin.

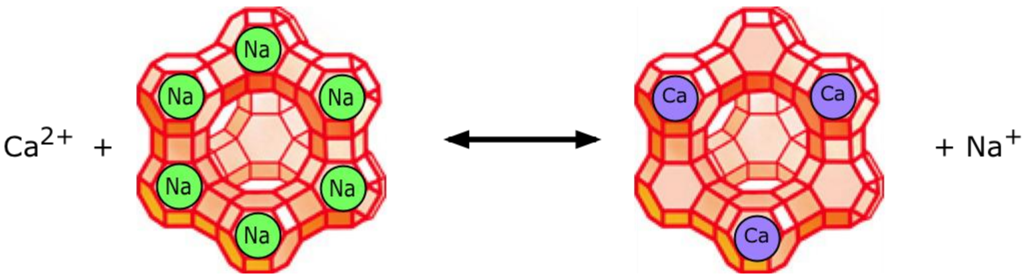


Fig. 1.2.9. Synthetic zeolites NaA, NaX or NaP in micrometric size used to be applied for detergents production since 1970.

When all the available Na^+ ions have been replaced with calcium or magnesium ions, the resin must be recharged by eluting the Ca^{2+} and Mg^{2+} ions using a solution of sodium chloride or sodium hydroxide, depending on the type of resin used. For anionic resins, regeneration typically uses a solution of sodium hydroxide (lye) or potassium hydroxide. The waste waters eluted from the ion-exchange column containing the unwanted calcium and magnesium salts are typically discharged to the sewage system.

1.2.1.5. pH adjustment

Pure water has a pH close to 7 (neither alkaline nor acidic). Sea water can have pH values that range from 7.5 to 8.4 (moderately alkaline). Fresh water can have widely ranging pH values depending on the geology of the drainage basin or aquifer and the influence of contaminant inputs (acid rain). If the water is acidic (lower than 7), lime, soda ash, or sodium hydroxide can be added to raise the pH during water purification processes. Lime addition increases the calcium ion concentration, thus raising the water hardness. For highly acidic waters, forced draft degasifiers can be an effective way to raise the pH, by stripping dissolved carbon dioxide from the water. Making the water alkaline helps coagulation and flocculation processes work effectively and also helps to minimize the risk of lead being dissolved from lead pipes and from lead solder in pipe fittings. Sufficient alkalinity also reduces the corrosiveness of water to iron pipes. Acid (carbonic acid, hydrochloric acid or sulfuric acid) may be added to alkaline waters in some circumstances to lower the pH. Alkaline water (above pH 7.0) does not necessarily mean that lead or copper from the plumbing system will not be dissolved into the water. The ability of water to precipitate calcium carbonate to protect metal surfaces and reduce the likelihood of toxic metals being dissolved in water is a function of pH, mineral content, temperature, alkalinity and calcium concentration.

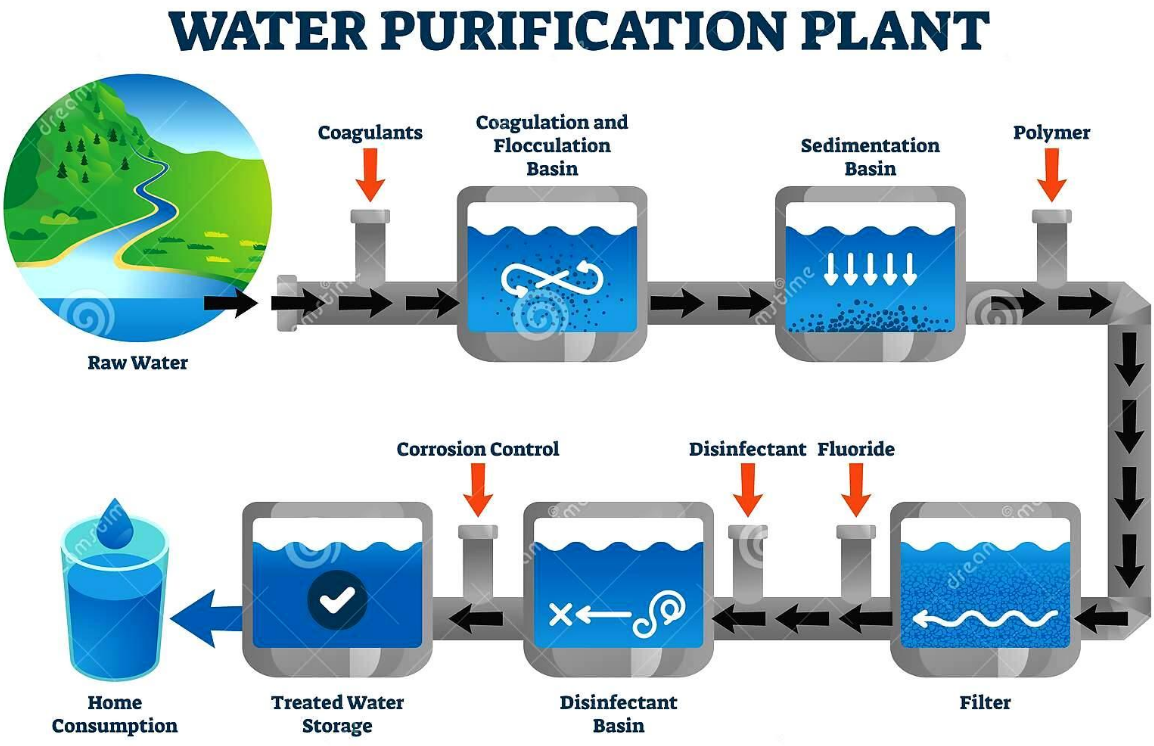


Fig. 1.2.10. Scheme of conventional surface water purification in waterworks (upper figure a typical surface water pumping into waterworks from the middle of reservoir).

1.2.1.6. Disinfection

Disinfection is accomplished both by filtering out harmful micro-organisms and by adding disinfectant chemicals. Water is disinfected to kill any pathogens which pass through the filters and to provide a residual dose of disinfectant to kill or inactivate potentially harmful micro-organisms in the storage and distribution systems. Possible pathogens include viruses, bacteria, including *Salmonella*, *Cholera*, *Campylobacter* and *Shigella*, and protozoa, including *Giardia lamblia* and other *cryptosporidia*. After the introduction of any chemical disinfecting agent, the water is usually held in temporary storage, often called a contact tank or clear well, to allow the disinfecting action to complete. The most common disinfection method involves some form of chlorine or its compounds such as chloramine or chlorine dioxide. Chlorine is a strong oxidant that rapidly kills many harmful micro-organisms. Because chlorine is a toxic gas, there is a danger of a release associated with its use. This problem is avoided by the use of sodium hypochlorite, which is a relatively inexpensive solution used in household bleach that releases free chlorine when dissolved in water. Chlorine solutions can be generated on site by electrolyzing common salt solutions. A solid form, calcium hypochlorite, releases chlorine on contact with water. Handling the solid, however, requires more routine human contact through opening bags and pouring than the use of gas cylinders or bleach, which are more easily automated. The generation of liquid sodium hypochlorite is inexpensive and also safer than the use of gas or solid chlorine. Chlorine levels up to 4 milligrams per liter are considered safe in drinking water. One drawback is that chlorine from any source reacts with natural organic compounds in the water to form potentially harmful chemical by-products. These by-products, trihalomethanes (THMs) and haloacetic acids (HAAs), are both carcinogenic in large quantities. Although chlorine is effective in killing bacteria, it has limited effectiveness against pathogenic protozoa that form cysts in water such as *Giardia lamblia* and *Cryptosporidium*.

Chlorine dioxide is a faster-acting disinfectant than elemental chlorine. It is relatively rarely used because in some circumstances it may create excessive amounts of chlorite, which is a by-product regulated to low allowable levels. Chlorine dioxide can be supplied as an aqueous solution and added to water to avoid gas handling problems. Ultraviolet light (UV) is very effective at inactivating cysts, in low turbidity water. UV light's disinfection effectiveness decreases as turbidity increases, a result of the absorption, scattering, and shadowing caused by the suspended solids. The main disadvantage to the use of UV radiation is that, like ozone treatment, it leaves no residual disinfectant in the water; therefore, it is sometimes necessary to add a residual disinfectant after the primary disinfection process.

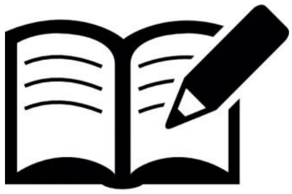
Conclusions

The water emerging from some deep ground water may have fallen as rain many tens, hundreds, or thousands of years ago. Soil and rock layers naturally filter the ground water to a high degree of clarity and often, it does not require additional treatment besides adding chlorine as secondary disinfectant. Such water may emerge as springs, artesian springs, or may be extracted from boreholes or wells. Deep ground water is generally of very high bacteriological quality (i.e. pathogenic bacteria or the pathogenic protozoa are typically absent), but the water may be rich in dissolved solids, especially carbonates and sulfates of calcium and magnesium. Depending on the strata through which the water has flowed, other ions may also be present including chloride and bicarbonate. There may be a requirement to reduce the iron or manganese content of this water to make it acceptable for drinking, cooking, and laundry use. Primary disinfection may also be required. Typically located in the headwaters of river systems, upland reservoirs are usually sited above any human habitation and may be surrounded by a protective zone to restrict the opportunities for contamination. Bacteria and pathogen levels are usually low, but some bacteria, protozoa or algae will be present. Where uplands are forested or peaty, humic acids can colour the water. Many upland sources have low pH which require adjustment.

Questions for self-control

1. How would you remove contaminants like fine solids, micro-organisms and some dissolved inorganic and organic substances from waters?

2. Describe individual treatment steps in conventional water purification process.
3. Explain the principle of coagulation and flocculation process.
4. What means disinfection and which disinfectants do you know?



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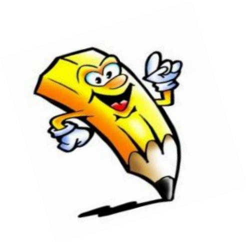
1.3. Wastewater and sewage treatment

In this section you will learn about

- ✓ Sewage treatment.
- ✓ Population equivalent.
- ✓ Screening and grit removal.
- ✓ Primary and secondary treatment, activated sludge process.
- ✓ Biological nutrient removal.
- ✓ Sludge handling.



Key words:

Sewage or municipal wastewater treatment
Sewage pretreatment: screening, grit, fat and grease removal, flow equalization
Primary and secondary clarifiers, activated sludge process
Nutrients removal and sludge handling

Sewage treatment (or domestic wastewater treatment, municipal wastewater treatment) is a type of wastewater treatment which aims to remove contaminants from sewage to produce an effluent that is suitable for discharge to the surrounding environment or an intended reuse application, thereby preventing water pollution from raw sewage discharges. Sewage contains wastewater from households and businesses and possibly pre-treated industrial wastewater. There are a high number of sewage treatment processes to choose from. These can range from decentralized systems (including on-site treatment systems) to large centralized systems involving a network of pipes and pump stations (called sewerage) which convey the sewage to a treatment plant. For cities that have a combined sewer, the sewers will also carry urban runoff (stormwater) to the sewage treatment plant. Sewage treatment often involves two main stages, called primary and secondary treatment, while advanced treatment also incorporates a tertiary treatment stage with polishing processes and nutrient removal. Secondary treatment can reduce organic matter (measured as biological oxygen demand) from sewage, using aerobic or anaerobic biological processes. With regards to biological treatment of sewage, the treatment objectives can include various degrees of the following: transform dissolved and particulate biodegradable components (especially organic matter) into acceptable end products, transform and remove nutrients (nitrogen and phosphorus), remove or inactivate pathogenic organisms, and remove specific trace organic constituents (micropollutants). Some types of sewage treatment produce sewage sludge which can be treated before safe disposal or reuse. Under certain circumstances, the treated sewage sludge might be termed "biosolids" and can be used as a fertilizer.

Sewerage (or sewage system) is the infrastructure that conveys sewage or surface runoff (stormwater, meltwater, rainwater) using sewers. It encompasses components such as receiving drains, manholes, pumping stations, storm overflows, and screening chambers of the combined sewer or sanitary sewer. Sewerage ends at the entry to a sewage treatment plant or at the point of discharge into the environment. It is the system of pipes, chambers, manholes, etc. that conveys the sewage or storm water.

1.3.1. Types of treatment processes

Sewage can be treated close to where the sewage is created, which may be called a "decentralized" system or even an "on-site" system (on-site sewage facility, septic tanks, etc.). Alternatively, sewage can be collected and transported by a network of pipes and pump stations to a municipal treatment plant.

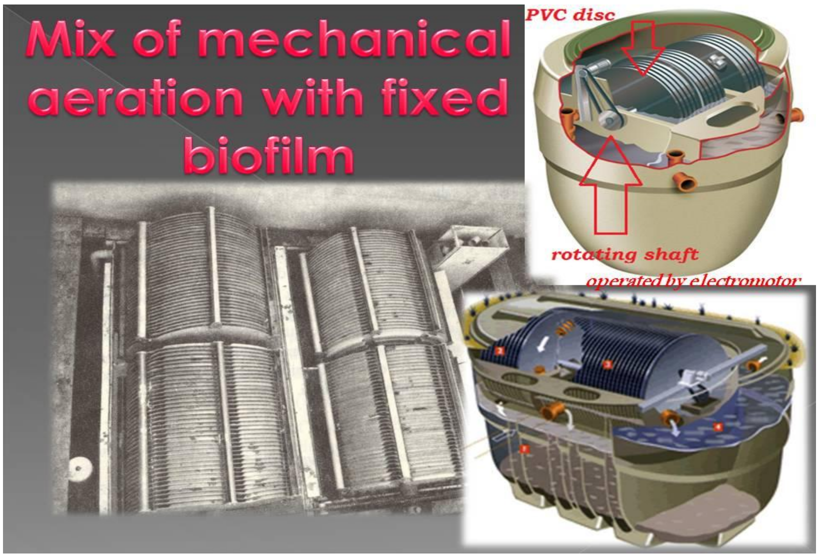


Fig.1.3.1. Municipal wastewater treatment using biodiscs.

This is called a "centralized" system (see also sewerage and pipes and infrastructure). A large number of sewage treatment technologies have been developed, mostly using biological treatment processes (see list of wastewater treatment technologies). Very broadly, they can be grouped into high tech (high cost) versus low tech (low cost) options, although some technologies might fall into either category. Other grouping classifications are "intensive" or "mechanized" systems (more compact, and frequently employing high tech options) versus "extensive" or "natural" or "nature-based" systems (usually using natural treatment processes and occupying larger areas) systems. This classification may be sometimes oversimplified, because a treatment plant may involve a combination of processes, and the interpretation of the concepts of high tech and low tech, intensive and extensive, mechanized and natural processes may vary from place to place.

There are other process options which may be classified as disposal options, although they can also be understood as basic treatment options. These include: Application of sludge, irrigation, soak pit, leach field, fish pond, floating plant pond, water disposal/groundwater recharge, surface disposal and storage. Application of sewage to land can be considered as a form of final disposal or of treatment, or both. It leads to groundwater recharge and/or to evapotranspiration. Land application include slow-rate systems, rapid infiltration, subsurface infiltration, overland flow. It is done by flooding, furrows, sprinkler and dripping. It is a treatment/disposal system that requires a large amount of land per person.

1.3.2. Population equivalent

The "per person organic matter load" is a parameter used in the design of sewage treatment plants. This concept is known as population equivalent (PE). The base value used for PE can vary from one country to another. Commonly used definitions used worldwide are: 1 PE equates to 60 gram of BOD per person per day, and it also equals 200 liters of sewage per day. This concept is also used as a comparison parameter to express the strength of industrial wastewater compared to sewage.

1.3.3. Available process steps

Sewage treatment often involves two main stages, called primary and secondary treatment, while advanced treatment also incorporates a tertiary treatment stage with polishing processes. Different types of sewage (Fig. 1.3.1.) treatment may utilize some or all of the process steps listed below. Preliminary treatment (sometimes called pretreatment) removes coarse materials that can be easily collected from the raw sewage before they damage or clog the pumps and sewage lines of primary treatment clarifiers.

1.3.3.1. Screening and grit removal

The influent in sewage water passes through a bar screen to remove all large objects like cans, rags, sticks, plastic packets, etc. carried in the sewage stream. This is most commonly done with an automated mechanically raked bar screen in modern plants serving large populations, while in smaller or less modern plants, a manually cleaned screen may be used. The raking action of a mechanical bar screen is typically paced according to the accumulation on the bar screens and/or flow rate. The solids are collected and later disposed in a landfill, or incinerated. Bar screens or mesh screens of varying sizes may be used to optimize solids removal. If gross solids are not removed, they become entrained in pipes and moving parts of the treatment plant, and can cause substantial damage and inefficiency in the process (Fig.1.3.2).

Grit consists of sand, gravel, rocks, and other heavy materials. Preliminary treatment may include a sand or grit removal channel or chamber, where the velocity of the incoming sewage is reduced to allow the settlement of grit. Grit removal is necessary to (1) reduce formation of deposits in primary sedimentation tanks, aeration tanks, anaerobic digesters, pipes, channels, etc. (2) reduce the frequency of tank cleaning caused by excessive accumulation of grit; and (3) protect moving mechanical equipment from abrasion and accompanying abnormal wear. The removal of grit is essential for equipment with closely machined metal surfaces such as comminutors, fine screens, centrifuges, heat exchangers, and high pressure diaphragm pumps.

Fig. 1.3.2. Manually-cleaned screens (left); sewage pumping into the next technology units of wastewater treatment plant (middle); horizontal flow grit chambers (right).

Grit chambers come in three types: horizontal grit chambers, aerated grit chambers, and vortex grit chambers (Fig.1.3.2.). Vortex grit chambers include mechanically induced vortex, hydraulically induced vortex, and multi-tray vortex separators. During periods of high flow deposited grit is resuspended and the quantity of grit reaching the treatment plant increases substantially. It is therefore important that the grit removal system not only operates efficiently during normal flow conditions but also under sustained peak flows when the greatest volume of grit reaches the plant.

1.3.3.2. Flow equalization

Equalization basins can be used to achieve flow equalization, with the aim to reduce peak dry-weather flows or peak wet-weather flows in the case of combined sewer systems. The benefits are performance improvements of the biological treatment processes, the secondary clarifiers and any effluent filtration equipment. Disadvantages include the basins' capital cost and space requirements. Basins can also provide a place to temporarily hold, dilute and distribute batch discharges of toxic or high-strength wastewater which might otherwise inhibit biological secondary treatment (such was wastewater from portable toilets or fecal sludge that is brought to the sewage treatment plant in vacuum trucks). Flow equalization basins require variable discharge control, typically include provisions for bypass and cleaning, and may also include aerators and odor control.

1.3.3.3. Fat and grease removal

In some larger plants, fat and grease are removed by passing the sewage through a small tank where skimmers collect the fat floating on the surface. Air blowers in the base of the tank may also be used to help recover the fat as a froth. Many plants, however, use primary clarifiers with mechanical surface skimmers for fat and grease removal.

1.3.3.4. Primary treatment

Fig. 1.3.3. Primary clarifier.

Primary treatment is the "removal of a portion of the suspended solids and organic matter from the sewage". It consists of allowing sewage to pass slowly through a basin where heavy solids can settle to the bottom while oil, grease and lighter solids float to the surface and are skimmed off (Fig.1.3.3.). These basis are called "primary sedimentation tanks" or "primary clarifiers" and typically have a hydraulic retention time of 1.5 to 2.5 hours. The settled and floating materials are removed and the remaining liquid may be discharged or subjected to secondary treatment. Primary settling tanks are usually equipped with mechanically driven scrapers that continually drive the collected sludge towards a hopper in the base of the tank where it is pumped to sludge treatment facilities.

1.3.3.5. Secondary treatment

The main processes involved in secondary sewage treatment are designed to remove as much of the solid material as possible. They use biological processes to digest and remove the remaining soluble material, especially the organic fraction. This can be done with either suspended-growth or biofilm processes. The microorganisms that feed on the organic matter present in the sewage grow and multiply, constituting the biological solids, or biomass. These grow and group together in the form of flocs or biofilms and, in some specific processes, as granules. In several treatment processes, the biological floc or biofilm and remaining fine solids can then be settled as a sludge, leaving a liquid substantially free of solids, and with a greatly reduced concentration of pollutants.

Secondary treatment can reduce organic matter (measured as biological oxygen demand) from sewage, using aerobic or anaerobic processes. The organisms involved in these processes are sensitive to the presence of toxic materials, although these are not expected to be present at high concentrations in typical municipal sewage (Figs. 1.3.4. and 1.3.5.).

Fig. 1.3.4. Sketch of secondary sewage treatment in activated sludge tank connected with secondary clarifier (activation – intensification of processes ongoing in nature).

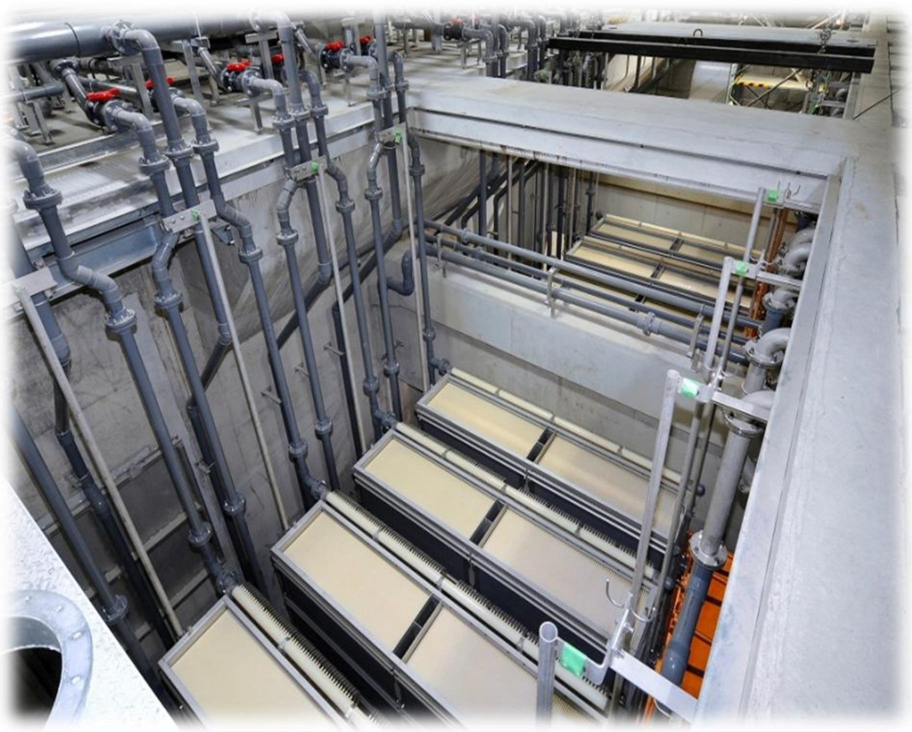


Fig. 1.3.5. Plate membrane reactor for N – microorganisms retention and high sludge age reaching (simultaneously cleaned using the air).

Secondary treatment is the removal of biodegradable organic matter (in solution or suspension) from sewage or similar kinds of wastewater. The aim is to achieve a certain degree of effluent quality in a sewage treatment plant suitable for the intended disposal or reuse option. A "primary treatment" step often precedes secondary treatment, whereby physical phase separation is used to remove settleable solids. During secondary treatment, biological processes are used to remove dissolved and suspended organic matter measured as biochemical oxygen demand (BOD). These processes are performed by microorganisms in a managed aerobic or anaerobic process depending on the treatment technology. Bacteria and protozoa consume biodegradable soluble organic contaminants (e.g. sugars, fats, and organic short-chain carbon molecules from human waste, food waste, soaps and detergent) while reproducing to form cells of biological solids. Secondary treatment is widely used in sewage treatment and is also applicable to many agricultural and industrial wastewaters.

1.3.3.6. Biological nutrient removal

Excessive release to the environment can lead to nutrient pollution, which can manifest itself in eutrophication. This process can lead to algal blooms, a rapid growth, and later decay, in the population of algae. In addition to causing deoxygenation, some algal species produce toxins that contaminate drinking water supplies. Ammonia nitrogen, in the form of free ammonia (NH_3) is toxic to fish. Ammonia nitrogen, when converted to nitrite and further to nitrate in a water body, in the process of nitrification, is associated with the consumption of dissolved oxygen. Nitrite and nitrate may also have public health significance if concentrations are high in drinking water, because of a disease called metahemoglobinemia.

Phosphorus removal is important as phosphorus is a limiting nutrient for algae growth in many fresh water systems. Therefore, an excess of phosphorus can lead to eutrophication. It is also particularly important for water reuse systems where high phosphorus concentrations may lead to fouling of downstream equipment such as reverse osmosis. A range of treatment processes are available to remove nitrogen and phosphorus. Biological nutrient removal is regarded by some as a type of secondary treatment process, and by others as a tertiary (or "advanced") treatment process.

Nitrogen removal

Nitrogen is removed through the biological oxidation of nitrogen from ammonia to nitrate (nitrification), followed by denitrification, the reduction of nitrate to nitrogen gas. Nitrogen gas is released to the atmosphere and thus removed from the water. Nitrification itself is a two-step aerobic process, each step facilitated by a different type of bacteria. The oxidation of ammonia (NH_4^+) to nitrite (NO_2^-) is most often facilitated by bacteria such as *Nitrosomonas, Nitrosocystis*, *Nitrosospira*. Nitrite oxidation to nitrate (NO_3^-), though traditionally believed to be facilitated by *Nitrobacter* (Fig. 1.3.6.).

Denitrification requires anoxic conditions to encourage the appropriate biological communities to form. "Anoxic conditions" refers to a situation where oxygen is absent but nitrate is present. Denitrification is facilitated by a wide diversity of bacteria. The activated sludge process, sand filters, waste stabilization ponds, constructed wetlands and other processes can all be used to reduce nitrogen.

Fig. 1.3.6. Layout of nitrification process by chemical equations.

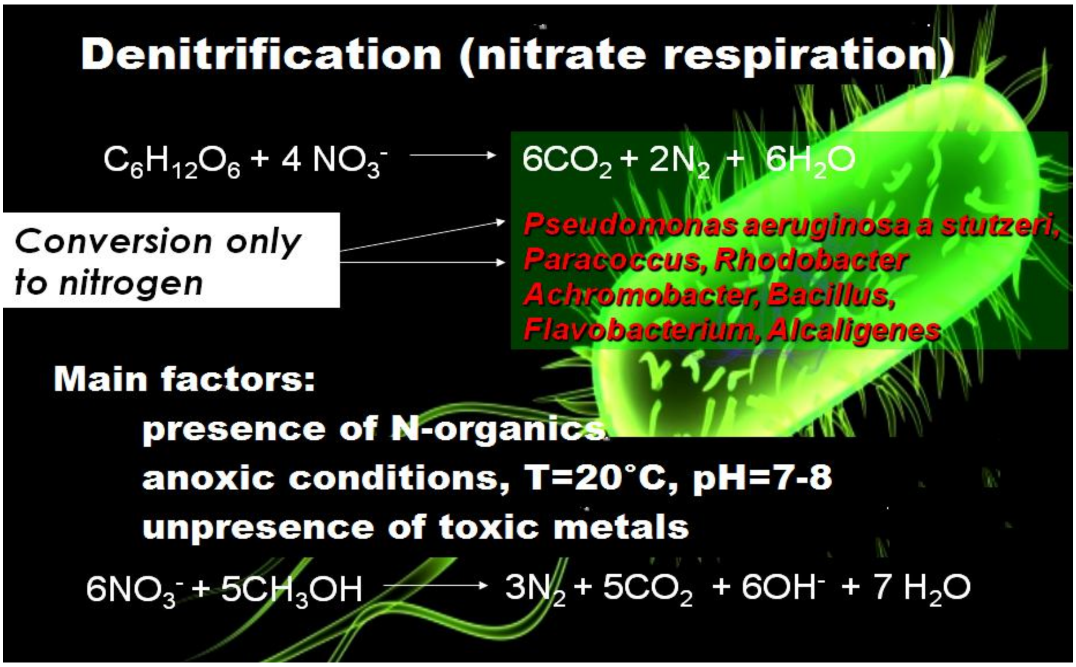


Fig. 1.3.7. Layout of denitrification process by chemical equations.

Since denitrification is the reduction of nitrate to dinitrogen (molecular nitrogen) gas, an electron donor is needed. This can be, depending on the wastewater, organic matter (from the sewage itself), sulfide, or an added donor like methanol. The sludge in the anoxic tanks (denitrification tanks) must be mixed well (mixture of recirculated mixed liquor, return activated sludge, and raw influent) e.g. by using submersible mixers in order to achieve the desired denitrification. Over time, different treatment configurations for activated sludge processes have evolved to achieve high levels of nitrogen removal. An initial scheme placed an anoxic treatment zone before the aeration tank and clarifier, using the return activated sludge from the clarifier as a nitrate source. The sewage (either raw or as effluent from primary clarification) serves as the electron source for the facultative bacteria to metabolize carbon, using the inorganic nitrate as a source of oxygen instead of dissolved molecular oxygen (Figs. 1.3.7. and 1.3.8.).

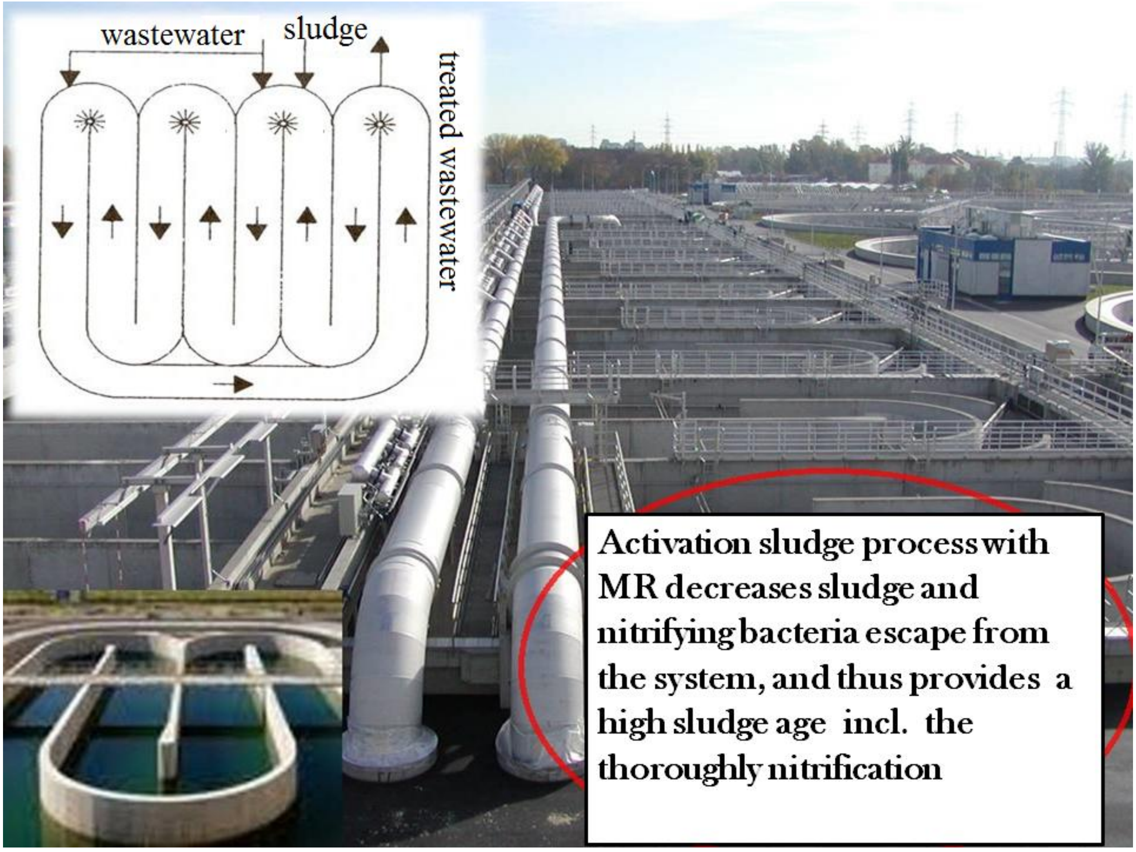


Fig. 1.3.8. Carrousel system as the most simple arrangement for the carbonisation, nitrification and denitrification of wastewater in wastewater treatment plants.

Phosphorus removal

Phosphorus can be removed biologically in a process called enhanced biological phosphorus removal. In this process, specific bacteria, called polyphosphate-accumulating organisms (PAOs), are selectively enriched and accumulate large quantities of phosphorus within their cells (up to 20 percent of their mass) - Fig.1.3.9.

Phosphorus removal can also be achieved by chemical precipitation, usually with salts of iron (e.g. ferric chloride) or aluminum (e.g. alum), or lime. This may lead to a higher sludge production as hydroxides precipitate and the added chemicals can be expensive. Some systems use both biological phosphorus removal and chemical phosphorus removal. The chemical phosphorus removal in those systems may be used as a backup system, for use when the biological phosphorus removal is not removing enough phosphorus, or may be used continuously. In either case, using both biological and chemical phosphorus removal has the advantage of not increasing sludge production as much as chemical phosphorus removal on its own, with the disadvantage of the increased initial cost associated with installing two different systems.

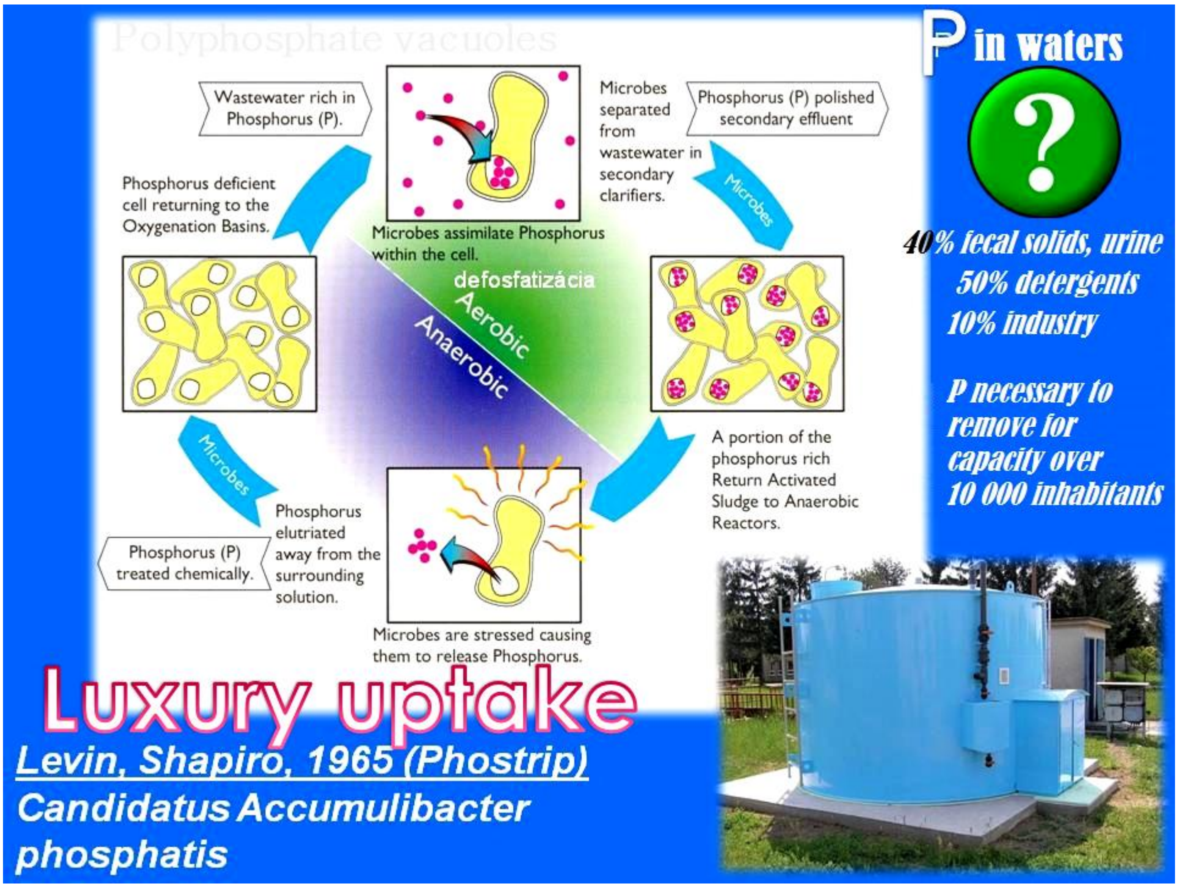


Fig. 1.3.9. Scheme of Luxury uptake phosphorus removal.

Advanced and complementary sewage treatments

Advanced sewage treatment generally involves three main stages, called primary, secondary and tertiary treatment but may also include intermediate stages and final polishing processes. The purpose of tertiary treatment (also called "advanced treatment") is to provide a final treatment stage to further improve the effluent quality before it is discharged to the receiving water body or reused. More than one tertiary treatment process may be used at any treatment plant. If disinfection is practiced, it is always the final process. It is also called "effluent polishing". Tertiary treatment may include disinfection and removal of micropollutants, such as environmental persistent pharmaceutical pollutants.

Advanced sewage treatment is defined as anything more than primary and secondary treatment in order to allow discharge into a highly sensitive or fragile ecosystem such as estuaries, low-flow rivers or coral reefs. Treated water is sometimes disinfected chemically or physically (for example, by lagoons and microfiltration) prior to discharge into a stream, river, bay, lagoon or wetland, or it can be used for the irrigation of a golf course, greenway or park (Fig.1.3.10.). If it is sufficiently clean, it can also be used for groundwater recharge or agricultural purposes.

Sand filtration removes much of the residual suspended matter. Filtration over activated carbon, also called carbon adsorption, removes residual toxins. Micro filtration or synthetic membranes are also used, for example in membrane bioreactors which also remove pathogens. Settlement and further biological improvement of treated sewage may be achieved through storage in large man-made ponds or lagoons. These lagoons are highly aerobic, and colonization by native macrophytes, especially reeds, is often encouraged.

Fig.1.3.10. Further biological improvement of treated sewage may be achieved through storage in large man-made ponds or lagoons.

Disinfection

Disinfection of treated sewage may be attempted to kill pathogens (disease-causing microorganisms) prior to disposal, and is increasingly effective after more elements of the foregoing treatment sequence have been completed. The purpose of disinfection in the treatment of sewage is to substantially reduce the number of pathogens in the water to be discharged back into the environment or to be reused. The effectiveness of disinfection depends on the quality of the water being treated (e.g. turbidity, pH, etc.), the type of disinfection being used, the disinfectant dosage (concentration and time), and other environmental variables. Water with high turbidity will be treated less successfully, since solid matter can shield organisms, especially from ultraviolet light or if contact times are low. Generally, short contact times, low doses and high flows all militate against effective disinfection. Common methods of disinfection include ozone, chlorine, ultraviolet light, or sodium hypochlorite. Monochloramine, which is used for drinking water, is not used in the treatment of sewage because of its persistence.

Chlorination remains the most common form of treated sewage disinfection in many countries due to its low cost and long-term history of effectiveness. One disadvantage is that chlorination of residual organic material can generate chlorinated-organic compounds that may be carcinogenic or harmful to the environment. Residual chlorine or chloramines may also be capable of chlorinating organic material in the natural aquatic environment. Further, because residual chlorine is toxic to aquatic species, the treated effluent must also be chemically dechlorinated, adding to the complexity and cost of treatment.

Ultraviolet (UV) light can be used instead of chlorine, iodine, or other chemicals. Because no chemicals are used, the treated water has no adverse effect on organisms that later consume it, as may be the case with other methods. UV radiation causes damage to the genetic structure of bacteria, viruses, and other pathogens, making them incapable of reproduction. The key disadvantages of UV disinfection are the need for frequent lamp maintenance and replacement and the need for a highly treated effluent to ensure that the target microorganisms are not shielded from the UV radiation (i.e., any solids present in the treated effluent may protect microorganisms from the UV light). In many countries, UV light is becoming the most common means of disinfection because of the concerns about the impacts of chlorine in chlorinating residual organics in the treated sewage and in chlorinating organics in the receiving water.

Membranes can also be effective disinfectants, because they act as barriers, avoiding the passage of the microorganisms (Fig.1.3.11.). As a result, the final effluent may be devoid of pathogenic organisms, depending on the type of membrane used. This principle is applied in membrane bioreactors.

Micropollutants such as pharmaceuticals, ingredients of household chemicals, chemicals used in small businesses or industries, environmental persistent pharmaceutical pollutants or pesticides may not be eliminated in the commonly used sewage treatment processes and therefore lead to water pollution. Although concentrations of those substances and their decomposition products are quite low, there is still a chance of harming aquatic organisms. For pharmaceuticals, the following substances have been identified as "toxicologically relevant": substances with endocrine disrupting effects, genotoxic substances and substances that enhance the development of bacterial resistances. Techniques for elimination of micropollutants via a fourth treatment stage during sewage treatment are implemented in

Germany, Switzerland, Sweden and the Netherlands and tests are ongoing in several other countries. Such process steps mainly consist of activated carbon filters that adsorb the micropollutants (Fig. 1.3.12.). The combination of advanced oxidation with ozone followed by granular activated carbon has been suggested as a cost-effective treatment combination for pharmaceutical residues. For a full reduction of microplasts the combination of ultrafiltration followed by GAC has been suggested.

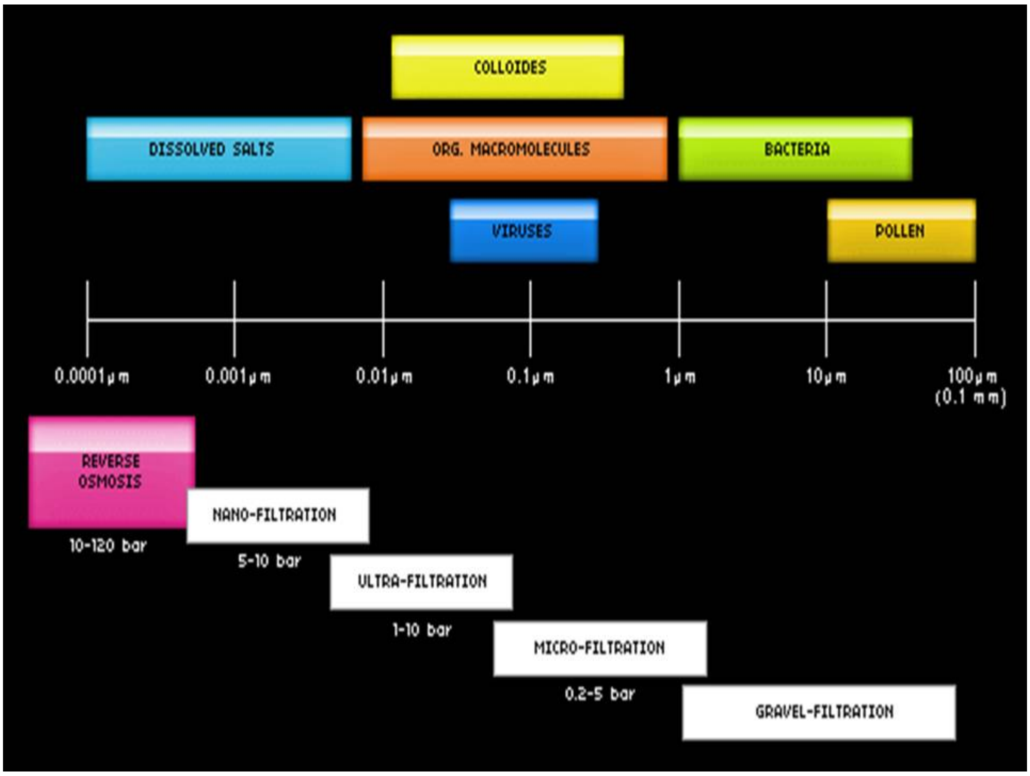


Fig.1.3.11. Depending on the type of membrane used various pollutants incl. microplasts can be removed from water.

Fig. 1.3.12. Principal sketch of presure filter (left) which may be filled with activated carbon (right).

1.3.3.7. Sewage sludge treatment and disposal

Sewage sludge treatment describes the processes used to manage and dispose of sewage sludge produced during sewage treatment. Sludge treatment is focused on reducing sludge weight and volume to reduce transportation and disposal costs, and on reducing potential health risks of disposal options. Water removal is the primary means of weight and volume reduction, while pathogen destruction is frequently accomplished through heating during thermophilic digestion, composting, or incineration. The choice of a sludge treatment method depends on the volume of sludge generated, and comparison of treatment costs required for available disposal options. Air-drying and composting may be attractive to rural communities, while limited land availability may make aerobic digestion and mechanical dewatering preferable for cities, and economies of scale may encourage energy recovery alternatives.

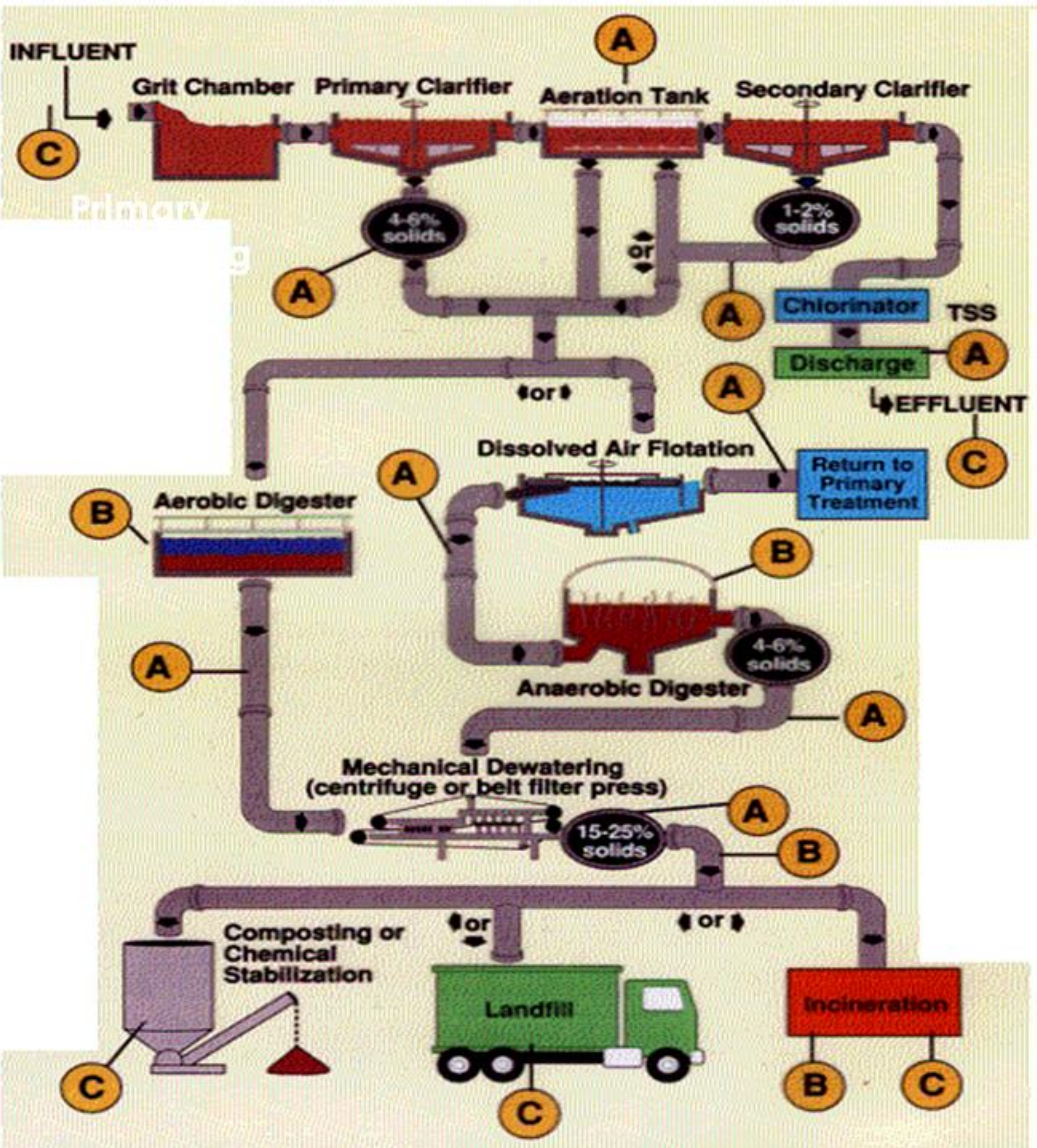


Fig. 1.3.13. Scheme of the entire wastewater treatment plant incl. sludge handling.

Sludge is mostly water with some amounts of solid material removed from liquid sewage. Primary sludge includes settleable solids removed during primary treatment in primary clarifiers. Secondary sludge is sludge separated in secondary clarifiers that are used in secondary treatment bioreactors or processes using inorganic oxidizing agents. In intensive sewage treatment processes, the sludge produced needs to be removed from the liquid line on a continuous basis because the volumes of the tanks in the liquid line have insufficient volume to store sludge. This is done in order to keep the treatment processes compact and in balance (production of sludge approximately equal to the removal of sludge). The sludge removed from the liquid line goes to the sludge treatment line. Aerobic processes (such as the activated sludge process) tend to produce more sludge compared with anaerobic processes. On the other hand, in extensive (natural) treatment processes, such as ponds and constructed wetlands, the produced sludge remains accumulated in the treatment units (liquid line) and is only removed after several years of operation.

Sludge treatment options depend on the amount of solids generated and other site-specific conditions. Composting is most often applied to small-scale plants with aerobic digestion for mid-sized operations, and anaerobic digestion for the larger-scale operations (Fig.1.3.13. and Fig.1.3.14.). The sludge is sometimes passed through a so-called pre-thickener which de-waters the sludge. Types of pre-thickeners include centrifugal sludge thickeners, rotary drum sludge thickeners and belt filter presses. Dewatered sludge may be incinerated or transported offsite for disposal in a landfill or use as an agricultural soil amendment (Fig. 1.3.15.).

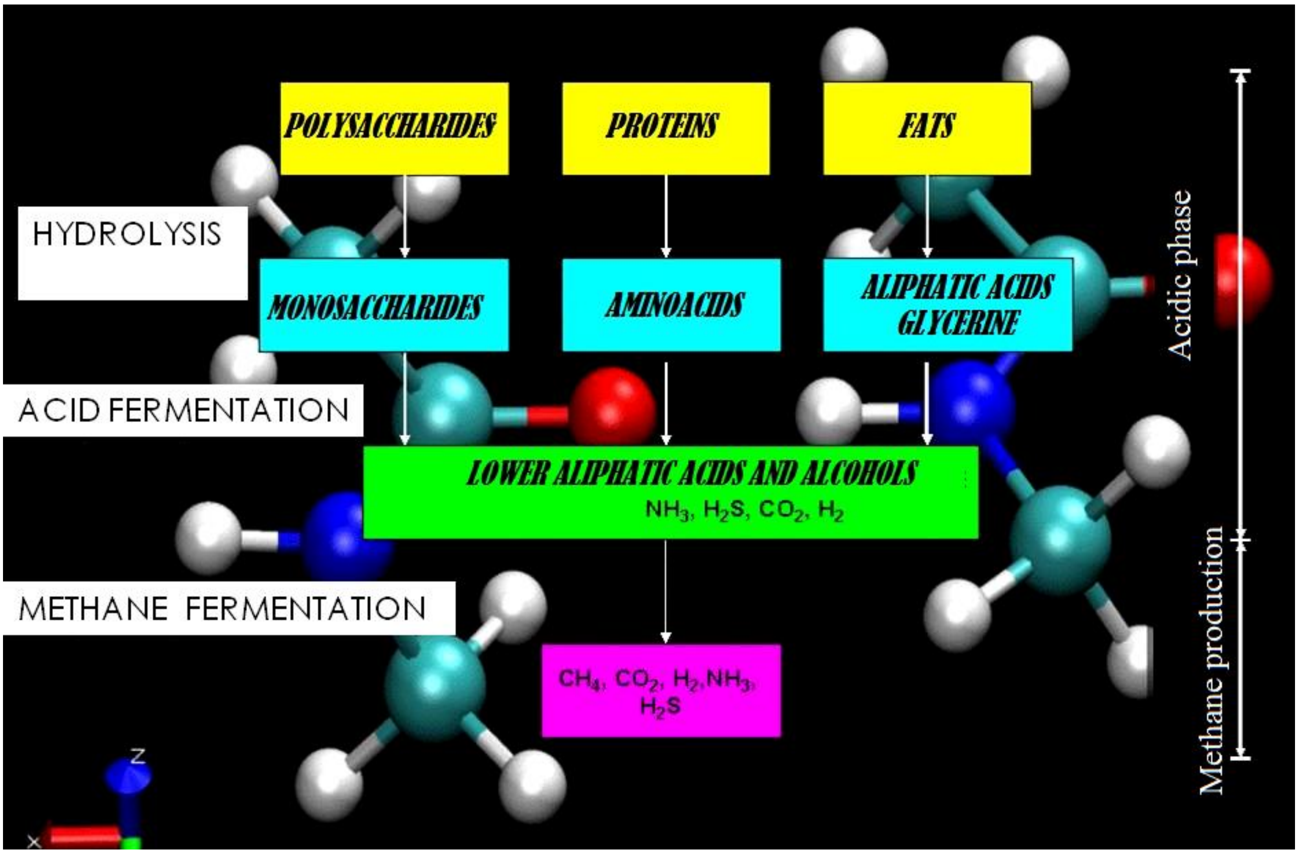


Fig. 1.3.14. Biochemical process layout for the anaerobic digestion.

Fig. 1.3.15. Sewage sludge dewatering.

Energy requirements

The energy requirements vary with type of treatment process as well as sewage strength. For example, constructed wetlands and stabilization ponds have low energy requirements, associated mainly with the occasional presence of pumps and other equipment. On the other hand, the activated sludge process includes an aeration step, which is highly energy consuming. Sewage treatment plants that produce biogas in their sewage sludge treatment process with anaerobic digestion can produce enough energy to meet most of the energy needs of the sewage treatment plant itself (Fig.1.3.16.). Most of this electricity is used for aeration, pumping systems and equipment for the dewatering and drying of sewage sludge. Advanced sewage treatment plants, e.g. for nutrient removal, require more energy than plants that only achieve primary or secondary treatment. Small rural plants using trickling filters may operate with no net energy requirements, the whole process being driven by gravitational flow, including tipping bucket flow distribution and the desludging of settlement tanks to drying beds. This is usually only practical in hilly terrain and in areas where the treatment plant is relatively remote from housing because of the difficulty in managing odors.

Co-treatment of industrial effluent

In highly regulated developed countries, industrial wastewater usually receives at least pretreatment if not full treatment at the factories themselves to reduce the pollutant load, before discharge to the sewer. The pretreatment has the following aims: to remove constituents that may pose risks to the sewerage system and its workers; prevent toxic or

Fig. 1.3.16. Anaerobic digestion towers (upper figure municipal wastewater treatment plant for the city residence Petržalka of Bratislava capital where biogas production during sludge digestion process is combined with electricity co-generation unit).

inhibitory compounds to the microorganisms in the biological stage in the municipal treatment plant; hinder beneficial use of the produced sewage sludge; or that will still be present in the final effluent from the treatment plant. Some industrial wastewater may contain pollutants which cannot be removed by sewage treatment plants. Also, variable flow of industrial waste associated with production cycles may upset the population dynamics of biological treatment units.

Environmental impacts

Sewage treatment plants can have significant effects on the biotic status of receiving waters and can cause some water pollution, especially if the treatment process used is only basic. For example, for sewage treatment plants without nutrient removal, eutrophication of receiving water bodies can be a problem.

Water pollution (or aquatic pollution) is the contamination of water bodies, usually as a result of human activities, in such a manner that negatively affects its legitimate uses.[48]:6 Water pollution reduces the ability of the body of water to provide the ecosystem services that it would otherwise provide. Water bodies include for example lakes, rivers, oceans, aquifers, reservoirs and groundwater. Water pollution results when contaminants are introduced into these water bodies. For example, releasing inadequately treated wastewater into natural waters can lead to degradation of these aquatic ecosystems. All plants and organisms living in or being exposed to polluted water bodies can be impacted. The effects can damage individual species and impact the natural biological communities they are part of. Water pollution can also lead to water-borne diseases for people using polluted water for drinking, bathing, washing or irrigation.

Increasingly, people use treated or even untreated sewage for irrigation to produce crops. Cities provide lucrative markets for fresh produce, so are attractive to farmers. Because agriculture has to compete for increasingly scarce water resources with industry and municipal users, there is often no alternative for farmers but to use water polluted with sewage directly to water their crops. There can be significant health hazards related to using water loaded with pathogens in this way. The World Health Organization developed guidelines for safe use of wastewater in 2006. They advocate a ‘multiple-barrier’ approach to wastewater use, where farmers are encouraged to adopt various risk-reducing behaviors. These include ceasing irrigation a few days before harvesting to allow pathogens to die off in the sunlight, applying water carefully so it does not contaminate leaves likely to be eaten raw, cleaning vegetables with disinfectant or allowing fecal sludge used in farming to dry before being used as a human manure.

Water reclamation (also called wastewater reuse, water reuse or water recycling) is the process of converting municipal wastewater (sewage) or industrial wastewater into water that can be reused for a variety of purposes. Types of reuse include: urban reuse, agricultural reuse (irrigation), environmental reuse, industrial reuse, planned potable reuse, de facto wastewater reuse (unplanned potable reuse). For example, reuse may include irrigation of gardens and agricultural fields or replenishing surface water and groundwater (i.e., groundwater recharge). Reused water may also be directed toward fulfilling certain needs in residences (e.g. toilet flushing), businesses, and industry, and could even be treated to reach drinking water standards. Treated municipal wastewater reuse for irrigation is a long-established practice, especially in arid countries. Reusing wastewater as part of sustainable water management allows water to remain as an alternative water source for human activities. This can reduce scarcity and alleviate pressures on groundwater and other natural water bodies.

Global targets

Sustainable Development Goal has a Target which is formulated as follows: "By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally." The corresponding Indicator is the "proportion of wastewater safely treated".

Data in 2020 showed that there is still too much uncollected household wastewater: Only 66% of all household wastewater flows were collected at treatment facilities in 2020 (this is determined from data from 128 countries). Based on data from 42 countries in 2015, the report stated that "32 per cent of all wastewater flows generated from point sources received at least some treatment". For sewage that has indeed been collected at centralized sewage treatment plants, about 79% went on to be safely treated in 2020.

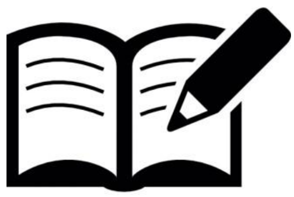
Conclusions

Sewage (or domestic wastewater) consists of wastewater discharged from residences and from commercial, institutional and public facilities that exist in the locality. Sewage is a mixture of water (from the community's water supply), human excreta (feces and urine), used water from bathrooms, food preparation wastes, laundry wastewater, and other waste products of normal living. Sewage from municipalities contains wastewater from commercial activities and institutions, e.g. wastewater discharged from restaurants, laundries, hospitals, schools, prisons, offices, stores and establishments serving the local area of larger communities. Sewage can be distinguished into "untreated sewage" (also called "raw sewage") and "treated sewage" (also called "effluent" from a sewage treatment plant).

The term "sewage" is nowadays often used interchangeably with "wastewater" - implying "municipal wastewater" - in many textbooks, policy documents and the literature. To be precise, wastewater is a broader term, because it refers to any water after it has been used in a variety of applications. Thus it may also refer to “industrial wastewater”, agricultural wastewater and other flows that are not related to household activities. The sewage is composed of around 99.9% pure water, and the remaining 0.1% are solids, which can be in the form of either dissolved solids or suspended solids. The suspended and dissolved solids include organic and inorganic matter plus microorganisms. About one-third of this solid matter is suspended by turbulence, while the remainder is dissolved or colloidal. The organic matter in sewage can be classified in terms of form and size: Suspended (particulate) or dissolved (soluble). Secondly, it can be classified in terms of biodegradability: either inert or biodegradable. The organic matter in sewage consists of protein compounds (about 40%), carbohydrates (about 25-50%), oils and grease (about 10%) and urea, surfactants, phenols, pesticides and others (lower quantity). In order to quantify the organic matter content, it is common to use "indirect methods" which are based on the consumption of oxygen to oxidize the organic matter: mainly the Biochemical Oxygen Demand (BOD) and the Chemical Oxygen Demand (COD). These indirect methods are associated with the major impact of the discharge of organic matter into water bodies: the organic matter will be food for microorganisms, whose population will grow, and lead to the consumption of oxygen, which may then affect aquatic living organisms. In raw sewage, nitrogen exists in the two forms of organic nitrogen or ammonia. The ammonia stems from the urea in urine. Urea is rapidly hydrolyzed and therefore not usually found in raw sewage. Total phosphorus is mostly present in sewage in the form of phosphates.They are either inorganic (polyphosphates and orthophosphates) and their main source is from detergents and other household chemical products. In most practical cases, pathogenic organisms are not directly investigated in laboratory analyses. An easier way to assess the presence of fecal contamination is by assessing the most probable numbers of fecal coliforms (called thermotolerant coliforms), especially *Escherichia coli*. *Escherichia coli* are intestinal bacteria excreted by all warm blooded animals, including human beings, and thus tracking their presence in sewage is easy, because of their substantially high concentrations (around 10 to 100 million per 100 mL).

Questions for self-control

1. Define sewage system and population equivalent.
2. Which preliminary sewage treatment steps do you know?
3. Describe sewage primary and secondary treatment in wastewater treatment plant.
4. How would you explain biological nutrient removal in wastewater treatment plant?
5. Which advanced and complementary sewage treatments do you know?



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