doi: 10.2166/9781789060362_0001

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Wastewater treatment development

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1.1 GLOBAL DRIVERS FOR SANITATION

Sanitation was voted the greatest medical milestone since 1840 in a British Medical Journal poll in 2007 (Ferriman, 2007). This confirms the absolute importance of sanitation in achieving and maintaining good public health. In many industrialized countries, wastewater is transported safely away from the households. However, proper sewage treatment is not always in place, in particular in many developing countries where there is far less sanitation coverage in comparison with water supply. The need for proper sanitation was made explicit in the United Nations Sustainable Development Goals (SDGs). This was further accentuated by announcing the sustainable development goal number 6 – Safe Water and Sanitation which states that clean and accessible water is essential for all people in the world in view of the fact that millions of people die from diseases associated with inadequate water supply, sanitation and hygiene (WASH). Sanitation plays a central role in achieving this goal. The UN World Water Development Report 2019 calls for access to safe water and sanitation for all as essential for eradicating poverty, building peaceful and prosperous societies, and ensuring that 'no one is left behind' on the road towards sustainable development. However, despite significant efforts, progress on sanitation improvement is still slow and lagging behind. The world needs to pay attention to the call to start implementing proper sanitation solutions for all. What is important in this is to not only connect people to sanitation solutions, but also to make this connection last in an environmentally sustainable way. Sewer systems and wastewater treatment plants have proven to be very efficient in conveying and removing pathogens, organic pollutants and nutrients but they require proper operation and maintenance, and a good understanding of the processes involved.

1.2 HISTORY OF WASTEWATER TREATMENT

Wastewater treatment development was the most visible in the 20th century. Sewage has for a long time been considered a potential health risk and nuisance in urban agglomerations. However, the

The chapter is from the book Biological Wastewater Treatment: Principles, Modelling and Design, Guanghao Chen, Mark C.M. van Loosdrecht, George A. Ekama and Damir Brdjanovic (Eds).

fertiliser value of human excreta was already recognized in very early days. In China from ancient times, *e.g.* the Xihan Dynasty (202 BC), up until recently (the 1970s), the vast majority of agricultural land was fertilized by human faeces from latrines. The ancient civilisations in the Indus valley (already in 2000 BC), the Euphrates region and Greece used public latrines which drained into sewers conveying the sewage and stormwater to a collection basin outside the city; from there, brick-lined conduits took the wastewater to agricultural fields which used the wastewater for irrigation and to fertilise crops and orchards. The sewers were periodically flushed with wastewater.

The Romans took this system further: in about 800 BC, they constructed the *Cloaca Maxima*. Initially, this central sewer system was used to drain the marsh upon which Rome was later built. By 100 AD, the system was almost complete and connections had been made to some houses. Water was supplied by an aqueduct system which carried sewage from the public baths and latrines to the sewers beneath the city and finally into the Tiber. The streets were regularly washed with water from the aqueduct system and the waste washed into the sewers.

This system worked very well because it could count on an effective government and the protection of a powerful army to maintain the far-reaching aqueducts. However, when the Roman Empire collapsed, their sanitary approach collapsed with it as well. The period between 450 and 1750 AD is therefore known as the 'Sanitary Dark Ages' (Wolfe, 1999). During this period the main form of waste disposal was simply to dispose of it in the streets, often by emptying buckets from second-storey windows. In around 1800 a collection system appeared in many cities, instigated by the city dwellers who did not want to put up with the smell any longer. It was also welcomed by the farmers around the city who found good use for this 'humanure'. In Amsterdam, a cart drove through the streets and buckets could be emptied into it. The cart was ironically named after a brand of Eau de cologne known at that time: the Boldoot cart. However, spilling during transportation and emptying of the buckets was unavoidable, and the olfactory burden on the citizens did not decrease much. By then, plans arose for a general sewer system but high investment costs and uncertainty over flushing and maintenance of the sewers put the fast implementation on hold.

In around 1900 Mr. Liernur came up with a solution. He developed a plan for separate collection of toilet water and of grey and storm water. Toilet water was to be collected through a vacuum sewer called the Liernur pneumatic sewerage system. This system found use in several European towns (Figure 1.1).

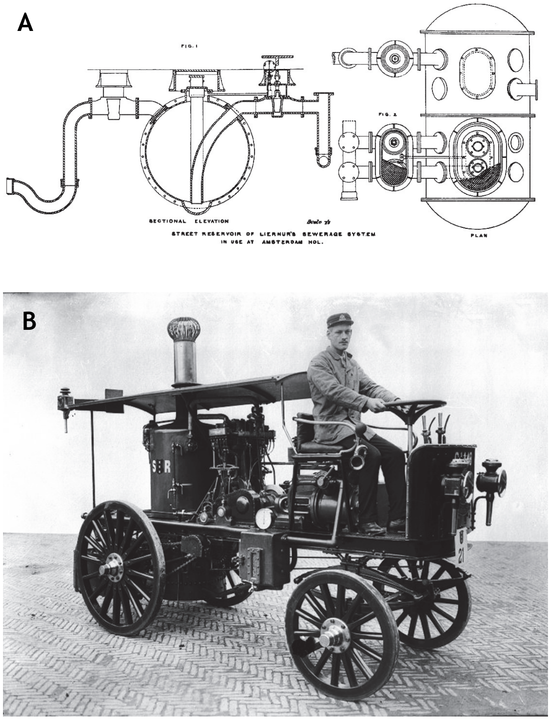

Figure 1.1 The Liernur vacuum sewer system (A) and the vehicle used for collection and transport of waste (B) (photos: Van Lohuizen, 2006).

The collected sewage did not undergo any treatment. Instead, it was spread out over land as a fertilizer. However, water-logging became a major problem, and the continuous expansion of the cities made it more difficult to find sufficient land nearby. The idea that there might be better ways, using 'organisms', gradually began to emerge (Cooper, 2001).

In the United States and the United Kingdom, organisms already found their way as applied water cleaners in what were termed biological filters: biofilms on rocks in the river bed. One of the earliest biological filters, in Salford near Manchester in the UK, stems from 1893. In the US the first filter was installed in 1901, in Madison, Wisconsin. Between 1895 and 1920 many were installed in the UK to treat sewage from towns and cities. This rapid application had a negative effect upon the later implementation of the activated sludge process in the UK after it was invented in 1913: investment money had already been spent on the biological filters.

The activated sludge process was discovered in the UK: experiments on treating sewage in a draw-and-fill reactor (the precursor to today's sequencing batch reactor) produced a highly treated effluent. Believing that the sludge had been activated, in a manner similar to activated carbon, the process was named 'activated sludge' (Ardern and Lockett, 1914).

During the first half of the 20th century, the river into which the wastewater was discharged was considered an integral part of the treatment process. The reason why 5 days is used in the biochemical oxygen demand (BOD) test is because 5 days was the longest time water spent in the rivers of the UK before it reached the sea. The book Stream Sanitation by Phelps (1944) uses mathematical modelling to calculate the maximum organic load from the oxygen sag curve to prevent the dissolved oxygen (DO) concentration falling below a minimum value at a point downstream of the wastewater discharge point. However, with the rapid growth of cities, it was soon realized that rivers could not cope with the ever increasing organic loads. As a response, the requirements increased for wastewater treatment to achieve better removal efficiencies. To reduce the oxygen demand in the river and to eliminate the toxic effect of ammonia on aquatic species, the requirement for nitrification was introduced. This led to the construction of many low-loaded trickling filter plants for organic removal and nitrification in the USA, Europe and South Africa. Anaerobic digestion was usually included in the trickling filter plants to treat the primary and trickling filter sludge produced. The discharge of nitrate from these plants was believed to be good because it provided a barrier against anaerobic conditions in the rivers and lakes. However, the trickling filters did not always nitrify very well - particularly in the winter - due to the requirement of high organic removal efficiency prior to efficient nitrogen removal.

In the second half of the 20th century a new problem in surface water emerged: that of eutrophication. Eutrophication stands for the explosive growth of algae and other water plants due to the fertilizing effect of the nitrogen (N) and phosphorus (P) discharged into rivers. In the 1960s it became clear that nitrogen and phosphorus also needed to be removed from wastewater to limit eutrophication. This inspired intensive research programs and during the 1960s the fields of bacteriology and bioenergetics were applied to wastewater treatment. By applying Monod (1950) kinetics from the field of bacteriology, Downing *et al.* (1964) showed that nitrification depends on the maximum specific growth rate of autotrophic nitrifying organisms which is slow compared with that of heterotrophic organisms. For the full-scale plant, this means that the sludge age has to be long enough to achieve consistently low effluent ammonia concentrations. So successful was the use of Monod kinetics in wastewater treatment that it is still used today in all simulation models for wastewater treatment, not only to model nitrification but also many other biological reactions. From bioenergetics, which was developed to a very advanced level by McCarty (1964), it was realized that the nitrate produced by nitrification could also be used by some heterotrophic bacteria instead of oxygen and converted into nitrogen gas. This insight led to the nitrification-denitrification activated sludge system, in which parts of the reactor were not aerated to induce denitrification. With all this new knowledge put successfully into practice, the suspended medium activated sludge system became the preferred wastewater treatment system. The post-denitrification system, in which the non-aerated (anoxic) reactor follows the aerobic reactor, was developed by Wuhrmann (1964) in Switzerland. To increase the denitrification rate in the anoxic reactor, methanol was dosed to supply the organics for the denitrification process. Because of the low nitrogen effluent values achieved with this method, this practice was widely adopted in the USA. However, methanol addition costs money, and it is rather contradictory to add organics to wastewater after first removing them. The pre-denitrification system developed by Ludzack and Ettinger (1962) formed a logical next step. In South Africa in 1972, Barnard combined the post- and pre-denitrification reactors and introduced recycle flows to control the nitrate entering the pre-denitrification reactor in the 4-stage Bardenpho system (Barnard, 1973). With this development, nitrogen removal activated sludge systems became increasingly common.

A different line of development was initiated by the work of Pasveer (1959) who progressed based on the work of Ardern and Lockett. They originally designed a fill-and-draw process. Pasveer was focusing on an economical system. The ditch system he developed was based on using one treatment unit only. There was no primary settler, no secondary settler, no digester, and so forth. In the fill-and-draw process with continuous feeding, simultaneous nitrification and denitrification occurred. The simplicity and low costs led to widespread use. Out of the Pasveer ditch system the continuous operated oxidation ditch systems evolved, based on the same principle but with a separate clarifier.

However, to control eutrophication, solely nitrogen removal was not sufficient. Phosphorus, mainly in the form of ortho-phosphate from detergents and human waste, also needed to be removed because in many ecosystems phosphorus proved to be the main enabling element for eutrophication. Unlike nitrogen, phosphorus can only be removed by converting to a solid phase. Phosphorus removal by chemical precipitation followed by tertiary filtration appeared during the 1970s. In regions where water is scarce however, like the south-western states of the USA, South Africa and Australia, indirect reuse of surface water was already high and chemical phosphate removal would cause a rapid increase in surface water salinity. Apart from the fact that salinity reduces agricultural use of surface water, its greater impact is on the durability of the water distribution system. To mitigate these impacts, water policy in South Africa in the late 1960s and early 1970s was aimed at full wastewater reclamation for redistribution to avoid both eutrophication and salination of surface water – if the high cost of chemical phosphate removal was going to be incurred, then the water may as well be reclaimed completely and returned to the distribution system rather than the environment (Bolitho, 1975; Van Vuuren, 1975).

Figure 1.2 The first (pilot) application of the Pasveer ditch system (at Voorschoten, The Netherlands in 1954). The plant capacity was 400 P.E. and 40 m^3/h at dry weather flow (photo: Van Lohuizen, 2006).

Biological phosphate removal is a unique biological process that was discovered by accident. The first indication of biological phosphate removal occurring in a wastewater treatment process was described by Srinath *et al.* (1959) from India. They observed that sludge from a certain treatment plant exhibited excessive (more than needed for cell growth) phosphate uptake when aerated. It was shown that the phosphate uptake was a biological process (inhibition by toxic substances, oxygen requirement). Later, this process, referred to as enhanced biological phosphate removal (EBPR), was noticed in other (plug flow) wastewater treatment plants. The first designed processes (the PhoStrip® process) for biological phosphate removal still arose from a time when the mechanism behind the process was unknown (Levin and Shapiro, 1965). In the early 1970s due to an increased demand for nitrate removal as well as for energy savings (the 1970s energy crisis), at several places worldwide it was discovered that biological phosphate removal could relatively easily be stimulated. For example in 1974, while optimizing nitrogen removal at the Alexandria activated sludge plant by switching aerators off at the influent end of the plant, Nicholls (1975) noted low effluent phosphorus (and nitrate) concentrations. He found very high phosphate concentrations in the sludge blanket which had settled to the floor of the reactor and into which the influent wastewater descended due to a higher density than the clear supernatant. Barnard (1976) developed the Phoredox principle for biological excess phosphate removal, which introduced anaerobic and aerobic cycling in the activated sludge system. EBPR is now an established technology which opened the opportunity for phosphate removal and recovery without increasing salinity so that treated effluents could be returned to the environment or efficiently reused. As so often happens, new developments are found by accident and the understanding of how they work follows afterwards. It took many years of research in South Africa, Canada and Europe to fully understand and control the process and today there are still several facets about it that are not clear. However, not fully understanding the underlying principles has never stopped engineers and scientists from building and operating wastewater treatment plants.

The energy crisis in the 1970s associated with an increased demand for industrial wastewater treatment shifted attention from aerobic wastewater treatment to anaerobic wastewater treatment. The slow growth rate of methane-producing bacteria had always been a limitation on the process development. For the concentrated and warmer industrial wastewaters, this was less of a problem and certainly the development of the upflow anaerobic sludge blanket reactors (UASB) by Lettinga and co-workers (Lettinga *et al.,* 1980) meant a breakthrough for anaerobic treatment. Not only was this technology feasible for industrial wastewater treatment but also anaerobic treatment of low-strength municipal wastewater in tropical regions of South America, Africa and Asia could be efficiently introduced.

After a century of constructing wastewater treatment plants, many treatment plants that were initially built outside the urban area had become engulfed by residential areas. Expansion of plants became a problem and the engineers started to find more compact treatment options. Moreover, industry started to treat its own wastewater, and for industry, land use is even more critical than for *e.g.* municipalities. One successful line of development was going back to the original biofilm-based trickling reactors. A whole range of new processes was developed (biological aerated filters, fluid-bed reactors, suspension reactors, biorotors, granular sludge processes or moving-bed reactors and membrane bioreactors) which overcame the original problems of the trickling filter process.

The development of these reactors originated from the 1970s. Another development initiated in this period only became widely introduced from the late 1990s: the activated sludge process with membrane separation instead of settlers. The breakthrough for the membrane bioreactors (MBR) was made by Yamamoto and his co-workers (Yamamoto *et al.*, 1989) by integrating the hollow fibre membrane module inside the aeration bioreactor. In the early 21th century another compact technology eliminating clarifiers was developed based on granular sludge. By recognizing the basic principles behind granular growth morphology it was possible to develop aerobic granular sludge technology (the Nereda® process) which allows for a more energy-efficient and compact nutrient removal process (Pronk *et al.,* 2015).

With ever increasing effluent demands, the need arose to upgrade treatment plants instead of building new plants. Around the turn of the last century, this led to the development of a range of new processes to be integrated in existing treatment plants. The problem tackled especially by these processes is the very high nitrogen and phosphate release during anaerobic digestion of waste activated sludge, which were traditionally recycled to the activated sludge process. Apart from struvite precipitation problems, this also results in high nutrient recycling and higher effluent nitrogen and phosphate concentrations from the activated sludge system when the dewatering liquor is recycled back to the influent. Research into this problem has led to many innovations in dewatering liquor treatment. In the Netherlands, processes have been developed such as the Single reactor system for High activity Ammonium Removal Over Nitrite (SHARON®), ANaerobic AMMonia OXidation (ANAMMOX®) and processes for improved nitrogen removal and mineral crystallization processes for phosphorus precipitation for phosphorus recovery and reuse (Crystalactor®**).** Especially the anammox process has been developed in an array of commercial process technologies.

In the last decade there has been far more attention paid to resource recovery. Water is an obvious resource to be recovered, just as biogas. An array of new possibilities is opening up that will change the planning and design of wastewater treatment facilities in the near future (Guest *et al.,* 2009; Kehrein *et al.,* 2020). Examples of recoverable resources are cellulose, hydrogen, heat, polyhydroxyalkanoates, phosphates, proteins, extracellular polymers, etc. (Van Loosdrecht and Brdjanovic, 2014).

An important aspect of wastewater plant operation has always been its controllability. This concerns direct process control as well as indirect control of *e.g.* sludge settleability or biofilm growth. Process control has been a limiting factor from the start. Ardern and Lockett (1914) as well as Pasveer tried to minimize costs by applying fill-and-draw cycles where settling would occur in the treatment plant. In fact the Nereda® technology is also based on this principle. This requires process automation. Since the early 1970s instrumentation, control and automation (ICA) has attracted the attention of the water and wastewater industry. Since then the technical development of new processes, sensor and instrumentation technology, computer performance, communication technology and the Internet of Things, detection methods, control theory and artificial intelligence has made good progresses in early warning, monitoring and operating of wastewater treatment plants. This improvement in ICA technology made over the last few decades meant that process control became sufficiently reliable and now sequencing batch reactors are increasingly being used again (*e.g.* Nereda® technology). The increasing effluent demands, combined with a demand to save and recover resources, is pushing the need for increased process control. Although mathematical models were already developed in the early days of wastewater treatment processes, they only became in widespread use with the introduction of low-cost personal computers and the presentation of a unified activated sludge model (Henze *et al.,* 1987).

The control of sludge properties has always been a point of concern as well. Filamentous sludge and foaming caused by specific bacterial groups has always been important. Control of filamentous bacteria by the application of selector systems (Chudoba, 1973) has been successful in many cases. Nevertheless, the filamentous organism *Microthrix parvicella* is still giving regular problems in nutrient removal processes. Despite much research, which has certainly helped to obtain a better understanding of the causes and control of filamentous bulking, it is still not clearly understood to the point where the sludge settleability is quantitatively predictable for different activated sludge systems. This means that larger secondary settling tanks have to be built to cater for possible periods of poorer sludge settleability. However, in recent years the understanding of biofilm and sludge morphology has significantly increased and seems to have come together. One outcome of these theoretical developments is the introduction of aerobic granular sludge systems which can be seen as the other extreme of filamentous sludge or as a particular form of the biofilm process (Beun *et al.,* 1999).

Another major concern is wastewater and sludge disinfection and final sludge disposal in an environmentally sustainable way. The fact that wastewater contains pathogenic organisms was the reason for the start of large-scale sewerage systems and wastewater treatment plants 150 years ago. This was more or less forgotten until the middle of the 20th century when disinfection of effluents came into use. This was partly given up due to the carcinogenic compounds created during chlorination of wastewater, but recently in several areas disinfection has become an issue again, using filters, UV and ozonation. With the advance of wastewater recovery and the drive to more individually based wastewater treatment processes, disinfection is now receiving renewed attention. Final sludge disposal was originally a health risk issue because of the risk of spreading pathogens. Nowadays sludge disposal to agricultural lands is becoming more and more limiting (also as food safety standards are tending to increase) and the handling of sludge becomes more and more important. In particular sludge dewaterability and dewatering and how to minimize the problem is a strong research focus. In recent years sludge pretreatment for improving sludge dewaterability has been attracting the wastewater industry. If dewatering could be efficiently performed then sludge incineration could be used as a means to recover the energy and resource (*e.g.* phosphorous) enclosed in the sludge.

The demands on the wastewater system are continuously increasing, with nowadays an increased attention on emerging micropollutants that might accumulate in the water cycle or affect natural ecosystems. Water shortage will lead to the further development and implementation of technologies for water reclamation and reuse. Water reuse is not only limited to water-scarce regions; in water-rich areas such as Western Europe, local regulations and demands can make it economically profitable to use wastewater effluent instead of natural water to produce water for industry. All these developments take time and after more than a century of separate development, wastewater treatment and drinking water treatment are growing closer to each other. A successful example comes from Hong Kong where seawater has been supplied for toilet flushing since 1958. Nowadays it covers more than 80% of the population (7 million inhabitants), saving 750,000 tons of freshwater per day at limited energy consumption compared with seawater desalination by reverse osmosis (Chen *et al.,* 2012; Van Loosdrecht *et al.*, 2012). This dual water supply practice has enabled development of the sulphur-based wastewater treatment process (*i.e.* the SANI® process, Wang *et al.,* 2009) with the local wastewater board.

Finally, and by no means least, a major problem in wastewater collection and treatment is the training and education of a new generation of engineers and scientists to design new and to retrofit old wastewater treatment plants and of operators to run them to achieve the limits of the technologies and processes developed to date. This is particularly pertinent in developing countries where political and economic uncertainty results in skill losses to the developed countries. With the development of the technology over the past 40 years the domain of the profession has expanded from a civil engineering activity to a more process engineering and microbiology-based activity. In many universities separate environmental engineering curricula have been developed to bridge both disciplines. Today, all these processes and their technologies are mixed to create complex treatment systems where the use of principles and models are needed in order to handle the full complexity of the applications. Thus today we have a complexity of wastewater treatment as never seen before. This can be confusing and the attempts of numerous companies to market their own processes and technologies is adding to the confusion. This second edition has updated and/or revised most of the chapters of the first edition which was published in 2008 and includes new developments such as aerobic granular sludge and sulfur-based wastewater treatment. All these processes and technologies rely on the same basic processes, and as has been said: *'the bacteria have no idea of the shape of the reactor or the name of the technology, it simply denitrifies if there is nitrate, carbon source and no oxygen.'*

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Figure 1.3 An example of a state-of-the-art wastewater treatment plant: Sha Tin Sewage Treatment Works in Hong Kong (photo: Drainage Services Department, HK).