16

Wastewater

From a Toxin to a Valuable Resource

David W.M. Johnstone[1], Saskia Nowicki[1], Abishek S. Narayan[2], and Ranu Sinha[1]

[1] *School of Geography and the Environment, University of Oxford, UK*
[2] *Aquatic Research, Swiss Federal Institute of Science and Technology (EAWAG), Zurich, Switzerland*

16.1 Introduction

This chapter discusses the development of wastewater treatment from the late 19th century when adequate treatment did not exist and wastewater was a major hazard to both public health and the environment. It uses Great Britain as a case study and charts the advancement of knowledge and process development up to the present day when all sorts of processes can be used to produce every possible quality of effluent including those for recycling. It traces the change in perception of wastewater from something toxic and nasty to one of a valuable resource from which materials can be recovered and energy generated. It also follows the rather tortuous development of the legal and institutional changes that made this development possible. It ends with a very brief discussion of the problems in developing countries where there are very few treatment facilities and gross pollution prevails.

16.2 The Early Formative Years

From the Middle Ages until the early part of the nineteenth century the streets of European cities were foul with excrement and filth to the extent that people often held a clove-studded orange to their nostrils in order to tolerate the atmosphere. The introduction of water-based sewerage systems merely transferred the filth from the streets to the rivers. The problem intensified, especially in Britain, by the coming of the Industrial Revolution and the establishment of factories along the banks of rivers where water was freely available for power, process manufacturing and disposal of effluents. This was accompanied by massive increases in urban populations needed to meet the demand of industrial labour, bringing with them large volumes of domestic sewage (Klein 1957). As a consequence, the quality of many rivers deteriorated to the extent that they were essentially no more than open sewers, aquatic life died, and water supplies and public health were placed in jeopardy. This is clearly illustrated by a series of cholera

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outbreaks, not only in Britain but all over Europe, the first in 1832–1833. That these were directly caused by contaminated drinking water was famously established in 1853/1854 in London by Dr John Snow who identified the water pump in Broad Street, Soho, as delivering sewage-contaminated water from the River Thames.

Dr William Budd described the situation in London during the hot summer of 1858, which has come to be known as the year of 'the Great Stink' (Klein 1957).

> For the first time in the history of man, the sewage of three million people had been brought to seethe and ferment under a burning sun, in one vast open cloaca lying in their midst. The result we all know… stench so foul had never ascended to pollute this lower air. For many weeks parliamentary committee rooms were rendered barely tolerable by suspension of blinds saturated with chloride of lime, and other disinfectants.

Even the construction of 132 km of interceptor sewers and 1800 km of trunk sewers by Joseph Bazelgette between 1858 and 1865 only transferred the waste outside the centre of the city; it did little at that time to improve the overall health risks. Conditions in other growing urban areas of the country and in parts of Europe were similar.

Finally, the government appointed two Royal Commissions on River Pollution, one in 1865 and one in 1868, to study and report on the problems. Both reported extensively on the shocking state of the country's rivers and a report of the second commission stated that 'of the many polluting liquids which now poison the rivers there is not one which cannot be either kept out of streams altogether, or so far purified before admission to deprive it of its noxious character'. The shocking reports of the two Commissions started to awaken public conscience and stir government into legislative action that resulted in the passage of the Public Health Act in 1875 and the Rivers Pollution Prevention Act 1876.

The 1875 Act is regarded as one of the most important sanitary reports of all time. It clearly recognized for the first time that care of public health was a national responsibility and established a system of local health administration setting down, amongst other things, the duties of local authorities with respect to the collection, disposal and treatment of sewage.

The 1876 Act formed the basis of all legal action connected with river pollution up until 1951. Two key offences were specified.

- Part I of the Act made it an offence to put solid matter into a stream, but it was necessary to prove that either pollution or interference with flow was caused.
- Part II of the Act prohibited the discharge of solid or liquid sewage matter into a river and it was no defence to argue that the river had already been polluted by sewage upstream.

Together these two Acts formed the legal and administrative basis of future developments. The 1875 Act resolved a major problem that beset progress in the later part of the nineteenth century. Up until then the only regular form of sewage treatment was by application to dedicated farms, which is very land-intensive, and there was considerable conflict between central and local government due to the reluctance of local government to occupy vast areas of development land with sewage farms; local government would not accept responsibility for sewage disposal. The 1875 Act solved that problem by specifying unambiguously that responsibility for treating sewage did indeed lie with local authorities, a situation that lasted up until 1973 with the passage of the 1973 Water Act that created ten Regional Water Authorities (RWAs) in England and Wales based on natural catchment boundaries and not political boundaries. The ten RWAs came into being on 1 April 1974. The RWA concept did not apply to Scotland where responsibilities were transferred to nine new Regional Councils in 1975.

Soon after the passage of the 1875/1876 Acts there was a particular legal problem that delayed any environmental improvement. The local governments that had become legally responsible for administrating the law were also the principal sources of sewage pollution. As a result, the government set up a number of river authorities and boards to administer the 1876 Act.

On the technical front, both Acts can be considered to have been before their time, as their ambitious targets were not achievable with the technology then available. However, they did stimulate research in treatment to add to the already established basic knowledge. As an alternative to land treatment there was a growing trend to use 'mechanical' methods. In 1898 Cameron and Cummins patented the 'septic tank', still often used in small treatment plants. Chemical precipitation methods were also developed during this period.

Much of the research was based on filtration aimed to simulate land treatment with a growing recognition that 'organisms' were responsible for degradation of the sewage. In 1882 Warrington wrote that 'sewage contains the organisms for its own destruction, and these may be so cultivated to effect the purpose'. And in 1887 William Dibdin stated that:

> In all probability the true way of purifying sewage will be first to separate out the sludge, and then turn into the neutral effluent a charge of the proper organism, *whatever that may be*, especially cultivated for the purpose, retain it for a sufficient period, during which time it should be fully aerated...

This is essentially the first statement of what would become the basic primary and secondary treatment method. However, despite this increasing knowledge, nothing much happened to put the knowledge into action, so the Government commissioned yet another Royal Commission which turned out to be the most critical, influential and effective study ever to be carried out on the subject. Many of the findings are still with us today, not only in the UK but internationally.

The Royal Commission on Sewage Disposal commenced work in May 1898 and completed the last of its nine reports 17 years later in 1915. The scope of the study was considerable, and the 8000 pages of the nine reports laid the foundations of much of today's wastewater practices. The eighth report (1912) introduced the BOD (biochemical oxygen demand) test which is still the most commonly used method for determining the strength of sewage and the effect that sewage would have on receiving watercourses. The fifth report (1908) introduced a rudimentary river quality classification based on oxygen absorption, but this was never passed into law. Perhaps the most famous outcome was the introduction of the 'Royal Commission Standards' of 20 mg/l BOD and 30 mg/l of suspended solids for treated sewage effluents based on a mass balance of river quality upstream and downstream of the discharge point, assuming an eight-fold dilution and an upstream BOD of 2 mg/l. These standards were used for decades as the norm for effluent quality and are still used today in many places. Even the basic European effluent standards for non-sensitive watercourses are not dissimilar; in fact, they are less strict.

In parallel to the work of the Royal Commission there was considerable research effort in various parts of the world. Ground-breaking research in Manchester resulted in the publication in April 1914 of the seminal paper on 'Activated Sludge' by Ardern and Lockett. Activated sludge and its variations form the bases for most modern suspended growth treatment processes, of which there are many, although there are other processes based on 'biological filtration' which had been applied in many towns and cities during the latter part of the nineteenth century.

16.3 Early Full-Scale Application and Process Development

Thus by 1914 there was, at least in Great Britain, a defined institutional and legal system, a rudimentary river quality classification with defined numerical effluent standards, and a basic knowledge of how to treat sewage. Under these circumstances, rapid application could have been expected, but that was not universally the case. Europe was to see the devastation of a major war that left little capital for sewage treatment well into the 1920s. The first British city to apply activated sludge was Sheffield in 1920, on a trial basis, but many municipalities had already invested in filtration plants and saw no reason to invest in the 'new-fangled activated sludge system'. As a consequence, the first very large treatment plants at Manchester and London (Mogden) were not completed until 1934 and 1935 (Cooper 2001). By contrast, development of activated sludge in the USA forged ahead in some places, but in others the municipalities decided to build filtration plants rather than pay steep royalties to UK companies that had taken out patents on activated sludge; hence the large-scale uptake was stalled until the 1940s when the patents expired (Schneider 2011). Although numerous activated sludge plants were built during the four or five decades following the initial discovery, much of the design was on a 'trial and error' basis and many of the early plants were unstable particularly with respect to secondary sludge settlement and nitrification.

16.4 The Age of Understanding

It was only from the early 1960s onwards that there were significant changes to our understanding of activated sludge using a more scientific bioengineering approach. The solution to the nitrification problem was discovered by Downing et al. (1964) with the elucidation of the kinetics of biological oxidation of ammoniacal nitrogen. Studies of aeration tank configuration using continuous flow reactor dynamics led to discoveries that different configurations produced different bacterial populations that had major effects on biomass settleability. The problem of poor settleability, known as 'bulking', had plagued the industry ever since the introduction of the continuous flow process. If uncontrolled, biomass solids can overflow into the receiving watercourse causing pollution and, at worst, can lead to the loss of the whole biomass and total system failure. Over the years 'bulking' had been attributed to overloading, underloading, over-aeration, under-aeration, short-circuiting, nutrient imbalance, high pH, low pH, high temperature, sewage septicity, and other causes (Tomlinson 1982). In fact, the real mechanisms were not understood until later when greater knowledge of the ecology of activated sludge and use of reactor dynamic studies showed that a 'completely-mixed' configuration produced poor settling sludge whilst 'plug-flow' configurations produced relatively good settling sludge. The simplistic answer is that each regime has a different effect on the generation of the filamentous bacteria that cause 'bulking'.

The biochemical engineering approach also led to the establishment of mathematical models that allowed process characteristics to be evaluated rapidly rather than waiting for the results of prolonged practical trials. This approach, along with the development of new monitoring devices, also led to the beginning of automatic control systems.

Not only had the understanding and knowledge of activated sludge systems been improved, but so also had that for so-called biological filters, a term which is a complete misnomer since these systems do not filter anything. They are biological treatment systems where the biomass is attached to the surface of a solid medium with a large surface area, originally coke or slag, although today there are many varieties that use plastic media. The biological reactions take place on a surface slime layer as the sewage percolates down through the bed, whilst air supplying oxygen travels upwards. These systems are the oldest of the constructed processes and pre-date activated sludge by decades. They are much in use today and are still referred to (wrongly) as biological filters. They have the advantage over activated sludge of being relatively low in energy consumption and are generally robust, but suffer the disadvantages of having a very large footprint, being rather inflexible, and performing poorly in very cold weather.

16.5 Some Important Legislative and Institutional Changes

At this juncture it is important to discuss some legal and institutional changes that influenced the development of wastewater treatment. Unfortunately, it is beyond the scope of this chapter to present the complete history of these changes, so only a few of the most significant are presented.

Paramount in establishment of all wastewater activities is the need to control industrial pollution, to which end the government passed the Public Health (Drainage of Trade Premises) Act 1937 that gave industry the right to discharge to a public sewer, subject to meeting conditions laid down by the appropriate public authority in a legal document giving ‘consent’ to discharge. This is essential to protect workers working in the sewer network, to protect the fabric of the sewer, and to protect downstream biological treatment plants and sludge disposal (see Johnstone 2003 for a more detailed account).

In 1948 a number of River Boards were formed to tackle the high levels of pollution that still permeated many rivers, with powers to set standards for rivers and effluent discharges. These powers were further strengthened under the Rivers (Prevention of Pollution) Act 1951, under which all new discharges had to have a ‘consent’ to discharge that specified both quantity and quality limits. This Act was further strengthened under the Rivers (Prevention of Pollution) Act 1961, and during the 1960s the River Boards were abolished and replaced with a smaller number of River Authorities with much wider powers. It should be pointed out that some of the legislation in Scotland was different from that in England and Wales, but the paths were similar.

These institutional and legal changes did drive improvements, but not enough, and sewage works of many Authorities failed to meet their designated ‘consent’ standards. Later the National Water Council introduced river water quality objectives (RQOs) based on the aquatic and anthropogenic requirements of a river, from which long-term targets were established. Effluent standards were then set to meet the relevant RQO, which in most cases led to a significant tightening of effluent quality. Another key legislative measure was the eventual enactment of the Control of Pollution Act 1974, with the establishment of Registers of Sewage Works Performance and easing of controls on prosecution. There then followed adoption of a number of European Directives such as those on Urban Wastewater (1991) and Bathing Water Quality (1992) that tightened regulation. More significantly, the EU introduced the Water Framework Directive (WFD) in 2000 that takes a more holistic approach to the aquatic environment by establishing basic management units within a river basin, which must address environmental, economic and social needs. A short but comprehensive history of the main long-term developments has been published by Woods (2003), whilst the Department for Environment, Food and Rural Affairs (DEFRA) presents an account of how the UK dealt with the European Directives (DEFRA 2002), and Chave (2001) gives an account of the WFD. All-in-all, this progressive drive to improve the aquatic environment with accompanying regulation did much to drive the development of better processes and promote enhanced resilience.

Two other institutional developments that led to significant increases in knowledge and understanding are worthy of mention. The first was the establishment of the Water Pollution Research Laboratory (WPRL), originally set up in 1927 by a Government that was 'increasingly concerned' with the problems of river pollution and its adverse effect on the supply of pure water for a growing population and industry. It moved to its own laboratory in 1947, and it was here that much of the fundamental research was carried out, including the aforementioned work on nitrification, mathematical modelling, 'bulking' and on the understanding of 'filter' beds.

The second event was the creation in 1974 of the ten RWAs in England and Wales based on managing the complete aquatic environment contained within natural catchment areas, and not bounded by political boundaries. These RWAs developed a much greater capacity to manage wastewater treatment than any of the previous disparate organizations, and developed large well-equipped centres of excellence devoted to the research, evaluation and application of wastewater processes, often in partnership with the WPRL. The result was arguably one of the most significant increases in wastewater process knowledge, with large positive influences on design and costs.

16.6 More Understanding and a Plethora of Processes

Up to the early 1970s the liquid stream at most treatment plants in Britain comprised preliminary treatment (removal of grit, coarse solids and rags, etc.); primary sedimentation (removal of settleable solids); secondary treatment (either based on activated sludge or 'biological filters') and occasionally a tertiary stage (usually rapid gravity sand filters) to improve effluent quality when necessary. Since then there have been very significant advances not only to the conventional process units, but also in the development of many alternative processes. Amongst the driving forces were:

- the need to meet increasing stringent effluent standards, particularly removal of nitrogen and phosphorus;
- a requirement to solve the problem of 'bulking';
- a desire to reduce the large 'footprint' of conventional systems;
- a need to improve the efficiency of aeration systems and reduce energy consumption and carbon footprint;
- a desire to minimize the production of sludge.

During this period many competing processes were introduced by contracting companies seeking a share of the large capital market behind the wastewater industry. Some were excellent, whilst others failed to live up to the claims. In fact, some of the claims turned out to be preposterous when examined against the rigours of scientific evaluation.

In addition to the introduction of many 'new secondary treatment processes', one of the most important but least heralded developments was the introduction of a new family of preliminary screens that continuously trap and remove particles greater than 6 mm from the incoming sewage. This made downstream operations much easier and helped the successful introduction of the 'new processes'; it also aided more effective control systems by minimizing the fouling of measurement probes.

Arguably the most important new processes were those aimed at the removal of nitrogen and phosphorus, especially from discharges to watercourses designated by the EU Directive (2000) as 'sensitive', which really means those with a potential for eutrophication. Following on from the discovery of the mechanism of nitrification, it became well established that subjecting a nitrified biomass to anoxic (very low dissolved oxygen) conditions would allow bacteria to use the oxygen atoms in nitrate for sustenance, liberating nitrogen in the process. Thus, incorporating 'anoxic zones' into aeration streams presented a way to remove nitrogen, and thus arose a number of processes with combinations of oxic (O) and anoxic (A) zones, some designed in a bespoke manner, and others proprietary processes with designations such as AO or A^2O.

The removal of phosphate can be achieved by adding chemicals such as ferric sulfate, but it can also be removed biologically by incorporating an anaerobic zone at the beginning of an activated sludge process which, if designed as a nitrogen removal system, yields a process for complete removal of the key nutrients, N and P. The key to biological phosphate removal was discovered by Barnard (1974) in South Africa. This is a biologically complex process beyond the scope of this chapter, but essentially when the biomass is subjected to anaerobic (An) conditions there is a release of phosphate from within the biomass cells into the surrounding liquor, which, when subjected to subsequent aerobic conditions, is taken up again: not only do the cells take up the phosphate released by the cells, but also the phosphate present in the incoming wastewater, with all the phosphate being incorporated into the biomass. And, as long as the biomass remains aerobic, the phosphate will stay there. However, there is a potential problem in that, if the biomass becomes anaerobic, the phosphate can be re-released. This gave rise to a number of modifications to the basic concept that seek to prevent reprecipitation and this produced even more 'new processes' with names such as Bardenpho, University of Cape Town (UCT), and many more. Most of these processes involve a series of (An), (O), and (A) zones in a plug-flow configuration with internal liquor recycling.

There are now many process options available that can achieve all standards of effluent and be located in any possible environment. It is beyond the scope of this chapter to discuss details, and the reader is directed to the many textbooks on the subject such as the massive 2018 pages in Metcalf and Eddy (2013). There is, however, one development that has completely changed the face of wastewater treatment and requires a more detailed description; that development is the introduction of membranes as a means of solid–liquid separation (see e.g. Faisal et al. 2013).

The possibility of using membrane technology was considered in the 1960s but was then thought too expensive. However, changes to manufacturing procedures in the 1970s and a subsequent competitive market brought down costs substantially to the extent that it is now an established, cost-effective system, especially when there is a need to produce very high-quality effluents. Asymmetric cellulose acetate membranes come in four size ranges with ever-decreasing pore size; microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), although NF and RO tend not to be used in wastewater treatment. Between them MF and UF can remove most bacteria, colloidal particles, many viruses and large organic macromolecules, depending on the choice of membrane. Thus, when combined with biological treatment (usually activated sludge), very high-quality effluents can be achieved in a range of processes known as membrane biological reactors (MBRs).

Superficially MBRs are not cheap; the capital cost is high, they have relatively high energy consumption, and maintenance requirements are high compared with non-membrane systems, since the membrane has to be frequently backwashed, occasionally cleaned chemically and replaced every 12 years or so.

The use of MBRs has to be placed in context with other competing processes, but where space is limited and/or very high-quality effluent is required, they are ideal. They can also be engineered across the complete size range of wastewater treatment from the very large to the very small, including package plants and single building applications. However, their greatest niche is in re-use and recovery of water as discussed below.

16.7 The Question of Sludge

A common feature of all wastewater treatment processes is that they produce sludge, some more than others and, like the liquid stream, the knowledge and developments in sludge treatment and disposal have advanced greatly since the late nineteenth century.

The capital cost of sludge treatment is a significant proportion of the overall capital costs, often greater than the cost of the liquid stream. The treatment and ultimate disposal of sludge is usually the greatest operational burden. There is an old axiom amongst sewage treatment managers that 'if you take good care of the sludge the rest of the plant will take care of itself'. Yet, when it comes to deciding on new facilities, sludge often comes as an afterthought, whereas good counsel would suggest that the first question to be addressed at that stage is 'what are we going to do with the sludge?' rather than 'how do we achieve effluent quality?'.

There are, in essence, two types of sludge; those emanating from primary sedimentation and from secondary (biological) treatment. Primary sludge is generally obnoxious, odorous and a considerable hazard; secondary sludges are much less obnoxious and can have an 'earthy smell' depending on the nature of the secondary process.

The most common disposal routes are:

- Landfill; either monofill or combined with garbage – not significant in Britain
- Land: either agricultural, forestry, or sacrificial
- Incineration – not widely practiced in Britain but growing elsewhere
- Drying/palletization and used as fuel, particularly in power stations and cement factories – again, not widely practiced in Britain but growing elsewhere.

There are three main public health issues with sludge; so-called 'heavy metals'; pathogens; and chemical contaminants, with the hazards minimized by strict control and regulation. Regulations are geared towards the specific risks attached to each disposal route, which, in turn, determines the type and extent of treatment required. Most of the sludge in Britain is spread on agricultural land as governed by EU Directive 86/278/EEC (OJ No. L181/6) 1986 and implemented through a *Code of Practice for Agricultural Use of Sewage Sludge, 1996.*

16.7.1 Heavy Metals

Almost all metals found in sewage end up bound to the sludge; very little is discharged in the effluent stream. The metals of most concern are As, Cd, Cu, Pb, Hg, Mo, Ni, Se and Zn. Some, like cadmium and mercury, are directly toxic to humans and animals, whilst others like copper, nickel and zinc are phytotoxic, that is, they have a negative effect on crop yields. Many of these metals have their origin in industrial processes and hence the need for strong control of industrial wastewaters. To this end the 1937 Act was considerably strengthened by Part III of the Water Industry Act 1991. The current regulations on metals in soil are very strict, and water companies are obliged to develop sludge disposal safety plans including the need for storage.

16.7.2 Toxic Organic Chemicals

It is generally accepted that the risk to humans, animals and the environment from toxic organic compounds in sewage sludge is not as high as the risks from heavy metals, due to the very low concentrations usually found. The compounds of most potential concern are dioxins and several polychlorinated hydrocarbons. General opinion accepts that the risk from toxic organic compounds in domestic sewage sludge is very low, and that only places accepting large volumes of industrial wastewaters from certain industries would pose any risk, in which case such compounds should be eliminated at source.

16.7.3 Pathogens

The European Directive does not place limits on pathogens, but Britain controls pathogens by specifying the use of effective treatment processes with stringent conditions in terms of retention times of digesters, elevated temperatures, pH conditions, storage times and composting conditions.

Over the last century there has been a steady growth in sludge treatment technologies, with significant developments in equipment to ‘thicken’ (concentrate) sludges before main treatment and various types of presses and centrifuges after main treatment to dewater sludges, all ably assisted by dosing with cationic polyelectrolytes; thermal drying is also a feasible option. The choice of equipment depends on cost and the needs of the final disposal route.

Over the years the foremost process for sludge treatment has been mesophilic (35–37°C) anaerobic digestion (AD), but the digesters of today differ considerably from those found in the 1960s. Today’s digesters are much more efficient and have been accompanied by other systems such as thermophilic (55°C) digestion, which is more effective in pathogen kill but can have stability issues. However, a development first implemented around 2010 is thermal hydrolysis (TH) applied upstream of AD. In this system, sludge is heated to around 160°C under pressure of about 7 bar where no pathogens can survive. The main benefit of TH, however, is that it changes the biodegradability and rheology of the sludge so that feed rate to the digester can be doubled and generation of methane greatly enhanced. Thus, energy recovery is greatly improved, but that is a subject for the next section.

16.8 A New Philosophy; A New Paradigm?

The developments so far discussed were driven initially by public health issues and later by ever-increasing environmental standards required to clean up rivers and improve aquatic life. This has been more or less very successful, with many river systems restored to good quality with considerable biodiversity, although the present should only be considered as a point in a continuing drive to further improvement, and there are still many issues to be resolved especially with sewerage networks and with the problems of residual pharmaceuticals and many other micro-chemical pollutants. The discussion also summarized very briefly the rather tortuous, but vital, institutional and legal developments that made these improvements possible.

The world of today is vastly different from that when this journey started, and so are our needs. The world now faces massive growth in urbanization caused by continuous population growth, and this is accompanied by a growing freshwater crisis in both quantity and quality. Increased demand for food and energy, along with reducing water resources, have resulted in complex food/energy/water nexuses that have to be managed in the future, all of which are further complicated by decaying assets, poor investment, and by the uncertainties of climate change. The future will not be easy and will require an entirely different philosophical approach to urban water issues and, in this respect, it will be essential that wastewater management is considered as an integral part of any management system that embraces all dimensions of sustainable development. It is no longer appropriate to take wastewater for granted.

Over the past decade or so, wastewater has been increasingly recognized as a valuable asset that can be re-used or recycled, and as a source of valuable materials that can be recovered. Indeed, the UN Sustainable Development Goal (SDG6a) advocates recycling and re-use. The most obvious recoverable materials are summarized below, but there are others.

16.8.1 Water

The most obvious material is water itself, since domestic sewage is at least 99% water. Of particular future importance will be wastewater re-use to supplement diminishing resources in procedures such as aquifer recharge, and in Indirect Potable Reuse (IPR). In the latter, highly treated effluents are discharged into river systems upstream of water intakes. More controversial is the use of treated wastewater for Direct Potable Reuse (DPR), which requires the application of much social science and public relations to convince populations of the safety of such an approach and to overcome the inherent 'yuck factor'. For comprehensive examples of the issues, research and application, visit www.WateReuse.org.

Today's technology allows re-use over a very wide size range. At one end, recycled wastewater arising from municipal networks can be re-used for either industrial or domestic (usually non-potable) purposes. At the other end, single building application with MBR/disinfection processes lodged in the basement are used to treat the building's wastewater and return treated water for toilet flushing or garden irrigation, often coloured to distinguish the recycled from the fresh.

16.8.2 Energy

Well-developed wastewater treatment is a large consumer of energy, most of which is used to keep aeration equipment constantly operational. It has been traditional practice to treat sludge by AD and use methane to generate energy for plant re-use to minimize other fuel purchases. More recently, efficient digesters and combined TH/AD means that much more energy is produced, and together there is a greater contribution to operating costs. In many places, energy production is supplemented by importing strong organic wastes and/or surplus food wastes for combined digestion. As a result, some treatment plants now generate an excess of biogas that can be sold directly to the national gas-grid; converted to electricity and sold to the national electricity grid; or used to fuel vehicles (for example, see http://geneco.uk.com). Not only does this practice produce an income for the operators, but it provides an environmentally sound solution to the problem of dumping food wastes.

16.8.3 Fertilisers

The disposal of sludge to agricultural land has been practised for decades in the UK, albeit that, in the past, farmers had to be persuaded to accept cost-free sludge on a regular basis. Today, with improved treatment processes and stringent regulations producing a better product, offsetting the high cost of inorganic fertilizers, farmers are willing to pay for sludge and for services to monitor and control application. This is a significant turn-around and highlights good recycling practice.

16.8.4 Phosphate

After recovery of water and energy, the recovery of phosphate is arguably the most important recoverable material, as described in Box 16.1.

16.8.5 Other Recoverable Materials

Over the last decade or so there has been much research and development on wastewater re-use and material recovery for a great variety of purposes, too many to be discussed here, but very well summarized by Lazarova (2013). In some parts of the world, materials such as building bricks and biofuel are regularly recovered and there is also current research on recovery of less obvious materials such as alginic acid and cellulose by, for example, Van der Hoek et al. (2016), to mention just one research group.

It is satisfying to say that wastewater is now recognized as a valuable resource. The philosophy has changed; now political and institutional paradigm shifts are required to implement the new philosophy on a very much wider scale.

16.9 The Uncollected and Untreated

The story reported in this chapter relates to Great Britain, and similar optimistic stories can be reported for most of the developed world, but it would be remiss not to mention the dire situation with wastewater in the developing world. Corcoran et al. (2010), in their report ‘Sick Water’, state that between 80% and 90% of all wastewater generated in developing countries receives no treatment whatsoever. They cite the situation in Jakarta by stating that 500 Olympic-sized swimming pools of wastewater are generated daily, but there is only capacity to treat 15 swimming pools’ worth. Urban rivers in much of the developing world are effectively open sewers, and conditions are much the same as those found in Britain at the end of the nineteenth century.

Box 16.1 Phosphorus Recovery: Value and Security from Wastewater

Saskia Nowicki

Phosphorus recovery from wastewater is an emerging opportunity and a long-term necessity. Mining, fertilizer production, intensive agriculture, and inefficient waste management have exacerbated phosphorus losses, unbalancing the global phosphorus cycle (see Figure 16.1) and creating conditions for scarcity. Since pre-industrial times, the amount of phosphorus in terrestrial and freshwater ecosystems – where it is inaccessible to us – has increased by at least 75% (Bennett et al. 2001).

Phosphorus has no substitute. It is an essential component of genetic material, the building blocks of cell membranes (phospholipids), and the energy currency of cells (adenosine triphosphate). Most mined phosphorus is used in fertilizers or feed supplements for agriculture. Demand is increasing due to population growth, increased meat and dairy consumption, and cultivation of non-food crops for purposes like biofuel. Concurrently, phosphate rock reserves are depleting. As the best deposits are targeted first, mined phosphate rock quality is likely to worsen, meaning an increase in impurities (metals and radionuclides) and processing costs. Peak phosphorus is projected for as soon as 2025 or, more mercifully, around 2085 (Cordell and White 2014).

Although enhanced food system efficiency will be important in addressing the coming deficit, supply measures are also needed. Phosphorus in manure and human excreta, which account for 40% and 16% of lost phosphorus flows (Rittmann et al. 2011), must be re-used and recovered. The processes already used by wastewater treatment plants to control nutrient pollution are prerequisites for phosphorus recovery. Currently, the most economical phosphorus recovery methods work in combination with biological nutrient removal processes to precipitate either calcium phosphate or magnesium ammonium phosphate (struvite). Controlling struvite precipitation reduces treatment plant maintenance costs and produces a high-purity, odourless commodity that is easy to package and transport. Beyond good aesthetics, struvite is bioavailable and breaks down slowly, so it requires relatively low application rates and helps reduce wasteful phosphorus runoff.

Conventional fertilizer manufacturers are plagued by depleting reserves, increasing impurities and rising processing costs. In contrast, wastewater treatment plants can anticipate increasing demand for recovered phosphorus. Thus, they are faced with an economic opportunity, and an obligation, to help secure supplies of phosphorus and, therefore, food.

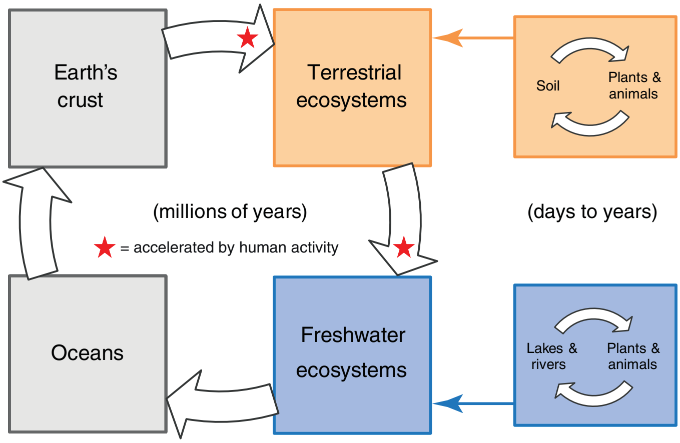

Figure 16.1 Global phosphorus cycle. *Source:* Authors. (*See color representation of this figure in color plate section*).

Why is this so? What are the barriers to wastewater development and what can be done to improve the situation? The problems are not treatment related; there are enough processes to suit all needs, including ones that are affordable and appropriate for developing world conditions. The problems are essentially related to governance, policy, regulation, institutions and finance. It is often said that the biggest barrier is that 'there are no votes in sewage', especially in countries facing other important investment needs. Two particular issues worth discussing are the problems with sewers and the lack of innovative institutional arrangements.

16.9.1 Sewers

The development of wastewater treatment is often inhibited by sewerage networks (or lack of) and problems in conveying wastewater to the treatment plant; the cost of supplying this infrastructure often far exceeds that for the treatment plant itself. In the developed world conventional networks are usually buried deep in the ground, making construction expensive, but there are many non-conventional sewerage systems that are much more affordable to the developing world, such as simplified sewerage and condominial systems (Reed 1995). Another option is to develop a decentralized network with a number of local treatment plants, which saves large network costs. One successful application in Addis Ababa is described in Box 16.2. There are many others.

16.9.2 Innovative Institutional Arrangements

It is axiomatic that development of wastewater treatment must be accompanied by robust institutional arrangements and the elements of good governance, including the legal and institutional framework for the control of industrial wastewaters. It is also vital to have some system that ensures adequate operation long after construction; the developing world is peppered with treatment plants that are either non-functional or abandoned for numerous reasons. In these cases, the costs have been high but the benefits zero. A system aimed at overcoming this has been developed in Brazil, and could easily find application elsewhere. It is described in Box 16.3.

16.10 Concluding Remarks

This chapter attempted to highlight some of the institutional and technical complexities ingrained in establishing sustainable wastewater treatment, and to show that wastewater itself can be considered a valuable asset. However, the discussion mostly concerned the developed parts of the world, whereas the bulk of wastewater in developing countries is neither collected nor treated. Dire though that statistic may be, it underestimates the problem: much of that wastewater is of industrial origin or highly polluted with industrial contaminants, many of which are toxic and banned elsewhere. Domestic wastewater is more-or-less biodegradable and, even if only partly treated, would eventually be incorporated into nature's self-purification processes. That is not the case with these toxic compounds, many of which are persistent, with devastating effects on human health and the environment. Of particular concern is that, if not treated (or

Box 16.2 Decentralized Wastewater Treatment in Addis Ababa, Ethiopia

Abishek S. Narayan

Rapid urbanization and a backlog of sanitation infrastructure provision has exacerbated the wastewater challenge in developing countries. Decentralized wastewater treatment (DWT) is an innovative strategy that Addis Ababa adopted for its affordable condominium housing schemes. This is a pro-poor and environmentally sustainable intervention that could be adopted in various high-density cities across the developing world.

Currently, over 40% of Addis Ababa does not have access to improved sanitation, and sewer connection exists for less than 10% of the population. The majority rely on vacuum truck emptying services. The wastewater infrastructure in the city is therefore limited, with insufficient capacity in central treatment plants to handle the wastewater produced. However, the ambitions of the federal government to reach the status of a middle-income country by 2025 places sanitation and urban housing as a priority (GTP-II 2016). To promote access to affordable housing as part of their poverty alleviation strategy, several condominiums were built in the capital city, Addis Ababa. The construction of condominiums without connections to the central wastewater systems put the local City Government (CG) under pressure to address this problem quickly.

In 2014, a decision was taken to introduce DWT systematically in 15 of the newly built condominiums at a cost of over 700 million Ethiopian BIRR (ETB) (US $25 million), by the CG, Water and Sewerage Authority, and the Addis Ababa Housing Development Project Office. Their combined treatment capacity is over 27 000 m^3/day, serving 185 000 residents. Although high-end membrane technology was initially used, considering its cost and labour-capacity requirements, simpler activated sludge technologies are being piloted for subsequent projects.

The transformation of a potential sanitation crisis into a sustainable long-term sanitation solution addressing the challenges of urbanization came about through a combination of long-term national goals and short-term situational urgency. The autonomy and fiscal independence of the CG provided the flexibility to enable public finance for the project with no reliance on external donors or federal budget allocations. Further, the positive public perception of DWT and recognition of the importance of urban water bodies by government agencies were crucial to this successful pioneering of DWT by a municipal government in a developing country (Sankaranarayan and Charles 2017).

better, eliminated), they reach the oceans, causing inhibition of the primary oceanographic productivity that is so important in stabilizing global warming. The recent recognition of substantial pollution by microplastics adds further to the problem. In 2005 the Millennium Ecosystem Assessment (MEA 2005) reported that 60% of global ecosystem services had already been degraded by human activity. It will be disastrous if world communities make matters worse by not giving urgent and appropriate attention to their wastewaters, which grow in volume every day. It is a massive challenge whose solution will require application of every element of good Wastewater Science, Policy and Management. That, however, is another story.

Box 16.3 River Basin Clean-up in Brazil

Ranu Sinha

The Programa Despoluição de Bacias Hidrográficas (PRODES) or River Basin Clean-up programme was set up by the Brazilian National Water Agency (ANA) in 2001 to reduce water pollution caused by discharge of untreated sewage, particularly in urban areas. PRODES operates as an incentive payment to utilities that invest in the construction, enlargement or improvement of wastewater treatment plants (World Bank 2018). There are five critical steps in the PRODES design, as described below.

Registration	Utility presents proposal to ANA for registration. Must contain pollution reduction goals, approvals from Municipalities and river basin committees
Qualification	Proposals evaluated; compatibility of process and goals
Selection	Proposal selected by ANA – criteria include quality improvements and water resources
Contracting	Proposals contracted on priority basis depending on budget
Certification	Evaluation over three years with 12 evaluations

The first four steps take place within a year and occur before construction begins, whilst the final phase lasts for three years and can only begin once the plant is operational. PRODES subsidy levels vary and are determined using per capita cost reference values associated with two basic parameters: removal efficiency of specific pollutants (technology); and final treatment capacity in terms of effluent pollutant loads (population). Hence the amount of funds available can vary depending on the size of the municipality. Payment of the subsidy is made only when it is proven that there is a reduction of pollution loads over a three-year period in accordance with performance targets pre-established on each contract (Libanio 2015). At first, the operators monitor pollution loads and provide results to ANA. ANA then verifies whether the operational results have achieved the contractual goals, which include inflow and pollutant loads treated as well as pollutant removal efficiency. Once targets are achieved, reimbursements are made of full or partial capital costs.

Some of the key design functions of PRODES include: (i) utilities must get approval of their proposals from municipalities and river basin committees, forcing collaboration and transparency; (ii) resources are transferred to a specific escrow account related to the project, linked to a Fund, and can only be withdrawn after authorization from ANA; and, (iii) the requirement of output verification prior to disbursement of payments provides a critical fiduciary safeguard for the accurate targeting of funds as well as evidence that public funding was well spent. Since its implementation, PRODES has represented a paradigm shift in the water and sanitation sector in Brazil, with increased wastewater services and improvements to water quality indices of a number of rivers.

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