A Review of Current Knowledge

Urban Drainage and the Water Environment: a Sustainable Future?

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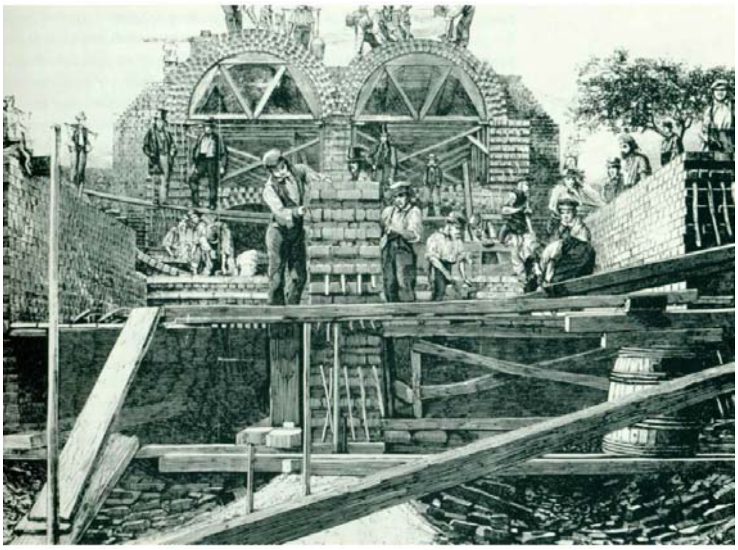
Review of Current Knowledge

This review is one of a series of Reviews of Current Knowledge (ROCKs) produced by FWR. They focus on topics related to water supply, wastewater disposal and water environments, which may be the subject of debate and inquiry. The objective of each review is to produce concise, independent scientific and technical information on the subject to facilitate a wider understanding of the issues involved and to promote informed opinion about them.

Urban Drainage & the Water Environment: A Sustainable Future?



Front cover image:
"Main drainage of the metropolis – sectional view of the tunnels from Wick Lane near Old Ford, Bow, looking westward" The Illustrated London News 27th August 1859.
(Thames Water)

Authors:
First Edition: J. M. Tyson
Second Edition: T. D. Evans and N. Orman

The monument to Sir Joseph Bazalgette, Victoria Embankment, London.
He built the interceptor sewers in London and much else besides.
The interceptors solved "The Great Stink" of 1858.

"*11,300 readers of the British Medical Journal chose the introduction of clean water and sewage disposal—'the sanitary revolution'—as the most important medical milestone since 1840, when the BMJ was first published*". Ferriman, A. (2007) Medical Milestones Supplement, Brit. Med. J. 344 Suppl. 1

Contents

1 Introduction

The purpose of this review is to describe the development of drainage systems in urban areas, to consider how well these systems meet present-day requirements and to identify what means are available to meet future needs in a sustainable way.

From the earliest times, people in cities and towns devised drainage systems to remove surface water from their streets and houses. These systems normally took the form of an open drain in the street into which flowed rainfall run-off from the surrounding surfaces. Often there was strict demarcation between surface water and wastewater or wastes and it was a punishable offence to contaminate surface water sewers with waste or manure: though in the days of animal-drawn transport, dung deposited on roads would have contaminated street runoff. In early civilisations the provision of water, the disposal of household wastewater, and human wastes was performed locally at either the level of single or small groups of houses.

As cities and towns developed and grew, so did the risk of seepage from cesspools into groundwater wells because of their close proximity (Figure 1). The problem was exacerbated by the adoption of the water closet. In the nineteenth century the policy of keeping waste separate from surface water was reversed in the largest cities, citizens were instructed to connect their dirty water to the [formerly clean] surface-water sewers, many of which had been culverted to allow more land for building. The system of water-borne waste became the norm in order to protect drinking-water wells and reduce "miasma".

Figure 1 The privy pit (cesspool) and drinking-water well at Benjamin Franklin's house in Philadelphia USA (1787) separated by less than 3 m. (Tim Evans)

The problem with this paradigm shift was that the sewers discharged into rivers. Natural aeration could not keep up with oxygen demand being placed on the rivers by the massive injection of organic matter. Dissolved oxygen was stripped from the water, fish and other aerobic life died and the rivers stank. The unintended consequence of protecting wells by discharging dirty water to the former surface-water sewers was that the rivers were killed. It was solved by intercepting the sewers before they got to the main river and diverting the dirty water initially far enough downstream to remove the stench from the city and later to land-based wastewater treatment so that only cleaned water reached the river and life in the river could recolonize and regenerate.

The widespread general success of urban drainage systems in protecting public health and in helping to maintain acceptable standards of life in towns and cities is undisputed. However, the demands on most urban drainage systems are increasing because of rapid population growth and increasing areas of impermeable surfaces (roofs, paving, etc.) so called "urban creep". This has resulted in additional hydraulic load and also treatment load. Hydraulic load is the volume to be conveyed. Treatment load is the amount of potential pollutants that have to be removed during wastewater treatment. The hydraulic load has become more 'flashy' (i.e. the volume increases rapidly after rain starts and decreases rapidly after rain ceases) because of rapid runoff from the hard surfaces. Figure 2 shows two simulated hydrographs, the total volume of runoff is the same in both cases (84.4 m^3); in the flashier catchment the peak flow is 54 litres/sec but in the other it is 35 litres/sec. The former might have exceeded a sewer's capacity whereas the latter might have been accommodated.

Additionally, treatment plants are being required to meet tighter environmental standards. Unless something is done to reduce this flashiness, the most likely effect of climate change on drainage networks in the longer term is significantly greater peak hydraulic loads and system overload. For both drainage networks and treatment systems, significant further investment may be required in many areas to prevent system breakdown. One question which is therefore pertinent in the developing scenario is "*will current approaches to urban drainage be fit for purpose in the longer term and if not what are the alternatives?*" This Review examines these matters.

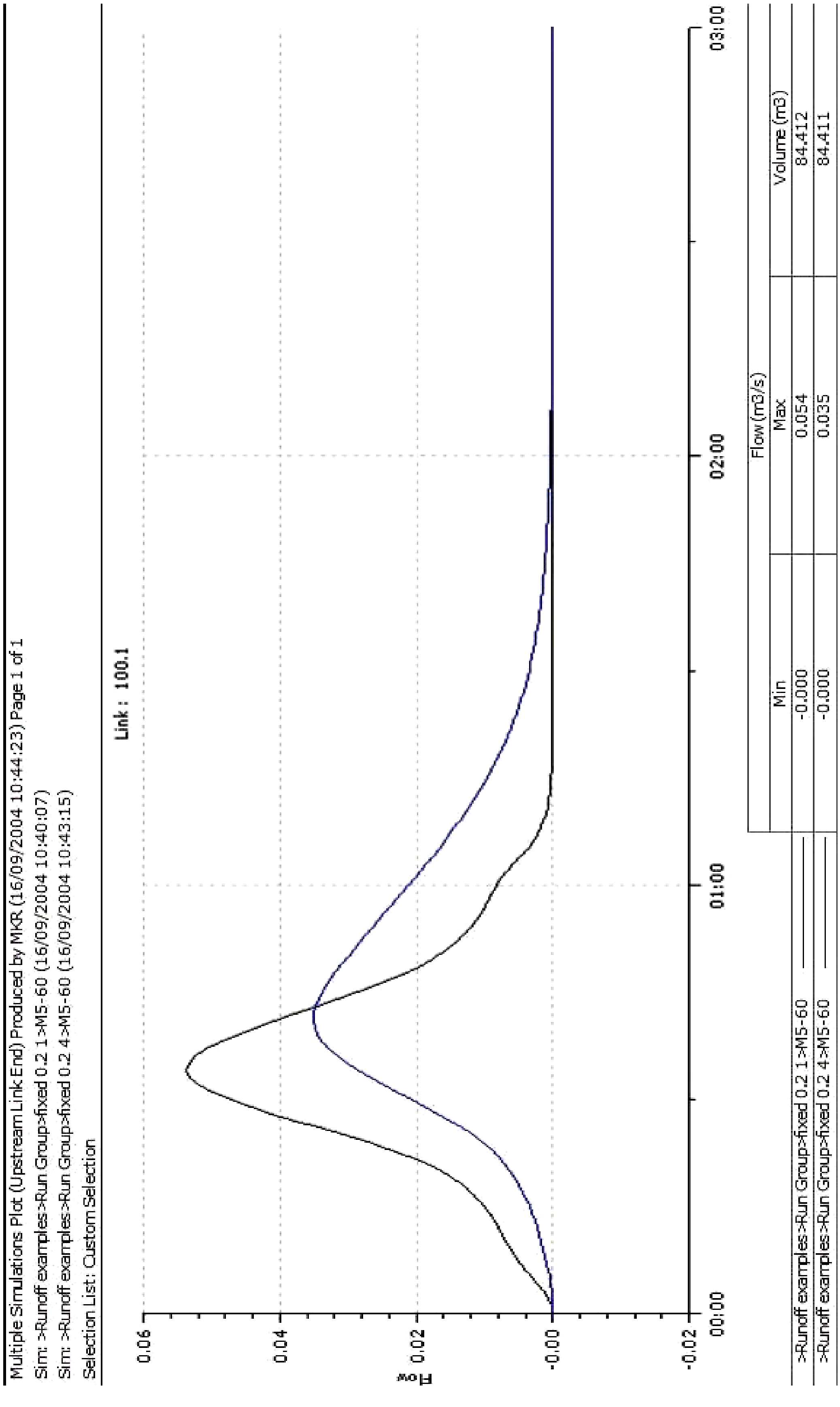


Figure 2 Simulated hydrographs with the same volume of runoff but over different durations
(Mike Reeves)

2 Evolution of Drainage Systems

2.1 Early civilizations

When the population of the world was small and thinly distributed the people tended to be nomadic, so there was no great accumulation of the waste products of humans and their activities. However, as humans began to congregate in fixed settlements the effects of the accumulation of waste products on the health of the community soon became evident and measures, however primitive, had to be taken to alleviate the problem. An early example of this is given in the Book of Deuteronomy. The tribes of Israel, after the Exodus from Egypt, had been leading a nomadic existence for several years in the Sinai desert, but they finally settled, for a considerable time, at the foot of Mount Sinai. The problem of disposing of the accumulation of waste matter in a settled camp then arose and the instructions to overcome this problem, are recorded in Deuteronomy Chapter 23, verses 12-13: - "*Thou shalt have a place also without the camp, whither thou shalt go forth abroad; and thou shalt have a paddle upon thy weapon; and it shall be, when thou wilt ease thyself abroad, thou shalt dig therewith, and shalt turn back and cover that which cometh from thee*." (Authorised Version of the Bible, 1611).

Archaeological excavations of many of the ancient cities have revealed evidence of sewers in these cities. The following examples provide an overview of drainage systems in four cities of the ancient world.

Mohenjo-Daro was an early city located in the south of what is now Pakistan, on the west bank of the Indus River. It was built between four and five thousand years ago, and lasted until around 1,700 BC. The city had at least 35,000 residents and archaeological excavations have revealed that most houses had small bathrooms and the streets contained baked brick drains (Figure 3).

Figure 3 A baked-brick sewage channel in Mohenjo-Daro: Indus valley 2500 BC
(Prof. Saburo Matsui)

At about the same time (1,700 BC) the Minoan civilisation in Crete built the palace at Knossos which has been found to have an elaborate water supply and drainage system, including a flushing water closet, to deal with wastewater and storm water as well as to supply fresh water.

The ancient city of Baghdad, which was in its prime around 800 AD, had a population of some 2 million. "*The city was divided into blocks or quarters, each under the control of an overseer or supervisor, who looked after the cleanliness, sanitation and the comfort of the inhabitants. The water exits, both on the north and the south, were like the city gates, guarded night and day by relays of soldiers stationed on the watchtowers on both sides of the river. Every household was plentifully supplied with water at all seasons by the numerous aqueducts which intersected the town; and the streets, gardens and parks were regularly swept and watered, and no refuse was allowed to remain within the walls*" (Davis, 1913).
Sections of Roman drainage pipes are still functioning in some towns and cities in Britain and across the former Roman Empire. The more than 2000 years old ceramic drainage pipes excavated at the Greco-Roman city of Ephesus (population 500,000 in 100 AD) look surprisingly modern (Figure 4). It was the most important city of the Eastern Mediterranean and the second city of the Roman Empire.

Figure 4 Drainage pipes excavated at Ephesus
(photo credit: Tim Evans)

Finally, in this quick look at the early development of urban drainage, mention must be made of the city of Rome where a sewer, the Cloaca Maxima, constructed around 600 BC is still in use as part of the sewer system of the modern city. Lanciani (1898) found that *"The sewers of ancient Rome answered their purpose pretty well, especially if we take into consideration the remote age in which they were constructed, and their engineers' ignorance of modern sanitary principles and of the theory of microbes. Their greatest defects are, first, that they were used at the same time to carry off the sewage and refuse of the town and the rain-water; second, that this double employment made it necessary to have large openings along the streets, so that the population was permanently brought into contact with the poisonous effluvia of the sewers. The third defect of Roman sewage was that each sewer emptied directly into the Tiber, thus polluting its waters, which were used not only for bathing and swimming, but even for drinking". … "The best apology for this state of things is to be found in the fact that not only modern Rome itself, but many other European capitals, not to speak of provincial towns and villages, remained until lately in an absolutely identical condition. The improvement in the department of sewers is one of the last, if not the very last achievement of modern science in connection with hygiene, and it is still far from perfection*".

Figure 5 Medieval sanitation - waterborne sewer at Riveaux Abbey
(photo credit: Nick Orman)

2.2 Development of Urban Drainage

The Roman (and Greek) pattern of constructing a latrine over the diverted branch of a stream was perpetuated in the medieval monasteries, which generally had well developed waterborne sewer systems, based on the Roman model (Figure 5); elsewhere water and sanitation were on-going problems. In 1189 the first Lord Mayor of London, Henry Fitzalwyn, required minimum distances between the "necessary chamber" [cesspool] and neighbouring buildings - at least 2½ feet (0.76 m) if it was made of stone and 3½ feet (1.07 m) if it was made of other materials. Edward III (1327-77) ordered the City of London to pay for 12 carts to remove excreta, dung and refuse and in 1354 ordered removal of waste on an appointed day each week. Richard II (1377-99) enacted a statute "none shall cast any garbage or dung or filth into ditches, waters or other places within or near any city on pain of punishment by the Lord Chancellor at his discretion". Henry VIII's 1531 Bill of Sewers was the first major attempt to regulate sewers systematically: *"Commissioners of Sewers shall be directed in all parts within this realm from time to time, where and when need shall require."* It specified the qualifications and wages of commissioners and gave them authority to survey wall, streams, ditches, banks, gutters, bridges, dams, weirs and other impediments to water courses and to fine offenders. Each commission was permitted to adopt its own specification of size, shape and inclination of sewers, which was to lead to difficulties when integrated systems were built in the nineteenth century. The Bill of Sewers was followed by local Acts, most of them envisaged sewers as carrying away surface water and forbade drainage of house waste; most Acts required the construction of cesspools (Halliday, 1999).

Cesspools had many problems. There were no traps so odour pervaded the house, especially when the cesspool was in the basement. There were cases of poisoning, asphyxiation and explosion from H_2S and CH_4 (hydrogen sulphide and methane gas respectively) in addition there were cases of people drowning when floors collapsed. Samuel Pepys wrote in his diary on 20th October 1660 *"Going down to my cellar … I put my feet into a great heap of turds, by which I find that Mr. Turner's house of office is full and comes into my cellar."* The rebuilding of London after the Great Fire of 1666 could have been an opportunity for comprehensive redevelopment of London's water supply and sewerage but plans by Sir Christopher Wren and John Evelyn were not adopted because of vested interests, lack of direction and prevarication.

During the 1830s only half of the babies born in Europe lived to the age of 5; the other half died of diarrhoea, dysentery, typhoid and cholera because sewage contaminated their drinking water. The foul drainage from houses was either thrown into the streets or collected in cesspools. The cesspools were supposed to be emptied regularly. People had to pay to have septage and "night-soil" removed, so called because it was soiled matter removed at night. It was then sold to farmers along with dung from the animals in the towns. It was called "town manure". In those days many horses and other animals (for transport) and cows (to provide fresh milk) were kept in towns and fed with crops brought in from the country. Cesspools were often allowed to overflow (to reduce the cost of emptying them). Because of the density of housing they were often not far from the nearest well (Figure 1) so wells got infected.

In the 1840s farmers typically paid 12 pence per load for town manure, there were few other external sources of fertility. However, in 1841 the first major import of guano (dried bird droppings imported from South America) was landed in Liverpool: it was a cheaper, less smelly and more concentrated alternative to town manure. In 1843 John Bennett Lawes invented superphosphate fertiliser, another off-farm source of fertility and in the same year he created the first agricultural experiment station in the world at his Rothamsted Manor. These fertiliser innovations reduced the price farmers were willing to pay for town manure which hit the incomes of the "rakers" and “gong-fermors” who had to increase their charges for removing night-soil. As the cost of night-soil removal increased so did people’s reluctance to pay and so illegal connections were made to the urban rivers, streams and sewers which were supposed to be for surface water only (i.e. rainfall). If the geology was right, people had their cesspools dug deeper so that they were in the permeable strata and water could seep away, and of course it seeped into wells. The problem was compounded by the introduction in about 1810 of water closets (made possible by piped water supplies) because of the water used for flushing. As the popularity of water closets increased, the volume of wastewater discharged almost doubled. Solving one problem created another.

City-dwellers in Europe were ordered to discharge wastes into the sewers so as to avoid contaminating the groundwater and the wells. These sewers discharged to the main rivers. The slogan in Paris changed from *tout-à-la rue* (all to the street) to *tout-à-l'égout* (everything to the sewers). In 1850 engineer Eugène Belgrand designed the present Parisian sewer network as subterranean well-ventilated multipurpose conduits. Dual water-supply pipes (one potable and one non-potable), telegraph, pneumatic pipes for postal services and now other services are hung from the roof of the sewers. The main sewers have walkways above normal water level for ease of inspecting these additional services and for maintenance. They were also useful for moving troops so that they could suppress civil unrest. Tours of the sewers started during the Paris Exposition of 1867 and continued until 1975. Tourists were taken through the sewers in wagons or boats attended by sewer men in clean white overalls. Larousse reported in 1870 *"no foreigner of distinction wants to leave the city without making this singular trip"*. There is still an interesting museum in one section (Reid, 1991).

William Lindley designed the sewer system for Hamburg, Germany in the 1840s as part of rebuilding following an extensive fire and influenced sewer design around the world (Figure 6). He and his son, William Heerlein Lindley, designed sewer systems for Altona, Budapest, Düsseldorf, Frankfurt am Main, Moscow, Leipzig, Prague, St. Petersburg, Stralsund and Warsaw. The benefits are demonstrated by the death rate from typhoid in Düsseldorf which fell from 80 per 100,000 inhabitants in 1868 to 10 per 100,000 in 1883.

Figure 6 An example of Lindley's sewer design, Prague
(Wikipedia)

In 1854 Dr John Snow traced the cause of a cholera epidemic in London to the Broad Street [drinking water] pump, which he believed was contaminated from local cesspools and a leaking sewer. His study was the birth of epidemiology. Other health professionals disagreed with Snow; they thought infection was from the air. This was the “miasma theory of disease” and its proponents said that piping faecal matter away removed the odour and the disease – a case of effect not proving cause. One of the deaths mapped by Snow was a lady who had made money and moved to a house well away from Broad Street but she liked the flavour of her old water supply and had it brought to her, with the cholera. Snow proved his point by removing the pump handle and the disease subsided.

The “miasma theory of disease” was not over though. When building bye-laws were introduced nationally in the 1870’s, the government insisted that every house should be protected from the miasma, by installation of a water trap in the sewer to prevent sewer gases getting into the drain and seeping up through the ground into the house and causing disease. These interceptor traps are also called Running Traps, Blind Syphons, Buchan Traps, Winser Traps, disconnecting traps and interceptors named after a number of local names [Blackpool, Bristol, Croydon,..].

Because the traps blocked frequently, the government commissioned research from Professor Sir Frederick Andrewes in 1908 to determine the matter. His report (Local Government Board, 1912) recommended some changes, but the traps were still required in most places for another 25 years and in many places for more than 50 years. Interceptor traps are still an unfortunate feature of many older sewer systems in the UK. They are a source of blockages and flooding and can even cause building subsidence. Not infrequently the U-trap is blocked and the stopper has been removed from the rodding eye [by-pass pipe] through which all the sewage flows. They are best removed.

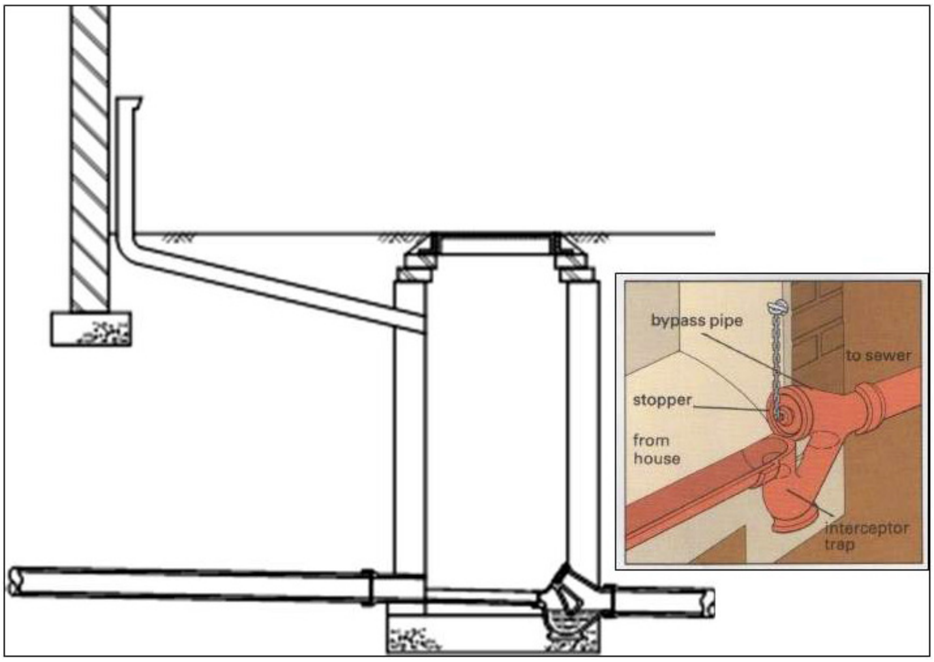


Figure 7 Interceptor trap installation in a manhole with detail inset
(WRc plc)

Transferring wastewater to the river solved one problem but it was soon found to have created another. London was one of the earliest to experience this problem for two reasons: its population was the largest (3 million by the 1860s) and the river was tidal so that which was discharged on a low tide was brought back by the next high tide. We can gain an idea of the effect on the River Thames from one Dr William Budd writing of the noxious odours proceeding from the river during the years 1858-9:-

"*For the first time in the history of man, the sewage of nearly 3 million people had been brought to seethe and ferment under a burning sun. Stench so foul, we may well believe, had never before ascended to pollute the air. For many weeks the atmosphere in the Parliamentary Committee Rooms was only rendered barely tolerable by the suspension before every window of blinds saturated with chloride of lime, and by the lavish use of this and other disinfectants. More than once, in spite of similar precautions, the Law Courts were suddenly broken up by an insupportable invasion of the noxious vapour*".

Parliamentarians were eventually forced to accept that something needed to be done in July 1858 because of the "great stink". In about ten years Joseph Bazalgette completed massive engineering works to intercept the sewers and divert them into pipes that carried away the water to be treated and discharged at a safe distance downstream of the city. Bazalgette calculated the diameter of the pipes from a most generous allowance for per capita sewage production and the greatest population density. He then said "*Well, we're only going to do this once and there's always the unforeseen*" and doubled the diameter to be used. The quality of materials and workmanship in his brick sewers were superb. If he had used his original, smaller pipe diameter the sewers would have overflowed in the 1960s. As it is they are still in use to this day.

Initially no treatment was given to the sewage, which was discharged directly to the tidal River Thames at Beckton (Northern Outfall) and Crossness (Southern Outfall) some 19 km downstream of London Bridge. It became evident, however, that the sewage discharge caused serious nuisance and inconvenience especially at times of hot, dry weather. On investigation, the Metropolitan Board of Works concluded that there was insufficient land available near the outfalls for the, then popular, method of treatment of sewage by land irrigation. Consequently, in 1887-91, treatment works to enable treatment of the sewage by chemical precipitation were constructed and brought into use at both Beckton and Crossness. This pattern was repeated in other cities in Europe and elsewhere though Lindley and Belgrand got there first. Some of today's sewerage infrastructure dates from the 19th century and is a tribute to the construction and engineering skills of those who built them.

However waterborne sewage was not without its detractors; Beder, (1990) wrote:

It is interesting to note that at the end of the 19th century there was rigorous debate among many western nations, including Australia, on the relative merits of the rapidly developing 'water-carriage' system and the 'dry conservancy' methods of dealing with human wastes. The movement against water-carriage gained much of its impetus from community dissatisfaction with the gross environmental pollution caused by the early sewer systems.

The dry conservancy systems, which were proposed as serious alternatives, included dry closet and pan systems. The dry closet (earth closet) was a means of collecting solid excrement in a container. The addition of earth, ashes, or charcoal after each visit to the closet deodorised the excrement, which was periodically collected at night by cart and taken to a processing plant where it was dried for use as manure. The pan system used a pan, under the toilet seat, which was collected by night-men at regular intervals and replaced with an empty one. The pan was able to take urine as well as faeces and did not require the use of earth for deodorising. Full pans would be carted to a processing plant where the contents would be made into cakes of manure, the pans being mechanically washed for reuse.

The main advantage put forward for dry conservancy systems was their ability to utilise the waste as a fertiliser. Advocates of these systems argued that by mixing water with sewage, as in the water-carriage system, the 'constituent parts were spoiled'. They also argued that the water-carriage method constrained the area over which fertiliser could be used whereas dry conservancy methods produced a dry product that could be stored and transported easily to wherever it was required. A further, big, advantage was that dry conservancy methods also conserved water since water was not needed for toilet flushing.

The debate was made difficult by a general lack of knowledge on the subject of sanitation which meant that there were no criteria on which to base comparisons. The outcome was that water-carriage sewerage systems were chosen being seen as the most modern and progressive, providing greatest convenience to householders."

Compounding the catalogue of environmental problems resulting from combined sewers discharging directly to rivers was the Industrial Revolution, which triggered a tremendous growth in the urban population (with consequential increasing volumes of sewage) together with discharges of industrial waste – also to the rivers. Although the impacts were severe in many areas of the country, those experienced in Lancashire were amongst the worst. So bad were conditions in the River Irwell that the Government of the day established, in 1868, a Royal Commission to inquire into the Pollution of Rivers, which reported in 1874 (RCPR, 1874) that, not only were the rivers severely polluted but that the public health was at risk. The language used by the Commissioners to describe the condition of the rivers in the basins of the rivers Mersey and Irwell was forceful - *"the rivers are polluted and filthy – the filthy state when (the Irwell) enters the Manchester boundaries – the abominable condition of the river in Manchester – the Lancashire rivers at the time of our visit were in an active state of putrefaction"*.

The Commissioners' report on the frequent outbreaks of typhoid states that "*in a great majority of cases these inquiries have resulted in establishing the fact that water polluted by sewage, if not by typhoid sewage, had been consumed by the individuals attacked*". The Commissioners' report was given effect in the Public Health Act, 1875 and the Rivers Pollution Prevention Act, 1876.

The 1875 Act recognised that the care of public health was a national responsibility and, amongst other things, it established a system of local health authorities; defined the duty of local authorities to treat and dispose of their sewage, and gave householders the right of connection to the public sewer.

The 1876 Act was the first milestone in water pollution control; it contained, inter alia, provisions that made it an offence to cause pollution of a stream by solid matter or by sewage, and also by trade effluent (subject to provisions which were biased towards the discharger). Implementation of this Act was in the hands of the sanitary authorities, which in many cases, was like asking a burglar to arrest himself.

Sewers are designed so that the water flows downhill [under gravity] and the rate of flow is sufficient to re-suspend particles that have settled and to carry them in suspension. Design standards for the "self-cleansing velocity" range from 0.48 to 0.9 m/sec (Ashley et al., 2004). Typically this means a gradient of about 1 in 200 (0.005). A rule of thumb for drains and sewers up to 300 mm diameter is a gradient of 1 in the nominal diameter of the pipe in millimetres; i.e. 1 in 100 for a 100 mm diameter pipe – 1 in 150 for 150 mm; 1 in 120 for 120 mm; etc. When a gravity sewer becomes too deep below ground level a pumping station is installed to lift the wastewater, which discharges to the head of the next section of gravity sewer. If there is a ridge that cannot be got around by following the contours it is necessary to either tunnel beneath the ridge or pump the wastewater to the top of the ridge up a rising main [sewer] also called a forced main. Wastewater in a gravity sewer is aerobic, with the dissolved oxygen being replenished from the headspace air (e.g. Raunkjaer, et al., 1995). The dissolved oxygen in wastewater in a rising main becomes depleted because of biological activity and, depending on residence time and temperature, can become anaerobic enough to reduce sulphur compounds to hydrogen sulphide, which in air oxidises to sulphuric acid that will corrode concrete. Rising mains can be dosed to prevent this 'septicity'. Pumping requires electricity, which (until we decarbonise the electricity supply) means climate change emissions. The amount of pumping required is directly related to the volume of wastewater – the hydraulic load. Reducing the hydraulic load reduces the climate change emissions associated with pumping.

Sewers incorporate a feature that has often been overlooked. The walls are coated with biofilms (slime layers) that are complex microbial ecosystems, which are acclimated to the composition of the wastewater flowing past them (Biggs and Jensen, 2009). Biofilms interact with and metabolise the dissolved constituents of the wastewater; the suspended biomass is of less consequence because it is being flushed through the network continuously, but this attached biomass can be significant. The biofilm surface adjacent to the aerated wastewater in a gravity sewer will comprise aerobic organisms, whereas adjacent to the sewer wall the organisms will be anaerobes (Figure 8). DNA profiling has shown that the microbial ecology is different in the different zones (submerged, inter-tidal, etc.) at a particular location and between different locations, presumably reflecting the composition of the wastewater that bathes the biofilms. Understanding of the functioning of biofilms is incomplete. Biological treatment of wastewater starts in sewers.

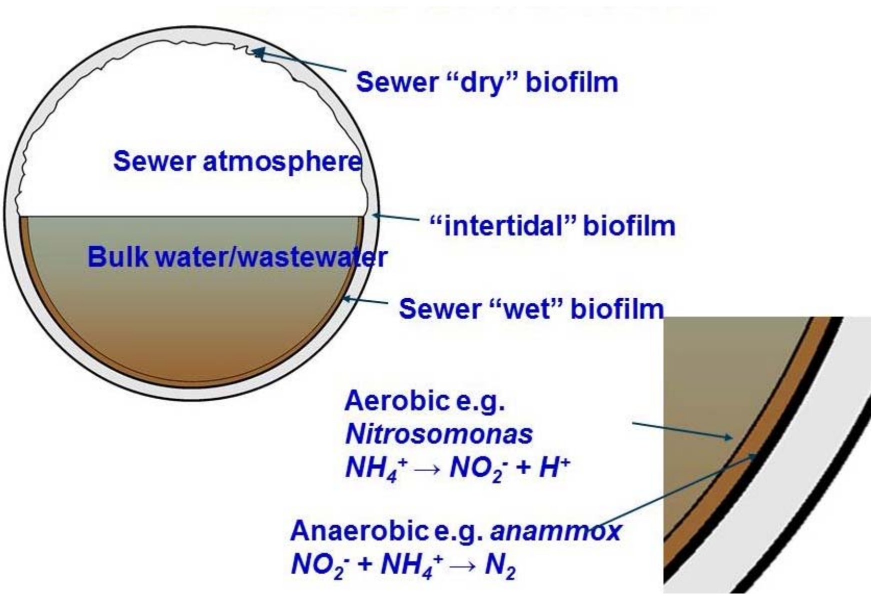


Figure 8 Representation of sewer biofilm ecology
(Biggs and Jensen, 2009)

2.2.1 Wastewater treatment

Initially the standards of wastewater treatment were fairly rudimentary. They improved over the years because of better understanding of the effects of pollution and because of technological development. Continuing with the example of the River Thames, in the 19^{th} century no salmon were caught after 1833. As a result of Bazalgette's drainage work, and considerable investment in wastewater treatment over the years, the river was clean enough to successfully reintroduce salmon in 1985 and subsequently major international prizes have been awarded for its cleanup. This success has been replicated in other European rivers.

Sewage treatment by land irrigation, whereby the interceptor sewers discharged to a land area, a 'sewage farm', over which the sewage was irrigated and the drainage collected for discharge, became accepted practice. This method of treatment came into prominence from about 1842, it being expected that the manurial constituents of sewage would prove to have a high economic value. In practice, however, the method had varying success. There were failures because of conflicts of financial and sanitary interests and because some soil was unsuited for the purpose and clogged up rapidly, becoming covered with a layer of putrefying filth; the presence of harmful industrial effluents and a generally low standard of management were also factors that contributed to failure. In contrast with these failures [of siting and management], many other sewage farms were very successful and continued from the second half of 19^{th} century for more than 100 years. By 1900 Berlin devoted 6900 ha to sewage farming and Paris 5000 ha. The Parisian sewage farms had declined to 4487 ha by 1948 but still accounted for 10% of the vegetables sold at the central market of Les Halles; the vegetables were prized by the best hotels (Reid, 1991).

In the years up to the First World War much research and experiment was carried out in the UK and America to discover an effective means of sewage treatment. With the growth of knowledge it became recognized that the purification of sewage was dependent upon bacterial action and in 1893 Corbett introduced the 'fixed-spray' filter beds at Salford to be followed at the turn of the century by the now familiar rotating percolating filter beds (Figure 9) which were first installed at the treatment plant serving Rochdale.

Figure 9 Percolating filter at Cockermouth wastewater treatment plant.
(United Utilities plc)

On 3rd April 1914 Edward Ardern and William Lockett presented a paper to the Society of Chemical Industry at the Grand Hotel, Manchester, entitled "Experiments on the Oxidation of Sewage without the aid of Filters". This resulted in the application of the other principal form of biological treatment of sewage - the activated sludge process (Figure 10) that is used around the world. Ardern's and Lockett's discovery, under the mentorship of Gilbert J. Fowler who had in turn been inspired by visiting the Lawrence, Massachusetts, experiment station, was that the time to clarify settled wastewater by aeration decreased if the sediment was recycled. In other words that the microbial biomass became "activated" and that recycling it selected for more efficient organisms. In the percolating filter the biomass is attached to the filter medium and is therefore not lost. Schneider (2011) recorded the history and development of wastewater treatment.

Figure 10 Surface aeration activated sludge plant at Davyhulme (Manchester) wastewater treatment plant.
(United Utilities plc.)

3 Present day sewer systems

The development of water-borne systems in the UK resulted, in the main, in each town or city having a centralised system in which all wastewaters were conveyed to a single location for treatment and disposal. As towns have coalesced into larger conurbations it has been common for the wastewater flow to be diverted from smaller WwTWs to larger ones in the interest of efficiency and so that the redundant sites can be closed and redeveloped. Some cities (e.g. in Australia) are reinventing the satellite WwTW as a facility to recover some of the water for non-potable use with some of the foul sewage continuing to the central WwTW for full treatment.

As stated previously, sewers were first developed as surface water drains which gradually became used also for the transport of human and animal wastes. Therefore it is common, in the older cities and towns in the UK and elsewhere, for the sewer system to be based on the principle of a single pipe for both surface water and wastewater – known as combined sewers (Figure 11).

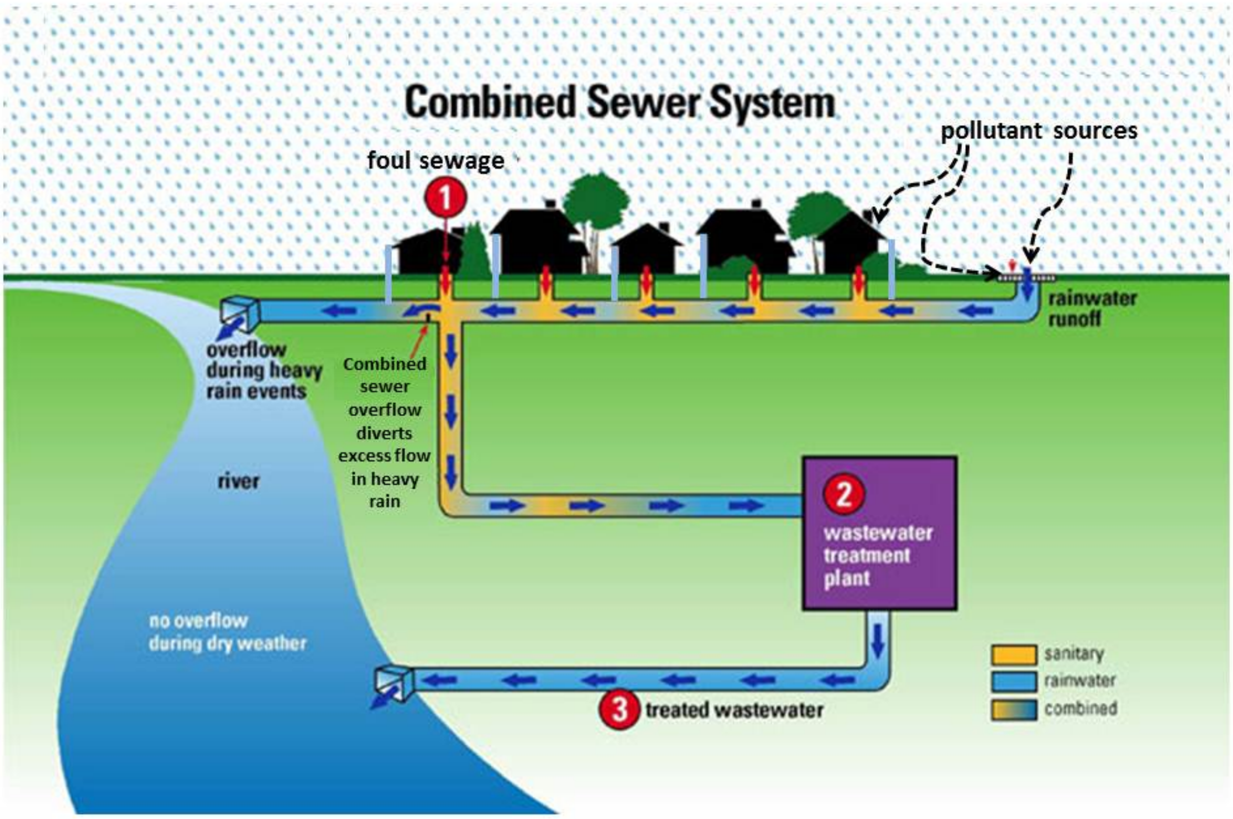


Figure 11 Schematic representation of combined sewer systems

The combined system has the benefit of one pipe, albeit of potentially large diameter, depending upon the distance to the treatment works, the area of urban surface drained and the topography. However there is often a need for Combined Sewer Overflows (CSOs). Also when flows have to be pumped there is usually an emergency overflow at the pumping station, which will operate in cases of power failure. As previously mentioned CSOs are significant causes of water pollution. They are meant to discharge only when the sewer flow has been diluted by rainfall (which should also mean the flow in the receiving water has increased and is therefore able to receive the discharge without significant adverse environmental impact. For many years, design of these devices had been on the simple concept of the overflow coming into operation only when a fixed (standard) multiple of the dry weather sewer flow was exceeded. This approach took no account of the size or nature of the receiving water and is one reason why, in the 1990s, there was a substantial legacy of unsatisfactory CSOs. This led to a huge investment in the UK over two decades.

The development of the Urban Pollution Management Manual (FWR, 1998) changed the approach to the design of CSOs. The Manual (now in its third edition, FWR 2012) presents a methodology that makes appropriate use of modern tools for analysis of sewer flows and quality together with the characteristics and the required uses of the receiving water – crucial to the achievement of the requirements of the EU Water Framework Directive (European Union, 2000). Combined sewer systems inevitably require CSOs, to avoid the practical problems and high costs of laying sewers of the huge diameters that would otherwise be required to accommodate surface water runoff and because the volume of wastewater to which a WwTW is capable of giving full treatment is finite.

In new towns, and in new developments on the periphery of older towns, it is common for drainage to be effected by a two-pipe or separate sewer system (Figure 12). In this system, one pipe, the foul sewer[1], conveys foul wastewater from properties to a treatment works, not uncommonly via the older combined sewers, whilst another pipe collects surface water and discharges it to a watercourse.

[1] Also called a sanitary sewer in the USA

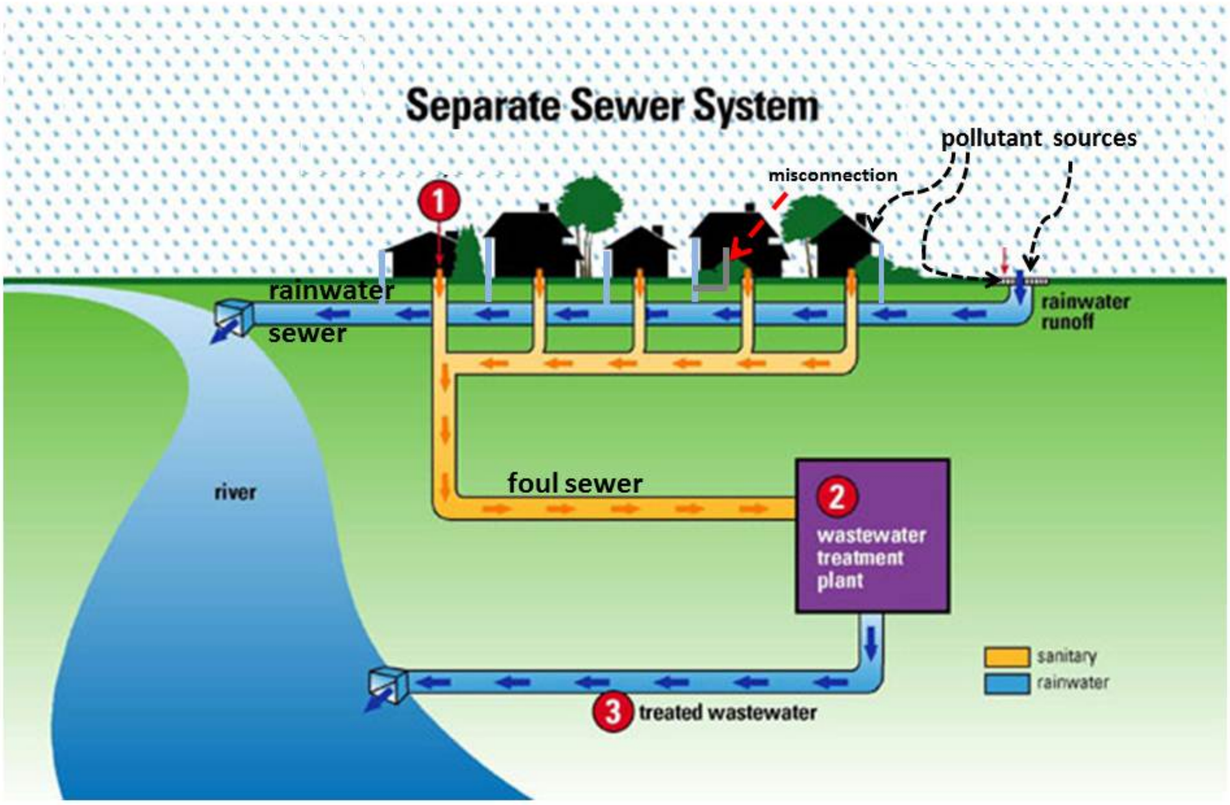


Figure 12 Schematic representation of separate sewer systems

The big advantage of the separate system is that surface water is discharged directly to the receiving water and so does not add to the flows carried by the foul sewer. Because of this it does not risk causing overflows and/or flooding of roads and property with foul sewage. Surface water sewers might overflow when their capacities are exceeded, and whilst bad, the consequence is not as bad as flooding with dilute foul sewage.

However there are also some serious disadvantages to the separate system. Surface water picks up contaminants (e.g. fuel, brake and tyre residues, bird and animal faeces, litter, etc.) from the urban surfaces across which it flows and this is discharged to the receiving water untreated. Sometimes people unwittingly introduce contaminants by for example washing out buckets or disposing of sump oil into surface water drains. The volume and rate of run-off from paved areas, roofs etc. is greater than it would have been from the natural land surface before it was “sealed”, this might exceed the capacity of the receiving water and cause downstream flooding. Another disadvantage is that people can inadvertently connect grey-water or even black-water into a surface water sewer, this is called "misconnection" or "wrong connection"; they are in fact unlawful. Local authorities are responsible for enforcement but misconnections are time consuming to trace from their manifestation in a contaminated water course. It would be useful if unlawful connections were reported when properties are bought and sold. Not only would this find and rectify them, it would also raise awareness of the issue and make people more careful about misconnecting. Better identification of surface and foul drainage is desirable (Figure 13). It has proved necessary in places to use different coloured pipes for foul and surface water to help reduce the risk of misconnections but nonetheless they continue to be sources of stream pollution. Also, flooding from the separate foul sewer may be caused by, for example, misconnecting roof water from a garage extension to a private house into a foul sewer.

Figure 13 Kerbside signage in USA and Australia of surface water drains
(Tim Evans)

The increased cost of the separate system, for two pipes rather than one, is offset by pipe sizes being generally smaller, as the foul sewer does not have to carry surface water. In addition, the surface water sewer may not need to go far to a point of discharge to a watercourse or other point of discharge.

The water industry in the UK operates nearly 1 million km of water mains and sewers, and more than 9,000 sewage treatment plants (Water UK, 2012). In October 2011 responsibility for a further 184,000 km of formerly private sewers and 36,000 km of lateral drains was transferred to water and sewerage companies in England and Wales (Defra, 2012). This increased the industry's length of drains and sewers to approximately 600,000 km. The network collects wastewater from 60 million people together with wastes from commercial and industrial premises equating to a further 15 million population equivalents and conveys it to treatment. The products of the wastewater treatment process are reclaimed water, treated to environmental standards and discharged to receiving water, sewage sludge (which can be recycled without harm to the environment to benefit soil fertility and crop yields) and possibly biogas (FWR, 2011a). In the UK, 80.6% of sewage sludge was recycled to agriculture, land reclamation and other beneficial uses during 2010/11. 80% of sewage sludge is treated by anaerobic digestion and the biogas used as renewable energy.

The UK has a very valuable heritage in its sewerage infrastructure worth many billions of pounds but for many years it has been a case of “out of sight, out of mind” and spending on inspection, maintenance and replacement has been inadequate. This is a situation that many other countries share. Sewers beneath today’s roads suffer more deformation and vibration than in the past because vehicles are heavier. In 2009/10 there were more than 3,700 collapses and more than 150,000 blockages in public sewers leading to more than 4,500 incidents of sewer flooding inside buildings and more than 36,000 incidents of external flooding (OFWAT, 2010). This indicates that more needs to be done to improve the serviceability of our sewer systems.

The biological filter and activated sludge methods of wastewater treatment are both still used extensively, together with high-rate methods developed more recently but embodying the same basic principles. These enable higher throughput and hence treatment plants with a ‘smaller footprint’ capable of being covered or constructed underground.

- **Fixed-film** or attached growth systems include trickling filters, biotowers, and rotating biological contactors (RBC), where the biomass grows on media and the sewage passes over its surface or the surface passes through the sewage. The fixed-film principal has further developed into Moving Bed Biofilm Reactors (MBBR) and Integrated Fixed-Film Activated Sludge (IFAS) processes. An MBBR system typically requires an even smaller footprint than suspended-growth systems. Biological Aerated (or Anoxic) Filters (BAF) combine filtration with biological carbon reduction, nitrification or denitrification.

- **Suspended-growth** systems include activated sludge, where the biomass is mixed with the sewage and can be operated in a smaller space than trickling filters that treat the same amount of water. Membrane bioreactors (MBR) combine activated sludge treatment with a [microfiltration or ultrafiltration] membrane liquid-solid separation process, which eliminates the need for clarification and tertiary filtration.

Nutrient removal has been added to the objectives required for secondary wastewater treatment. This could be nitrification/denitrification (which is oxidation of ammonium to nitrate and then reduction of nitrate to nitrogen gas), nitritation/denitritation (where conditions are poised so that oxidation only progresses as far as nitrite, which is reduced to nitrogen) or reduction of ammonium with nitrite to nitrogen gas using anammox bacteria. Each of the examples in this list uses less oxygen (and energy and alkali and supplemental carbon) than the preceding process. Phosphorus removal is accomplished by chemical precipitation (with iron or aluminium) or by luxury uptake into phosphate accumulating bacteria, which are then removed into the sludge. Biological P-removal is much less expensive than the chemical P-removal provided there is sufficient carbon in the wastewater; normally there is not and it has to be supplemented. There are processes to remove/recover N and P during wastewater and sludge treatment and thus eliminate internal recycling within treatment works and these are starting to be installed. Urban wastewater presents an important opportunity for phosphate conservation (CIWEM, 2012).

4 Surface Water Management

When rain falls on a greenfield site, some may soak into the ground directly and recharge the groundwater, some will move slowly through the top layers of soil eventually reaching a watercourse and, in heavy rain, some will flow across the surface. As a result, the rate of flow, even across the surface, is relatively slow. The flow that reaches a watercourse is therefore spread out over a long period of time. Many of the pollutants in the flow are also retained and broken down in the soil.

The effect of paving over greenfield land is twofold. Firstly, rainfall runs off the surface more quickly, reaching watercourses in a few minutes and at a much higher flow rate. Secondly, pollutants, including spillages onto the paved areas, are not retained but washed directly into the watercourse.

Discharges of runoff from impermeable surfaces in urban areas can cause a variety of adverse hydraulic and water quality impacts on receiving waters and downstream land areas including flooding, erosion, sedimentation, oxygen depletion, nutrient enrichment, toxicity and, as a consequence, reduced biodiversity. Surface water runoff is therefore a significant contributor to diffuse water pollution.

To mitigate these effects, surface water management should therefore seek to achieve a runoff and pollutant retention profile that matches as closely as possible to the runoff profile from the undeveloped site.

Surface Water Management (SWM) should include a variety of control and treatment strategies designed to mitigate the impacts on water quality and flood risk. These have been practised in many developed countries, including North America, Japan and Scandinavia for over 30 years (Ellis, 1995). They have also been increasingly used in the UK in recent years. Much information and field experience is therefore available (Pratt, 2001).

Projections of the effects of climate change suggest that we are likely to be subject to more frequent extreme rainfall. A review of flood risk management policy in the UK (Defra, 2004) identified that it would be very expensive to upgrade our piped drainage systems to cope with more intense rainfall and proposed that flows from extreme rainfall are commonly managed on the surface. This is in line with practices in countries that are subject to more extreme rainfall than the UK.

SWM is applied through specific measures, which are referred to as Sustainable Drainage Systems (SuDS) or Sustainable Urban Drainage Systems (SUDS) in the UK, or as Best Management Practices (BMPs) in North America. The term Water Sensitive Urban Design (WSUD) was coined in Australia and sums up the concept nicely, i.e. urban design that is sensitive to the requirements for managing water.

The processes involved can be classified by effect as follows:

- **Interception** – the prevention of runoff from the first part of any rainfall event until a threshold depth of rainfall has fallen. This significantly reduces the number of runoff events discharging to watercourses with significant water quality benefits.
- **Attenuation** – the temporary storage of rainwater to reduce peak flows. This can be used to manage downstream flood risk.
- **Treatment** – the removal of pollutants from run-off. The extent of pollutant removal possible in low intensity rainfall will clearly be more than will be possible in more extreme rainfall.
- **Exceedance flood routing** – management of flows in extreme rainfall along defined paths to limit the damage from flooding.

In addition, disposal can be to the ground (infiltration drainage) or to surface receiving waters. When using infiltration drainage techniques, particular care is required to ensure that this does not result in groundwater pollution.

SuDS include tried-and-tested techniques that are being implemented on a range of projects in England, Wales, Scotland and elsewhere. They incorporate cost-effective techniques that are applicable to a wide range of schemes, from small developments to major residential, leisure, commercial or industrial operations with large areas of roof and hard-standing. They can also be successfully retrofitted to existing developments.

There is a wide choice of techniques, which may be used alone or in series in a 'treatment train' (SEPA). They fall into the following seven main groups. (See the Bibliography for where to find full details of these techniques.)

- **Soakaways** – underground permeable storage chambers filled with coarse crushed rock; used to dispose of surface water from buildings and/or paved areas.

- **Porous Pavements** – paved surfaces, which allow the free passage of surface water, which then drains directly into the subsoil or is held in a 'reservoir' structure for gradual release. Especially useful for large impermeable areas such as car parks where attenuation of the run-off is important. May also incorporate oil separators for pollution control.
- **Green roofs** - roofs which are covered with an impermeable membrane and a growing medium planted with low growing plants. They provide a means of interception, attenuation through temporary storage and evaporation of surface water from the roof. The vegetation also provides some treatment.
- **Rainwater harvesting** - a means of interception of rainwater for storage and use for garden watering or within the building, typically as a non-potable water supply (e.g. for toilet flushing).
- **Swales and basins** – grassed depressions, which allow the temporary storage of surface water and its controlled release to the ground or to a surface receiving water. These devices are effective in reducing pollutants in surface water. Rain gardens are a form of basin that commonly uses a wider range of plants.
- **Ponds and Wetlands** – provide settlement for suspended matter and reduction in other pollutants e.g. heavy metals.
- **Filter drains** – drains and infiltration trenches designed to hold surface water for gradual release. Often used by Highway authorities for dealing with road drainage.

SuDS have the following potential benefits, they: -

- help to reduce the environmental footprint of development;
- manage environmental impacts at source, rather than downstream;
- manage water runoff rates, reducing the impact of urbanisation generated flooding;
- protect or enhance water quality, by reducing the number of discharge events and by providing treatment;
- are sympathetic to the environmental setting and the needs of the local community;
- provide opportunities to create habitats for wildlife in urban watercourses;
- can encourage natural groundwater recharge (where appropriate).

There are, however, some constraints on the use of SuDS:-

- Surface features might take more space than conventional systems, however this is offset if they can be combined with other land uses such as public open space;
- Limitations to the applicability of infiltration SuDS (but not necessarily attenuation SuDS) occur where:-
    - the soil is not sufficiently permeable
    - the water table is too close to the surface
    - the quality of groundwater under the site might be put at risk if the runoff is polluted
    - infiltration of water into the ground, particularly if concentrated in a limited area, could affect the stability of some soils adversely.

Marselek et al. (2000) wrote "*SuDS represent man-made complex environmental systems whose performance/benefits may be difficult to quantify and may change over time. Examples of changes that may occur include vegetation growth; species distribution and maturity; reduction of storage volumes/flow areas due to sediment deposition; clogging of pervious layers; storage of contaminated sediments with contaminant release; transfer of contaminants from sediments to biota etc. Such secondary impacts on the environment are not always well understood or considered in the initial design. For sustainability of SuDS devices and mitigation of long-term impacts, maintenance – both short term corrective measures and long term preventative maintenance and rehabilitation of structures – is of paramount importance*".

The use of SuDS in Great Britain is mandated through the development planning process.

In England the requirement for SuDS in certain new developments was first introduced in 2001 through Planning Policy Guidance Note 25: Development and Flood Risk (PPG25) (Office of the Deputy Prime Minister, 2001). This has since been superseded by the National Planning Policy Framework document (DCLG, 2012) but the provisions remain largely unaltered. This guidance explains how flood risk should be considered at all stages of the planning and development process in order to reduce future damage to property and loss of life. One of the requirements is that run-off from development should not increase flood risk or increase water pollution elsewhere in the catchment and that developments should incorporate sustainable drainage systems where practicable.

Planning Policy Wales (Welsh Government, 2012) and the National Planning Framework 2 in Scotland (Scottish Government, 2009) contain similar provisions for Wales and Scotland respectively.

Supplementary technical guidance is provided in the National Planning Policy Technical Guidance (Department for Communities and Local Government, 2012) in England, in the Technical Advice Note 15 Planning and Flood Risk (Welsh Government, 2004) in Wales and in the Scottish Planning Policy (Scottish Government, 2010). A number of local planning authorities also provide supplementary planning guidance covering SuDS.

Building Regulations also consider disposal of surface water. In England and Wales the Building Regulations 2010 (SI 2010/2214) imposes a hierarchy of disposal routes for disposal of surface water. Where practicable, surface water must be discharged to the ground and where this is not practicable, it should be discharged to a watercourse or as a last resort to a sewer. In Scotland, the Building Standards (Scotland) Regulations (SI 2004/0406) require surface water drainage systems to have facilities for the removal of pollutants.

However, other issues remain that are not easily resolved through the planning or building control system. These include:-

- Who should be responsible for the ownership of SuDS?
- Would legislative changes provide better incentives for the application of SuDS, in particular:-
    - Modifying the current largely automatic right of connection of piped surface water drainage to the existing sewer?
    - Linking the right of connection more closely with development control requirements?
    - Making it easier for those responsible for SuDS to discharge into water bodies without necessarily having to seek consent of riparian land owners, while preserving arrangements for their compensation?
    - Extending the scope of Building Regulations, so that the requirement to keep surface water drainage separate from sewage applies where SuDS is a viable option?

In Scotland these matters were mainly addressed in the Water Environment and Water Services (Scotland) Act 2003 which gave responsibility for adoption of SuDS to Scottish Water.

In England and Wales these issues are prospectively addressed by Section 33 and Schedule 3 of the Flood and Water Management Act 2010, which when commenced designate upper tier local authorities and SuDS approval and adoption bodies, and limits the right to connect surface water to the sewer system to situations where the local authority approval includes this provision.

5 Urban drainage going forward

We have already concluded that today’s urban drainage infrastructure will not cope with the weather that is predicted for the future, the increase in urban population and the increase in hard surfaces particularly because of the way that rainwater has been managed until now. Today’s approach in a large part of most of our urban areas is still “*tout-à-l'égout*” – get the water down the drain and away to a remote centralised wastewater treatment works as quickly as possible. En route it will be pumped, which requires energy and when it gets to the wastewater treatment works, the treatment uses energy, which all has additional climate change emissions. It should not be forgotten that in addition to the intentionally connected rainwater (including misconnected), some of the rainwater in sewers is “infiltration”, i.e. water that gets in through cracks and manhole covers.

It is inevitable that the underground infrastructure will not be able to accommodate the surges of rapid runoff on every occasion unless it is enlarged massively. In very heavy rainfall, either surface water will be unable to enter the system or the underground infrastructure will overflow somewhere because its hydraulic capacity is exceeded. Already London’s underground trains have been halted because of summer floodwater, which has caused massive disruption and misery.

The other extreme of climate change is drought and high temperatures. In Australia, which has been more drought prone than most other countries, surface water is regarded as a misplaced resource.

Evapotranspiration from green infrastructure is credited with reducing urban heat island effect. Plants are credited with having a positive psychological effect that improves “liveability” if compared with a “concrete jungle”, even reducing urban violence and increasing productivity (Barton, 2009).

5.1 Sustainable development

The concept of sustainable development has been around for many years. Perhaps the best-known international definition is that of the Brundtland Commission "*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development, 1987).

In March 2005, the UK Government published ‘*Securing the future – delivering UK sustainable development strategy*’ (Defra, 2005): “water” is mentioned 86 times. It claims to build on the earlier 1999 report.

It agreed four priorities:

- sustainable consumption and production,
- climate change,
- natural resource protection and
- sustainable communities

and it established 5 principles:

- **Living Within Environmental Limits** - Respecting the limits of the planet's environment, resources and biodiversity – to improve our environment and ensure that the natural resources needed for life are unimpaired and remain so for future generations.
- **Ensuring a Strong, Healthy and Just Society** - Meeting the diverse needs of all people in existing and future communities, promoting personal wellbeing, social cohesion and inclusion, and creating equal opportunity for all.
- **Achieving a Sustainable Economy** - Building a strong, stable and sustainable economy which provides prosperity and opportunities for all, and in which environmental and social costs fall on those who impose them (polluter pays), and efficient resource use is incentivised.
- **Promoting Good Governance** - Actively promoting effective, participative systems of governance in all levels of society – engaging people's creativity, energy, and diversity.
- **Using Sound Science Responsibly** - Ensuring policy is developed and implemented on the basis of strong scientific evidence, whilst taking into account scientific uncertainty (through the precautionary principle) as well as public attitudes and values.

5.2 Towards sustainable urban drainage

The majority of tomorrow's urban areas will be evolutions of today's urban areas. To be sustainable it is vital that there is sufficient investment in inspection, maintenance and replacement of the existing sewerage infrastructure. There will be some new communities that could and should be built to eco-designs but it is inconceivable that the major cities will be torn down and rebuilt; adaptation is therefore the nettle that needs to be grasped, which means retrofitting. The problem is excessive dynamic hydraulic loading but it can also be an opportunity.

5.2.1 Combined sewer overflows

CSOs are essential safety valves on the sewer system. When there is excessive flow in a sewer, which would exceed the capacity further downstream, the excess flow is diverted and discharged somewhere less damaging.

Figure 14 shows the principle of an overflow in a sewer, the excess flow in the sewer is diverted when it overtops the side weir; overtopping could also be because of a blockage or pump failure downstream. A modern CSO would be fitted with screens to prevent solids larger than 6 mm in 2-dimensions passing forward to the discharge. Safety valves are essential (for example the circuit breakers on an electrical system) but if they operate too frequently it indicates there is something wrong with the system.

Figure 14 Conventional side weir storm overflow in a sewer
(Mark Shimwell)

5.2.2 Tank sewers

One conventional approach to modulating flow is to build an enlarged section in a sewer at a location where it is feasible to make a suitably large excavation. Stormwater tanks may be in-line or off-line. Essential to the design of both types is the means of emptying and of flushing stormwater tanks clean of sediment. It is important that a tank sewer is emptied before the next rainstorm otherwise it will have no benefit. Non removal of sediment would be undesirable on two counts, (a) accumulated sediments reduce the effective volume of the tank and (b) sediment can become septic, anaerobic and odorous. When sewage becomes septic (i.e. anaerobic), sulphate is reduced to sulphide; hydrogen sulphide is toxic and smells of rotten eggs, when it later becomes aerobic bacteria oxidise it to sulphuric acid, which corrodes concrete and steel.

5.2.3 End of pipe – stormwater tunnels

In this solution to excessively frequent CSO discharges, the CSOs are connected to a new sewer tunnel, which conveys the combined wastewater to treatment. A stormwater tunnel protects the river (or other receiving water body) but does not alter the risk of surface water flooding in the drained area because it is an end-of-pipe solution. CSOs discharge when there is insufficient capacity downstream in the sewer, i.e. only when water is in the sewer system. Like tank sewers, stormwater tunnels must be pumped out promptly to avoid septicity and so that there is capacity for the next rainstorm.

For London, a 7.2 m diameter stormwater tunnel 35 km long and 75m deep at its deepest into which the CSOs will be connected is proposed. When full it will contain 356,000 m^3 of dilute combined sewage. The current estimated capital cost is £4.1 billion though the outturn cost will probably be greater. In addition there will be on-going financial and carbon costs of pumping it out and treating the dilute wastewater. When the tunnel is full of wastewater it cannot serve its purpose so it is essential that it can be pumped out quickly. The return on investing £4.1 billion (which is assured under the rules by which the company’s finances are regulated) must be very attractive to the owners of Thames Water who bought the company for assured income. It will satisfy the requirements of the Water Framework Directive but it will not prevent a single property from being flooded. Green infrastructure is being promoted as an alternative or complement but implementation is considered rather slow because it is under the direction of 32 autonomous boroughs.

Portland, Oregon, USA is an acknowledged exemplar of green infrastructure for surface water management, which it has implemented to stop property flooding and also so that it can install a much smaller stormwater tunnel (to protect the salmon fishery in the Willamette River) than would have been needed had there been no control of runoff at source. Portland's average annual rainfall is 950 mm (London 650 mm) and the infiltration rates of soils range from very slow to moderate. Philadelphia (also USA) has decided on the basis of whole life costing having monetised all of the benefits, to rely entirely on green infrastructure.

5.2.4 Separating foul and surface sewerage

Separating foul and surface sewerage has been required for new developments for many years though the foul sewers very often connect into a combined sewer further down the network. Digging up and duplicating the sewers in central business and densely built residential areas would be hugely disruptive but some cities in some countries have been suffering the pain for the anticipated gains of a better future.

In many places the opportunity has been taken to separate the sewers when areas are redeveloped. Many dismiss this as too little to have an effect. However, although it would be wrong to overestimate what could be achieved by this approach in (say) 5 years it would equally wrong to underestimate what it might achieve in (say) 50 years. This type of long term approach is being pursued in Wales (Jones, 2012).

5.2.5 Reducing the volume or rate of runoff

A fundamental element of the problem is that much of the urban area comprises surfaces from which rainwater runs off rapidly, and this area is increasing. This means that rainwater is discharged rapidly and consequently the peak flow rate is greater than if the duration of runoff was extended (Figure 2) as it would have been when the area was more open space. The problem is often compounded by kerbs, walls, hedges, buildings, etc. that divert flow and concentrate it.

A contribution that has been deployed successfully to reduce the problem in several cities is "green stormwater infrastructure" (GSI) (also called LID Low Impact Development, BMP Best Management Practice, SuDS Sustainable Drainage Systems, WSUD Water Sensitive Urban Design) has been referred to already. It has been reviewed extensively in another ROCK (FWR, 2011b) so it will only be treated briefly here. GSI reduces the total amount of runoff through absorption, evaporation and transpiration and also extends the duration of runoff thus reducing the peak height of the hydrograph (Figure 2).

Measures to reduce the rate of runoff and to "spongify" catchments are included in the sections that follow. Options that include infiltration are opportunities for some degree of groundwater recharge. Often former boreholes in urban areas have become redundant either because the [commercial] user has relocated or mains supply is a more convenient alternative. In some cases because of lack of abstraction rising groundwater is a problem. However in a drought-stressed future groundwater under urban areas could once again be a useful asset. All of the options that include vegetation have the additional benefits of:

- reducing urban heat-island effect by evapotranspirational cooling;
- providing a softer more relaxing visual and audio aesthetic experience;
- increasing biodiversity and
- absorb airborne pollutants
- reducing wind-chill by decreasing wind speed [depends on nature of vegetation]

5.2.5.1 Green roofs

A large proportion of the rapid-runoff surface in urban areas comprises roofs. Many roofs are suitable for converting to green roofs (also called living roofs) with the additional benefits of thermal insulation [against heat as well as cold] and extending the life of the roofing membranes. Of course, it is essential that the structure is able to carry the extra weight. It has been estimated that within a 6 mile radius of Trafalgar Square in London there is 10,000 ha of roofs suitable for converting to green roofs; that is approximately 40 times the combined area of Hyde Park and Kensington Gardens (FWR, 2010). London already has a very credible area of green roofs but it could be doing much better if there was the will and the business case. Green roofs are also compatible with solar photovoltaic electricity generation because the living roof helps to prevent excessive temperatures, which reduce the efficiency of PV.

5.2.5.2 Downspout disconnection

Cities in North America in particular have programmes and incentives to encourage people to disconnect their [roof drainage] downspouts from the piped drainage network. Often property owners are given "I have disconnected" plaques, which encourages neighbours by example, especially in the case of early adopters (Figure 15).

Figure 15 Downspout disconnection:
Gresham, Oregon (left) Diverter kit, Toronto (right)

5.2.5.3 Rainwater harvesting

Rainwater harvesting can be part of managing the rate of runoff and can in addition be a contribution to supplementing water resources. The water can be used for garden watering or for non-potable use within the building such as toilet flushing, washing machine, etc. The latter is year-round and therefore more useful for both functions; however it requires dual pipework (colour coded) and may require first-flush-diversion, filters or disinfection. The capital cost and maintenance are not insignificant considerations. However by siting rainwater harvesting strategically it can make a valuable contribution to managing runoff.

Some water utilities incentivise rainwater harvesting with rebates, for example Sydney Water in Australia provide a rebate on water charges for customers who installed a rainwater tank – the rebate being related to the size of the tank and the degree to which it is 'plumbed in'. This has been so successful that the rebate has been discontinued except for schools, where it can also help to teach children about the water cycle.

5.2.5.4 Permeable surfaces

Permeable pavement, parking, etc. can reduce the rate and amount of runoff. It can be a route for infiltration on permeable soils and on impermeable soils it can be built over geogrids that store and discharge later. The cost of permeable paving can be two to three times that of conventional asphalt paving but reduces the cost of other means of managing surface water. It is generally considered only suitable for light or medium weight traffic but HGV capable media are also available.

5.2.5.5 Rain gardens

A rain garden is a planted depression that receives rainwater runoff from impervious urban areas like streets, roofs, driveways, walkways, parking lots, and compacted lawn areas. This reduces rain runoff by allowing surface water to soak into the ground (as opposed to flowing into surface water drains and watercourses which causes erosion, water pollution, flooding, and diminished groundwater). They can be designed for specific soils and climates. The first raingardens were installed in about 1990; flow monitoring has shown they resulted in a 75–80% reduction in surface water runoff during normal rainfall events.

The plants, a selection of wetland edge vegetation, such as wildflowers, sedges, rushes, ferns, shrubs and small trees, take up excess water flowing into the rain garden and slow the rate of release of any that exceeds the raingarden's capacity. Water filters through soil layers before entering the groundwater system. Root systems enhance infiltration, maintain or even increase soil permeability, provide moisture redistribution, and sustain diverse microbial populations involved in biofiltration. Also, through the process of transpiration, rain garden plants return water vapour to the atmosphere.

Figure 16 A chain of kerbside raingardens in downtown Portland, Oregon
(Tim Evans)

5.2.5.6 Infiltration, including swales and soakaways

Swales or bioswales are landscape elements designed to remove silt and pollution from surface runoff water. They consist of a swaled drainage course with gently sloped sides (less than six percent) and filled with vegetation, compost and/or riprap. The water's flow path, along with the wide and shallow ditch, is designed to maximize the time water spends in the swale, which aids the trapping of pollutants and silt. Depending upon the geometry of land available, a bioswale may have a meandering or almost straight channel alignment. Biological factors also contribute to the breakdown of certain pollutants.

A common application is around parking lots, where substantial automotive pollution is collected by the paving and then flushed by rain. The bioswale, or other type of biofilter, wraps around the parking lot and treats the runoff before releasing it to the watershed or surface water sewer.

5.2.5.7 Detention basins, wetlands

A detention basin is a surface water management facility installed on, or adjacent to, tributaries of rivers, streams, lakes or bays that is designed to protect against flooding and, in some cases, downstream erosion by storing water for a limited period of a time. They are categorised as "dry ponds", "holding ponds" or "dry detention basins" if no permanent pool of water exists or "wet ponds" that permanently retain some water at all times. In its basic form, a detention basin is used to manage water quantity while having a limited effectiveness in protecting water quality, unless it includes a permanent pool feature.

They are storm water best management practices (BMPs) that provide general flood protection and can also control extreme floods such as a 1 in 100-year storm event. The basins are typically built during the construction of new land development projects including residential areas or shopping centres. The ponds help manage the excess runoff generated by newly constructed impervious surfaces such as roads, parking lots and rooftops.

A basin functions by allowing large flows of water to enter but limits the outflow by having a small opening at the lowest point of the structure. The size of this opening is determined by the capacity of underground and downstream culverts and washes to handle the release of the contained water.

Frequently the inflow area is constructed to protect the structure from some types of damage. Offset concrete blocks in the entrance spillways are used to reduce the speed of entering flood water. These structures may also have debris drop vaults to collect large rocks. These vaults are deep holes under the entrance to the structure. The holes are wide enough to allow large rocks and other debris to fall into the holes before they can damage the rest of the structure. These vaults must be emptied after each storm event.

5.3 Planning for exceedance

Whatever strategy is adopted, grey or blue/green/grey, it is likely to be overwhelmed by exceptionally heavy rainfall (Balmforth et al., 2006). When the capacity of everything is exceeded, the only way to prevent damage and loss is to route the water on the surface to places where it will not cause damage. Pompeii shows that the Romans realized this because some of the roads have higher kerbs than the general run of roads; these roads had been designated as flood routes. The camber on flood route roads could be reversed. Some cities designate roads and highways as flood routes for exceedance and prohibit obstruction (e.g. by parking vehicles) when they are brought into use. Exceedance flood routes are required in new developments but retrofitting them into our existing urban areas remains a challenge.

5.4 Other sustainability issues

The following measures improve the sustainability of the urban water cycle though they have little impact on the capacity of the infrastructure to deal with surface water.

The intensity of domestic wastewater discharge is dwarfed by rainfall; for example, 1 mm rain on 1 hectare (100 x 100 m) is 10,000 litres. Metered water use in the UK is 129 litres/person/day (Water UK, 2012) so 10 mm rain in 1 hour on 1 hectare is equivalent to the total water use (used water discharge) by 775 people in 24 hours. The drainage network can cope with dry weather flow; it is wet weather that challenges the hydraulic capacity. Reducing per capita water usage is valuable for extending water resources and reducing the carbon-footprint of supplying water, but it is a distraction from adapting the drainage network to climate change and urban creep (i.e. the expanding area of rapid run-off surface: roofs, paving, etc.).

5.4.1 Greywater Recycling

Greywater is the wastewater other than toilet water. Greywater from baths, showers and hand basins and washing machines is generally cleaner than wastewater from dishwashers and kitchen sinks. The least demanding use for greywater is for irrigation. Greywater recycling reduces the input to combined sewers and thus makes some space for rainwater but the intensity factors differ so widely that greywater recycling is really a water resources feature rather than a means of creating capacity to receive runoff.

5.4.2 Reducing per capita water use

In the UK, domestic water demand for metered properties was 129 litres/person/day in 2010/11 and unmeasured demand was reportedly 159 litres/person/day (Water UK, 2012). The difference might be that homes with meters have more water efficient appliances or that the occupants are more "water wise" but there must also be some scepticism that the disparity just reflects a substantial element of error in the estimate for unmetered properties and that it probably includes some leakage from the distribution system.

The admitted leakage in UK was 22% in 2010 (Water UK, 2012) whereas in Singapore it was 4.5% in 2008 and in Sydney it was 6.6% in 2010 (Owen, 2012). Where there is a will, small levels of leakage can be achieved, which obviously mitigates the need to develop new resources.

Toilet flushing is said to account for 25-30% of domestic water use, greywater recycling, vacuum toilets and composting toilets would all reduce the demand for potable water, which would be beneficial to water resources but the intensity of discharge is more protracted than the intensity of rainwater entering the sewers so alternatives to flushing are of little relevance to the hydraulic capacity for rainwater.

5.4.3 Urine separation

Urine diverting toilets (UDT) separate urine and faecal matter at source. The urine is piped separately from the toilet, collected and used as a fertiliser. Urine contains the majority of nutrients (as well as the pharmaceutical residues) we excrete, and contributes a very significant proportion of these substances to the wastewater stream (typically around 80% of the nitrogen, 50% of the phosphorus and 90% of the potassium). It has negligible biogas potential. From healthy individuals it is also relatively pathogen free. With UDT, faecal matter is flushed to sewer as in conventional systems. Urine source separation systems are in use in several countries (e.g. China, Germany, Sweden, the Middle East, Africa, and South America). UDT use less water, which is more a water resource benefit than a contribution to the problem of hydraulic loading (see 5.4.2). More importantly they reduce the loadings on wastewater treatment plants and hence the climate change emissions from treatment and UDT help to conserve fertiliser nutrients. It is possibly something for new builds or retrofitting into hotels etc. but since the domestic wastewater charge is not linked to the wastewater composition currently, there is no financial incentive to install UDT.

Figure 17 Urine diverting toilet

5.4.4 Vacuum Toilets

These are normally found in aircraft, boats and trains. However they may also be used in dwellings, especially in high-rise developments. The volume of water for flushing is only 1 litre (compared with 8 litres for a "conventional" and 3/6 litres for a “dual-flush” toilet). Water is used only for rinsing the bowl. The sewage is transported by air and pressure differential (vacuum), and is typically treated in a biogas reactor where it is treated together with organic waste from kitchens. After the treatment the hygienic end product is used as fertiliser. Vacuum toilets are not a practical, or economic, proposition at the individual house level and are most appropriate to serve new areas of housing development. If a vacuum toilet development connects into conventional drainage, water and gravity will be needed to transport the waste.

5.4.5 Composting Toilets

These are applicable in rural areas or suburban areas with low housing densities. Here the composting chamber is in the cellar and receives excreta and kitchen waste. Forced ventilation provides oxygen to the composting process and obviates odour problems. A post-composting period in the garden completes the process and, after about a year in total, the compost is ready for application to the garden. Water use is minimal at 0.2 litres per flush and the environmental benefits are evident.

6 A sustainable future?

The UK has recognised that the increasing demands on water and the environment arising from the combination of climate change, population growth, rapid urbanisation, and increased water demand to meet higher standards of living, demands alternative approaches to urban sanitation and drainage in order to minimise impacts on the water environment. However, it is essential that there is adequate investment in the existing infrastructure without unrealistic implied expectations about its longevity.

The increasing pressures on the urban drainage system and the water environment indicate that development and adoption of new concepts and technologies is now necessary. But, in contrast to the development of the conventional centralised urban drainage system as described earlier in this report, there is no 'one-size fits all' solution. Rather we need to develop practices that are innovative and completely effective and apply them in accord with local circumstances.

A promising way forward is the concept of Integrated Urban Water Resources Management (IUWRM), which is an integral part of Integrated Catchment Management – itself a key component of the EU Water Framework Directive (FWR, 2003). IUWRM has been defined as "*a structured planning process to evaluate concurrently the opportunities to improve the management of water, sewerage and drainage services within an urban area in ways which are consistent with broader catchment and river management objectives*" (Andersen and Iyaduri, 2003). It therefore requires that we abandon the current approach of treating water supply and wastewater transport and treatment separately and instead deal with all urban water related issues 'in the round'. It is relevant here to note that the United Nations Economic and Social Council stated in “*No higher-quality water, unless there is a surplus of it, should be used for a purpose that can tolerate a lower grade*" (United Nations, 1958).

Andersen and Iyaduri, (2003) reported three Australian case studies, which have shown that an IUWRM approach can reveal opportunities that are not apparent when separate strategies are developed for each service. The results are better-integrated, more sustainable solutions, and substantial cost savings.

In spite of the fact that the provision of water supply and wastewater services in England and Wales have largely been the responsibility of single bodies since 1974, it remains common practice that the planning for each service is carried out separately. Thus it is rare that deficiencies of one service are considered against possible solutions from the other. For example, it may be possible to cure water resource shortages by increasing infiltration of rainwater at source and reinstating aquifer abstraction (which would reduce sewer overloading) or by reclaiming wastewater and returning it to (non-potable) supply directly or by means of a dual distribution system rather than by increasing the amount of drinking water put into supply.

It is evident that a dual distribution system, achieved by the integrated planning of water supply and drainage, would constitute a third water utility service. Dual distribution systems are rare in the UK but are more common elsewhere. For example, Australia, France, Japan, Singapore and USA all have dual systems, ranging in size from a few thousand to more than a million people. The largest reclaimed water distribution system for non-potable reuse in the USA is San Jose in water rich northern California with a capacity of 450,000 m^3/day (Okun, 1997). The acceptance of dual systems in the USA is evidenced by the publication in 1994 of the second edition of AWWA Manual of Practice on Dual Water Systems (AWWA, 1994).

Dual distribution systems might be discounted because of their initial cost but there are several factors which make them financially viable (Okun, 1997). Even if they are available, obtaining additional water supplies is generally far more costly and poses more environmental problems (e.g. new impounding reservoirs). Savings can accrue because reuse of wastewaters reduces the cost of treatment required for disposal to receiving waters – the city of St Petersburg, Florida, one of the earliest dual systems in the USA, has four wastewater treatment plants that would have been required to reduce nutrients for continued discharge to coastal waters whereas, for non-potable use, only conventional biological treatment, sand filtration and chlorination is required (Okun, 1997).

Dual distribution systems for reclaimed water can also enable urban growth. Instead of enlarging the existing WwTW serving a city, together with the associated sewers, new developments can be served by a local sewer and a treatment plant. The effluent may be returned as reclaimed water through a dual distribution system and the sludge from the treatment plant may be discharged to the main sewer system for treatment and disposal at the original wastewater treatment plant. In this way the size of the treatment plant may be reduced, enabling the plant to be enclosed and acceptable in residential areas. The city of Los Angeles has implemented this approach building an entirely enclosed treatment plant, of some 300,000 m^3/day capacity, near the heart of the city, to provide reclaimed water for non-potable use (Okun, 2002).

The Rouse Hill is a newish development in the north-west of Sydney, Australia. The Reclaimed Area Water Project, which started in 2001, provides an excellent example of IUWRM in practice. By 2012 more than 20,000 homes were using up to 1.7 billion litres of recycled water each year for flushing toilets, watering gardens, washing cars and other outdoor uses. The objective of the project is to help decrease the environmental impact of urban development on the Hawkesbury Nepean River. It is Australia's largest residential water recycling scheme (Sydney Water). On average the Rouse Hill scheme has reduced demand for drinking water by about 40%. Eventually it will serve around 36,000 homes.

"*The homes have two water supplies: recycled water and drinking water. To ensure that drinking water is not confused with recycled water it is delivered by a separate supply system. This is known as dual reticulation. The recycled water taps, pipe-work and plumbing fittings are coloured lilac for easy identification.*

There are three main elements to the integrated project: -

- ***Stormwater or river management***
  Stormwater in Rouse Hill is collected in grass lined channels which feed the stormwater system through a series of rubbish traps and wetlands in order to reduce the pollutants entering the river system. Wherever possible these channels follow the natural water course through the area. In areas where flood waters may cause erosion some concrete channels have been used.

- ***Wastewater and recycled water***
  Wastewater in Rouse Hill is treated to a very high standard. This wastewater has an extra treatment known as ozonation and microfiltration. This allows it to be recycled. This recycled water is fed back to homes in the area in a separate pipeline for outdoor use and toilet flushing. Any wastewater that is not recycled is released into the man-made wetlands in Second Ponds Creek. When treated wastewater is discharged to the river, the advanced treatment ensures that the impact on water quality is minimised. By managing these elements together we can consider the water cycle as a whole unit. This allows us to make better use of a valuable resource by imitating and speeding up the natural processes of the water cycle.

- ***Stormwater***
  Stormwater is not used in the production of recycled water because the volume changes dramatically with weather conditions. The drainage system has been designed to protect the area from floods and can carry a one-in-one-hundred-year storm without disrupting the community. A recycling system designed to cope with this storm flow would be wasted when the area has average or low rainfall."

In Australia, as in many other countries, local councils generally control surface water management but in the Rouse Hill Development Area, Sydney Water manages the main surface water system and street and house drainage are managed by local councils. To cover the cost of this service, residents are charged a River Management Fee by Sydney Water. Sydney Water also provides flood management, up to a one-in-one-hundred-year flood level, via its river management programme.

6.1 Paying for surface water management

Water supply and wastewater removal (including surface water) are paid for in the UK and many other countries as a combined service based either on the amount of water supplied or the value of the property. A small rebate can be claimed in the UK if rainwater is not discharged to a sewer system, but it is not a sufficient incentive for a property owner to invest in installing an on-site solution.

An illustration of the inequity of the system is an apartment in a high-rise building compared with a detached bungalow with equal occupancy and per capita water use. The area of roof and other surface draining to sewer for the former is much less than for the latter but on the "water supplied" method of charging both pay the same amount of money for surface water management.

In Germany the surface water discharged from a property is regarded as "pollution" and is charged for on the "polluter pays" principle, which means that property owners have a financial incentive to build on-site solutions.

Some cities in the USA have introduced charges for surface water management related to the total impervious area draining to the municipal system. They have also given rebates calculated on the same basis, which has been an incentive to people to invest in disconnecting part or all of their impervious surfaces from the municipal system. This has also spawned businesses that will install on-site solutions predicated on a number of years of rebates. Philadelphia is probably the most advanced in this approach to sustainable and equitable charging for surface water management and incentivising disconnection and new businesses through rebates (Francis, 2010). Because of this cost-recovering charge combined with rebates, businesses are developing with shared cost and savings models that have been seen in the renewable electricity sector, e.g. solar photovoltaic installation.

7 Conclusion

Many countries (including the UK, albeit belatedly) are realising, or have realised, that "business as usual" as regards urban drainage (i.e. getting surface water into underground pipes as quickly as possible) is not going to be fit for purpose in the future. Approaches that keep water on the surface for longer have more resilience to climate change; they also have additional benefits such as reducing urban heat island effect and absorbing air pollutants. Approaches that treat wastewater and rainwater as potential resources that can substitute for developing new sources also have great merit in an integrated approach based on whole life costing.

Changing the charging model for supplying water and for managing foul and surface wastewater so that people, organisations and businesses pay equitably for the cost of the services they receive (including expected investment in new infrastructure) has been shown to give incentives for on-site solutions and for new businesses founded on providing them.

Many developed countries, including the UK, are realising that the current practice of supplying potable water for all domestic requirements and discarding rainwater as quickly as possible is not sustainable in the medium to long term. The demand for water is increasing (due to population growth and/or movement) and there is a concurrent growth in the volume of wastewater to be removed from urban areas. In many areas the water resource is set to decrease from the effects of climate change, yet the increased frequency and intensity of rainfall may create flooding problems. Therefore the preservation and restoration of our water environment will become increasingly dependent on technologies such as those described in this review to reduce the demand for water (through water conservation measures), to use water more efficiently (by reclaiming water for re-use), to reduce the rapidity of rainwater runoff from urban areas and to reduce the loadings of wastewaters being discharged to rivers, lakes and coastal waters.

More joined-up thinking about the urban environment with respect to rainfall, drainage, temperature, biodiversity, recreation and the water environment will give better adaptation to climate and population change, a better whole life cost and improve the liveability of urban areas. It is essential that maintenance of the existing (inherited) infrastructure is not neglected and that it is not taken for granted.

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