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Asset management, operation and maintenance

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Chapter 10
Asset management, operation and maintenance

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10.1. Introduction

Operation and maintenance are activities undertaken to ensure the performance of a drain or sewer system continues to meet the required performance. The two terms are often used interchangeably; however, in broad terms operational activities will be considered as those activities that involve no permanent physical change to the asset (e.g. adjustment of penstocks, switching of pumps). Correspondingly, maintenance activities will be considered as those that involve some form permanent or semi-permanent physical change to the asset (e.g. repair, removal of debris or sediment). The future, long-term development of urban drainage and sewer systems is discussed in Chapter 3.

Asset management is defined in BS ISO 55000:2014 as the ‘coordinated activity of an organization to realize value from assets’, with an asset being defined as an ‘item, thing or entity that has potential or actual value to an organization’ (BSI, 2014). An asset is recognised when the investment results in future economic benefit to the business. An asset may be either tangible (i.e. physical, such as sewers or pumps, and included within a company’s asset register) or intangible, such as the reputation of a company. All these things can bring value to a company and need to be well managed in order to make the most of that value.

The institutional arrangements for the management of drain and sewers systems and the split between the responsibilities of property owners and public sewerage authorities varies widely across Europe and internationally. In the UK, sewerage authorities are typically responsible for any pipe in the network that is outside the boundary of a property. In other countries, the public sewerage authorities only become responsible for the larger sewers taking groups of properties, leaving the smaller sewers as the shared responsibility of the individual property owners. In the UK, road drainage is the responsibility of the highway authority, which is separate from the sewerage authority, while in much of the world these responsibilities are held by a single organisation, often the municipality. In many countries the responsibility for rivers is held by a different entity, while in some it can be part of the same organisation as the sewerage authority.

Where there are split responsibilities, specific arrangements need to be made to coordinate activities between the various entities responsible.

10.2. Asset management

Asset management is about knowing what we want to achieve with an asset and how to make it happen, in addition to assessing risks associated with that asset. It translates the objectives of the organisation into asset-related decisions, plans and activities based on a risk-based approach to ensure the performance of their assets aligns with the owner's or operator's requirements. All assets need maintaining and as such will benefit from long-term plans and strategies.

There are numerous sources of information and supporting guidance related to asset management. Of perhaps greatest significance is the BS ISO 55000 series of standards, which has a strong focus on the organisational aspects of asset management – that is, how to organise asset management. BS ISO 55000 reflects the general approaches towards asset management adopted by the urban drainage community over the past decade(s) in many countries, such as described in some detail in BS EN 752:2017 (BSI, 2017a) and in BS ISO 24516-3:2017 (BSI, 2017b). Assets are (usually) tangible things in regard to water systems; however, there are numerous non-water initiatives and sources of information that are relevant to effective management in the water domain. Increasingly these relate to the circularity of systems, including economics, energy and resources (e.g. Syed and Lawryshyn, 2020).

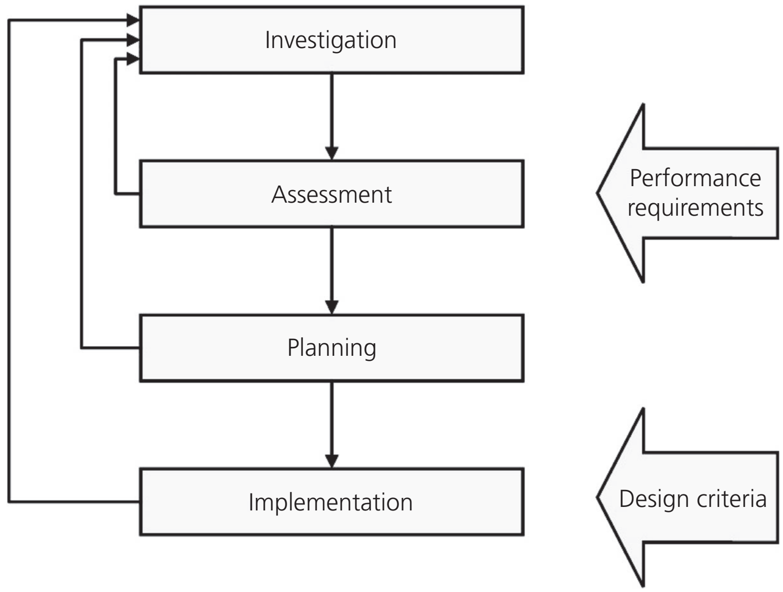
The Global Forum on Maintenance and Asset Management's *The Asset Management Landscape* (GFMAM, 2014) publication recognises asset management as a continual and iterative process designed to deal with complex and dynamic systems. The main feature of asset management systems is that they allow organisations to learn from their actions, plans and decisions by requiring information feedback loops. These feedback loops are typically expressed in terms of the well known 'plan-do-check-act' cycles and inform business decisions at various levels, ranging from strategic to tactical to operational. Sewer asset management is generally seen as a prerequisite for cost-effective sewer management and the main solution to deal with future, long-term challenges such as climate change, resource recovery and urban development.

Sewer infrastructure represents a major investment in essential services contributing to public health and the protection of the environment. Some assets are identified as critical infrastructure, and management activities should be set at strategic, tactical and operational levels. However, sewerage infrastructure has not been maintained over the years on a truly sustainable basis, with funding and implementation of rehabilitation programmes postponed, and a focus on short-term repairs or an allowed decrease in the level of service provided.

Optimisation will become necessary to compensate for aging and wear and tear and respond to changing societal and economic conditions. There is a need not only to focus on maintenance and rehabilitation, but also to keep future requirements and developments in mind. The systematic management of assets and a risk-based investigation should be undertaken to determine maintenance and rehabilitation priorities. The aim in the effective management of assets is to provide an appropriate service life while fulfilling given requirements in a cost-effective manner.

European Standard BS EN 752:2017 Drain and sewer systems outside buildings – Sewer system management (BSI, 2017a) specifies the functional requirements for achieving the objectives and principles for strategic and policy activities relating to planning, design, installation, operation, maintenance and rehabilitation. It recommends that an integrated approach is taken to the management of the drain and sewer systems and sets out a four-stage process that should consider all aspects of the system, including the hydraulic, environmental, structural and operational performance. The process is summarised in Figure 10.1. Procedures for the first two stages are described in more detail in BS EN 13508-1:2012 Investigation and assessment of drain and sewer systems outside buildings – General requirements (BSI, 2012).

Figure 10.1 Integrated sewer system management planning process (BS EN 752:2017; BSI, 2017a). Permission to reproduce extracts from British Standards is granted by BSI Standards Ltd. (BSI). No other use of this material is permitted. British standards can be obtained from BSI Knowledge

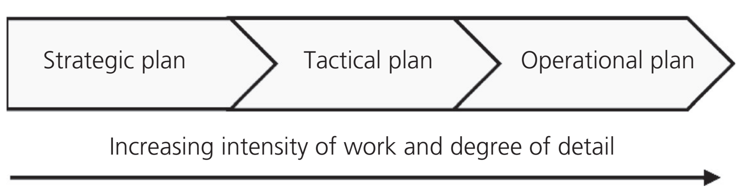


An almost identical process is described in BS ISO 24516-3:2017 Guidelines for the management of assets of water supply and wastewater systems – Wastewater collection networks (BSI, 2017b).

The processes can be applied in stages for strategic planning, tactical planning and operational planning (see Figure 10.2).

A more detailed description of this staged approach is given in BS EN 14654:2021 Drain and sewer systems outside buildings – Management and control of activities – General requirements (BSI, 2021a).

Figure 10.2 Stages in the planning process (BS ISO 24516-3:2017; BSI, 2017b). Permission to reproduce extracts from British Standards is granted by BSI Standards Ltd. (BSI). No other use of this material is permitted. British standards can be obtained from BSI Knowledge



The investigation stage can use a variety of techniques, including the analysis of operational data, specific surveys (e.g. closed-circuit television (CCTV) inspection, flow surveys or water quality surveys) and hydraulic or water quality models, to measure the current and possibly the future performance of the system. The assessment stage then compares the measured performance with a set of performance requirements to identify the performance deficiencies. The third stage involves the development of an integrated sewer systems development plan to overcome the performance deficiencies. This should incorporate a rehabilitation plan, a new development plan and an operations and maintenance plan for the system. The final stage involves implementation and monitoring. The investigation stages are described in more detail in BS EN 13508-1:2012 Investigation and assessment of drain and sewer systems outside buildings – Part 1: General requirements (BSI, 2012).

The hydraulic performance of the drain and sewer system is interrelated to the flow in the rivers and coordination is therefore required with river and coastal flood planning; frameworks such as the Flood Risk Management Plans under the EU Floods Directive (EC, 2007) can provide the basis for this. Water quality is impacted by discharges from combined sewer overflows (CSOs) and surface water outfalls. Initiatives to improve river water quality include those in the River Basin Management Plans produced through the EU Water Framework Directive (EC, 2000).

10.2.1 Risk

As failure of the sewer system is irregular, the most useful measure of risk of sewer failure over time is an annualised risk. Risk is defined as the product of the likelihood of a failure occurring and its effect. The concept of risk has been used in flood management for many years (MAFF, 2001) and is now a requirement of the EU Floods Directive (EC, 2007). The concept allows a range of possibilities to be considered to mitigate a failure. Risk can be managed by reducing the likelihood of the failure, reducing the impact of the failure, or reducing both. Risks can be managed, for example, by engineered solutions, such as bigger pipes or attenuation structures, use of warning systems and measures to prevent the failure or limit its impact, such as increasing the level of the first floor of new dwellings, or improving the resilience to the failure, such as by using tiles instead of wood for flooring. When the risk is expressed in monetary terms then an economic assessment of risk management measures can be undertaken by comparing the present value of the reduction in annualised risk (e.g. in £ per year) with the cost of the proposed investment. This approach is used in the UK in the appraisal of flood and coastal erosion risk management schemes (Defra, 2009).

While it may be relatively easy to identify some assets as having a high risk of failure (e.g. large sewage pumping stations), for gravity sewers the most difficult step in setting up a proactive maintenance regime, whether it is for collapse or blockage, is to distinguish those sewers with a high failure risk from those with a low failure risk.

In determining the risk of failure there are three main considerations. The first is the likelihood that the asset failure will occur (e.g. the collapse or blockage). The second is what effect that asset failure will have on the performance or serviceability of the system. Finally, there is an assessment of the magnitude of that effect.

When the difficulty is in identifying the likelihood of failure of the asset, one approach is to prioritise purely on the magnitude of the consequence. An asset in which the consequence of failure is high is called a critical asset.

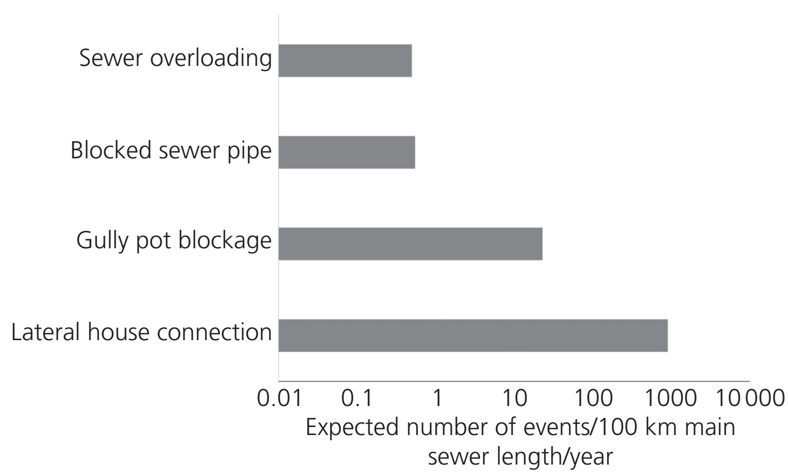
The criticality of sewers in relation to their collapse risk has been used to prioritise CCTV inspection of sewers since the early 1980s, when the first edition of the *Sewerage Rehabilitation Manual* (WAA/WRc, 1983) was introduced. In recent years, however, it has been recognised that the assessment of the consequence of collapse did not always give proper weighting to the possibility of flooding or pollution resulting from collapse. Greater consideration therefore needs to be given to the assessment, particularly of flooding impacts due to a collapse or blockage, with appropriate weight given to the magnitude of the consequence.

10.2.2 Maintenance

There are many approaches to maintenance, such as incident-based, preventive, condition-based or predictive. These can be broadly classified based on two basic types: reactive and planned. Reactive maintenance is the execution of remedial work in response to a performance failure (e.g. flooding, or fish kills due to dry weather CSO discharges) or an asset failure (e.g. a pump failure, pipe blockage or collapse). There will always be a role for reactive maintenance in any sewer system because incidents will continue to arise even when planned maintenance is undertaken. As, by definition, reactive maintenance is a response to a failure it cannot reduce the number of failures. However, poor execution of maintenance work can make the recurrence of a failure more likely. For example, poor blockage clearance practice can make another blockage more likely.

Reactive maintenance approaches are the most appropriate where the risk of failure (the likelihood and the consequence) is low. The likelihood of failure differs strongly depending on the sewer component. Figure 10.3 shows the observed failure rates of main sewers, gully pots and house connections, expressed in events per 100 km main sewer/year. A failing house connection has a very strong impact on the serviceability of one household, whereas a failing main sewer may have a much broader impact, including flooding and road collapse. Good asset management limits the risk to society to a predefined acceptable level, balancing the cost of pre-emptive inspection and, if necessary, repair or rehabilitation of a particular asset.

Figure 10.3 Failure rates of sewer components (after Post *et al.*, 2016)



Pro-active or planned maintenance is a strategy to ensure that the necessary requirements can be economically achieved. It can be more economic than crisis maintenance and is more appropriate where the risk of failure is high. It can be carried out either at regular intervals (regular maintenance) or irregularly (in response to monitoring or inspection).

Examples of assets in which planned maintenance is preferred include sewage pumping stations, where both the consequence and likelihood of failure can be high, or a sewer collapse, which would result in extensive flooding. The risk could consider only the financial costs to the sewerage utility, but it is usually more appropriate to consider the costs to society as a whole. The cost of failure therefore includes, for example, not just the direct repair and reinstatement costs, but also the direct and indirect costs of any damage to third parties, including damage to property, loss of earnings, pollution impacts, traffic disruption, etc. When considering costs to society as a whole care must be taken to exclude costs that are merely transfers between the parties. For example, the inclusion of damage costs as well as the insurance claim would count a cost twice, because the insurance payment is just a transfer of the damage cost to another party, the insurance company.

10.3. Serviceability and performance indicators

BS EN 752:2017 and BS EN 13508-1:2012 give a clear description of the process for sewer performance assessment, which can also be applied to sustainable drainage systems (SuDS) components, such as surface water infiltration facilities, ditches and swales. BS EN 752 assesses the performance of sewers based on four types of criteria, covering hydraulic performance, environmental impact, structural condition and operational deficiencies (see Figure 10.4). The hydraulic performance is generally considered to be the basic function of sewers. However, other aspects of the performance of a drain or sewer system are also important. These can include a range of issues such as nuisance from odour or vermin and health and safety issues, for example due to defective manhole covers.

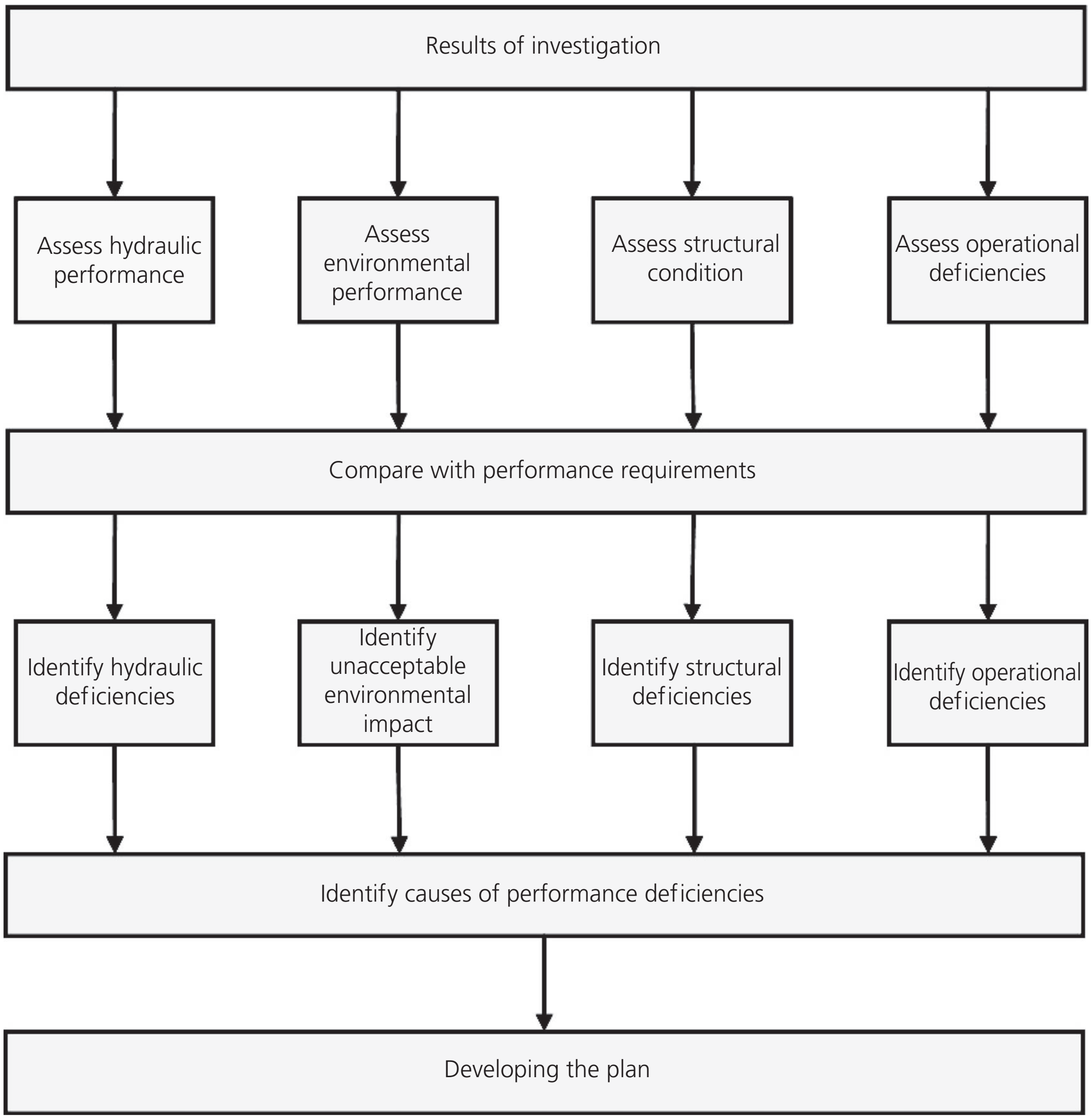
The set of performance assessments, Figure 10.4, allows us to determine the ‘serviceability’ of the system, which has been defined as the capability of a system of assets to deliver a reference level of service to customers and to the environment, both now and in the future (UKWIR, 2005).

The performance or serviceability of the system can be considered in two relevant ways: the level of service experienced by the end users, and the performance of the total system and/or each individual asset or component in the system.

The level of service is only partly determined by the actual performance of sewer systems. For example, overland flows are tolerated when the urban drainage system is hydraulically overloaded by an intense storm event exceeding the design capacity, but not when there is a storm event smaller than the design capacity. This means that the context also plays an important role in the experienced level of service.

The performance of the (individual) assets depends on the condition of the asset and the context. For example, a wide crack in the sewer (condition) will only result in infiltration of groundwater if the groundwater table is above the sewer (context). This means that in sewer asset management, information on the context is very relevant, but this is often overlooked.

Figure 10.4 Process for sewer system performance assessment (BSI, 2017a). Permission to reproduce extracts from British Standards is granted by BSI Standards Ltd. (BSI). No other use of this material is permitted. British standards can be obtained from BSI Knowledge



10.3.1 Levels of service

The level of service can include any performance issues as perceived by the customer or impacting on the environment. Levels of service issues may include

- flooding of buildings, land or roads (other than designated flood storage or conveyance routes)
- restricted use of sanitary facilities
- pollution of surface receiving waters
- pollution of groundwater
- obstruction of roads

- hazard to road users
- odour nuisance
- nuisance from vermin
- untidiness of vegetative treatment systems.

As failures to provide an acceptable level of service have a direct impact on customers or the environment, they are useful to regulators. However, they are typically of more limited use in the management of operation and maintenance as the perceived performance is also affected by the (often unknown) context.

10.3.2 Asset performance

Asset performance relates purely to the performance of an asset or group of assets in fulfilling their intended function (UKWIR, 2005). However, even if some parts of drainage systems are performing poorly, the sewer system robustness and redundancy limits the impact on serviceability. Only if the asset is a critical asset could its poor performance impact serviceability in a noticeable way.

Causes of poor asset performance in underground drain or sewer systems can include

- cracking, fracturing or deformation of pipes or ancillary structures
- collapse of the pipes or ancillary structures
- sedimentation of pipes or tanks
- blockage of pipes
- failure of power supply to pumps
- failure of pump control systems
- blinding of screens
- illegal connections or illicit discharges.

For non-piped urban drainage systems, asset performance issues may include

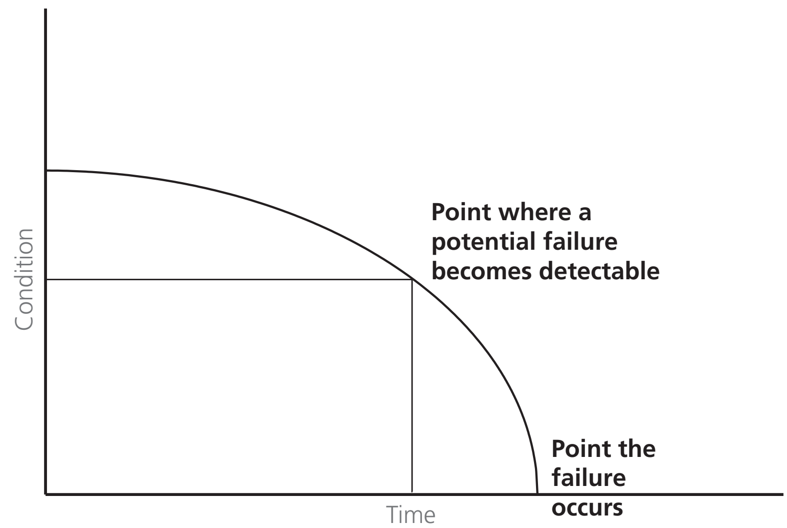
- blockage of infiltration systems
- sedimentation of ponds or channels
- death of vegetation
- untidiness or overgrowth of vegetation
- illegal connections or illicit discharges.

Asset performance indicators record the functional failure of a component of the system, even if the failure has not led to a functional failure of the whole system. They are therefore useful to operators in monitoring the effectiveness of maintenance regimes.

10.3.3 Asset condition

Asset condition is different from asset performance. It can be defined as a measure of deterioration in the physical state of the asset when compared to its new state (WRc, 2009). The effect of deteriorating condition on performance of a mechanical component has been described by Moubray (1997) (see Figure 10.5). The condition of a component can deteriorate over a long period of time without any detectable reduction in performance. The condition deteriorates, usually at an accelerating rate, until the reduction in performance of the component becomes apparent (potential failure) and further until it eventually fails (functional failure).

Figure 10.5 The effect of condition on performance (Moubray, 1997)



Asset condition can be assessed by inspecting the assets. Until recently, CCTV has been perceived as the one-size-fits-all inspection technique. However, research has shown that CCTV inspections are also error prone, mainly due to human errors (Dirksen *et al*., 2013). Alternative techniques are being proposed, such as the use of laser profilers to measure the internal diameter and calculate wall losses (Clemens *et al*., 2015), the use of acoustics for detecting any anomalies in the pipe cross-section (Plihal *et al*., 2016), and conductivity methods for leak detection (Tuccilo *et al*., 2011).

10.3.4 Performance indicators

Performance indicators (or serviceability indicators) can either be service indicators or asset performance indicators.

A service indicator has been defined as a quantity that may be measured, calculated or estimated in order to provide an indication of a particular aspect of the service being provided by a utility to customers and the environment. This includes compliance with statutory obligations (UKWIR, 2005).

An asset performance indicator has been defined as a quantity that reflects the performance of an asset or group of assets in fulfilling its intended function (UKWIR, 2005).

Performance indicators can either measure the level of performance by comparison with a reference standard or just measure the performance without any such reference. Where performance is measured against a reference standard, then this can either be explicit (e.g. the number of properties at risk of flooding internally more frequently than once in 10 years) or implicit (e.g. the number of sewer collapses). An extensive list of performance indicators for wastewater services has been produced by the International Water Association (IWA, 2003).

In using performance indicators to compare the performance of different systems or parts of systems, the indicators are frequently normalised based on the population served, the number of connected properties, the length of sewer, etc. The most appropriate method of normalisation will depend on the particular aspect of performance.

Performance indicators can be used for benchmarking performance between countries. However, different arrangements influence management and working practices and make direct comparisons of performance between different countries difficult. For example, a sewerage authority in a country where sewerage authorities are not responsible for smaller diameter sewers would be expected to have far fewer sewer blockages than one ina country in which sewerage authorities are responsible for sewers right up to property boundaries.

Where performance indicators are used as part of regulatory compliance measurement, the reference level of service is often compared with a fixed performance requirement.

Performance requirements should be clearly separated from design criteria. If the performance requirement is used as the basis for design, then only a small amount of deterioration will mean that the system fails to meet the performance requirements. To allow for this, design criteria should be set at a higher level than the performance requirements to allow some headroom for future growth in the system and for expected deterioration.

Traditionally, performance indicators are defined to measure the status or performance of piped systems. However, the application of SuDS and the acknowledgement that urban flooding can best be managed by using the optimal combination of above- and below-ground infrastructure and urban design requires that performance indicators are expressed to cover the whole range of serviceability indicators. The selection of appropriate performance indicators is a very important driver for asset management.

10.4. Maintaining performance and directing development

Urban drainage systems, including traditional pipe sewers and SuDS, fail as soon as the load to the system exceeds the capacity. This may be due to an increase of the load (which may be hydraulic or structural) and/or due to a decrease in the carrying capacity. Asset management is a means to maintain performance: in the short term by recognising or anticipating failures and taking direct actions (repair, cleaning), and in the long term by increasing system capacity or adapting systems to anticipated future developments, such as climate change or demographic changes. Integrated asset management should include both short-term optimisation and long-term development. The selection of appropriate performance indicators is fundamental in this respect.

10.4.1 Failure modes

Urban drainage systems can fail in a number of different ways including the following.

- Increase in flows leading to hydraulic incapacity. These can increase above design levels for a variety of reasons.
  - Development growth increases foul and surface water flows, and surface runoff from impermeable areas in new developments.
  - Urban creep is the increase in impermeable area associated with existing development (e.g. land that naturally soaks up the water removed by impermeable surfaces, such as paving a front garden for parking, the construction of extensions and conservatories and patios). Urban creep could be considered as placing additional obligations on water companies and

highway authorities without any associated increase in income. In England, development control requirements were changed in 2008 (OPSI, 2008) to limit the extent of creep.
- Misconnection of surface water to foul sewers. It has been estimated that up to 2% of properties in England and Wales are misconnected (Ellis and Butler, 2015), a number that can also be found in international literature (Schilperoort *et al*., 2014).
- Misconnection of land drainage to the sewer system. There is no legal right of connection for land drainage to sewer systems in the UK, and sewerage undertakers have no legal powers for land drainage. However, land drainage is sometimes connected to the system and. Land drainage flows have relatively low peaks, but they often have significantly longer durations than direct surface water connections, and can have a disproportionate impact on those systems relying on storage to provide peak flow capacity.
- Infiltration: Leakage of groundwater into the sewer system through defective joints in pipes or manholes or other defects in the system or areas where there are high groundwater levels. The problem is often not just confined to the sewer system; significant infiltration can also come from building drainage systems. There can also be direct connections of groundwater to the sewer system.
- Excessive rainfall: Current predictions of the effect of climate change in much of the UK suggest an increase in the frequency of high-intensity rainfall, which will lead to deterioration in the flood performance of sewer systems. Current guidance from Defra suggests that the effect on rainfall intensities will vary across the country, but might increase by up to 40% by the 2050s and up to 50% by 2070s. The effects on peak river flows might be significantly greater (see Environment Agency, 2022).
- Changing patterns of water use in recent years, through an increased number and use of water-using appliances and changing habits.
- Changes in the use of drain and sewer systems, with an increased disposal of inappropriate materials to sewers such as fats, oils and grease (FOG), wet wipes, etc. (Chapter 2).

■ Decrease in sewer capacity caused by a chronic build-up of sediment and gross solids or other causes.

- Sediment build-up due to a lack of self-cleansing velocity. More information on sediments can be found in the IWA's *Solids in Sewers* (Ashley *et al*., 2004).
- Sewer blockage due to gross solids, typically consisting of paper, rags, wet wipes and miscellaneous sewage litter.
- Fats, oils and grease (FOG) discharged to sewers by industrial wastewater, food catering establishments and domestic customers.
- Tree root intrusion: Root penetration can occur due to inadequate leak tightness, poor installation or pipe damage. Contrary to popular belief, the root system of a tree is not a mirror image of the branches, nor is there usually a 'tap root'. Typically, the root system of any tree is limited to the surface 600 mm of soil, by the need for roots to have both air and water. The roots extend radially in any direction for distances frequently more than the tree's height. There are many factors to be considered in understanding growth habit and root development. The rate of growth is dependent on the age of the tree. Vigorous young trees are the most likely to be capable of rapid growth or rapid root regeneration. The deeper the root system, the less rapid the growth. Other factors influencing the rate of growth are

  (*a*) ground conditions
  (*b*) temperature of the soil

(*c*) temperature of the air
(*d*) level of flows within the sewer.

The construction of a sewer can create a favourable environment for root growth at much greater depths by providing a free-draining filling material. Research carried out by IKT, Germany, showed that a tree root tip can develop a lateral pressure in excess of 12 bar and that the root is seeking a void, and not water and nutrients (Stützel *et al*., 2004). Once in the pipe, the tree root can grow into a mass of small fibrous roots or into a tap root, obstructing the flow.

- Structural failure of the fabric of the system due to overloading of the system by traffic or overburden or to decreasing structural strength. There are several different mechanisms of structural failure of drains and sewers causing asset deterioration, including the following.

  – Ring failure, where a rigid pipe is overloaded and fractures.
  – Beam failure, where lack of support under part of a single pipe causes excessive bending moments along the length of the pipe leading to its failure. As with ring failure, migration of soil into the pipe caused by surcharge or groundwater movement can lead to further subsidence and eventual misalignment and blockage of the pipe.
  – Joint failure: Failure of joint sealing materials can allow migration of soil into the pipe leading to progressive subsidence and eventual failure. Older jointing materials, including puddle clay, lime mortar, hemp and mortar and natural rubber joints, are all subject to failure in time.
  – Buckling: Flexible pipes (e.g. plastic pipes) derive their strength from the passive side support of the pipe under loading. Any loss of side support or overloading is therefore likely to cause deformation of the pipe and, in extreme cases, to buckling of the pipe.
  – Chemical attack: Different materials can be subject to different forms of chemical attack. Metallic pipes can be subject to corrosion; cementitious pipes are vulnerable to acid attack, including attack as a result of septicity in sewage; plastic pipe can also be vulnerable to various hydrocarbons. The attack can be external, due to natural chemicals in the groundwater or from contaminated soils, or it can be internal, as a result of chemicals in the sewage.
  – Wear: Sediments (particularly mineral sediments) or debris in the sewage can cause wear of the pipe material, particularly where the flow velocity is very high (e.g. at the foot of deep drop pipes). It can also cause wear of pump impellers, which can significantly reduce the performance of the pumps.
  – Third party damage: In many locations third party damage, particularly during work on other utility services, is a major cause of sewer failure.
  – Sewer works: Maintenance and upgrading should improve the sewer structural condition and hydraulic performance. However, poorly performed sewer works are one of the main causes of sewer failure. Examples include cleaning the sewer with too high a pressure, which can result in erosion, and forgetting to remove ‘temporary’ concrete or other barriers placed in manholes to allow safe working downstream, etc.

- Mechanical or electrical failure of pumps, valves or screens.
  - Wear of pump impellers reduces the capacity and efficiency of pumps, and sharp edges on chipped impellers increase the probability of pump blockages, which can lead to motors overheating and sometimes burning out.
  - Changes in pressure and flow velocity, particularly rapid changes, during starting and stopping of pumps can create surge pressures, or water hammer, which can exceed the design pressures and cause fatigue in some materials. This can significantly reduce the design life of a pumping main, as well as damage pumps and valves.
  - Low pressures on the inlet to a pump can result in the formation of vapour-filled bubbles, or cavitation. This can lead to the formation of pressure waves in the liquid, which are likely to cause serious mechanical damage to the impeller.
  - Excess vibration, noise or heat can result in mechanical damage.
  - Wear on other mechanical equipment can lead to unreliability.
  - Septicity and the generation of hydrogen sulphide can result in the production of sulphuric acid, which can cause corrosion of metal parts such as valves.
  - Failure of seals on electrical equipment or breakdown of insulation can lead to electrical failure.
  - Air valves can become blocked with FOG in the sewage, making them ineffective. The resulting accumulation of air increases friction and can cause an airlock, increasing the pressures and reducing the capacity of the pumps.
  - Seizure of reflux valves can cause backflow when pumps stop, emptying the main back into the wet well.
- Exfiltration, where leakage of foul or combined sewage through a defective sewer can lead to unacceptable pollution of groundwater and aquifers. The risk is particularly high when the sewer is close to a groundwater source protection zone or water abstraction point, or when the sewage contains chemicals from industrial effluents.

10.4.2 Maintenance activities

Maintenance activities can include the following.

- Sewer cleaning.
  - Blockage removal: Blockage removal is typically the most frequent sewer maintenance activity. To prevent re-occurrence it is important that the blockage material is either removed completely from the drain or sewer or is broken up into small fragments. Dislodging the blockage without breaking it up is a major cause of further blockages. The most common methods of removal are jetting and rodding.
  - Grease removal from sewers: Blockages caused by FOG can affect quite long lengths of drain or sewer and are difficult to remove. Where the grease has totally blocked the pipe then the flow should first be restored by jetting or by rodding. However, further cleaning should

then be carried out to remove the remainder of the grease. Where grease has adhered to the wall of the pipe over a large area, removal can sometimes cause the grease to become detached in large plates which can block the sewer downstream. The use of spinning jets at right angles to the wall of the pipe can be used to ensure that grease removed from the wall is broken up into small pieces. A jetter with a suction pipe should be used to ensure that the material is removed from the sewer to prevent further blockages and consequent flooding or pollution. In large sewers where there are severe grease deposits, manual removal is sometimes the only practical option. As FOG-related blockages are known to re-occur, regular inspection is advised after grease removal.

- Tree root removal: Fine tree roots can usually be removed by jetting; however, sometimes the effect of the jetting is merely to clean the strands of root rather than remove them. Wire brushes, either rodded or winched through the sewer, can also be used to remove fine roots that are growing into the sewer. For tap roots, conventional jetting or specialised high pressure water cutting equipment may be necessary. For repeat regrowth, the opening through which the roots entered the pipe should be sealed, usually by lining.
- De-sedimentation: Settled deposits in the invert of the sewer can be removed by jetting, winching or rodding. Where sewer sediments have been in place for some time they can accrete and become difficult to remove. In small diameter sewers, a small high-pressure/low-volume jetter can be effective as for blockage removal. However, in large diameter sewers, larger HGV-mounted low-pressure/high-volume machines will be necessary. The use of vacuum extraction equipment to remove the sediments can be advantageous, as it avoids the risk of re-deposition downstream and also allows the recycling of the water. Winching was the traditional method of sediment removal but is now less frequently used. Various tools can be used with winching for sediment removal, including buckets ploughs and brushes. Skill is required to avoid damaging the sewer. Rodding is only practical for removing sediment from small drains. When removing sediment from surface water sewers discharging to a waterbody, measures should be taken to prevent the sediment-laden flow from entering the receiving water as it could cause environmental damage. Also, where a sewer is discharging to a small wastewater treatment plant the sediment load could adversely impact on the performance of the plant.
- Cleaning of pumping stations: Sediments, grease and sanitary solids collect in the wet wells of pumping stations and if not properly controlled can cause failure of the control sensors or pump blockage. Pumping station wet wells should therefore be cleaned periodically to prevent failure of the pumping station. Cleaning is generally done by vacuum extraction and a high-pressure water lance.

■ Structural repair, renovation or replacement: Damaged pipes can often continue to function without further intervention; however, structural repair, renovation or even replacement is sometimes necessary. Where there are extensive structural problems, solutions should be developed that take into account other problems in the system.

  - Replacement: Where much of a length of pipe is in poor condition the traditional solution has been to replace the pipe. This still can be the best option when an increase in flow capacity is also required or where renovation of the pipe is not practicable.
  - Renovation: Where a damaged pipe is still able to carry all the imposed load it is often possible to stabilise it by sealing the defects or pipe wall. Linings can also be used to provide additional strength, either by creating a composite structure by bonding the lining to the existing structure or by designing the lining to take the whole of the imposed load.

For smaller pipes, where the existing pipe is deformed, re-rounding techniques are available. These usually involve the insertion of a tool that restores the shape of the pipe and inserts a clip to stabilise it prior to the insertion of a lining. There is a wide range of techniques available, which are described in BS EN 15885:2018 (BSI, 2018).

- Localised repairs can be undertaken by replacement of the damaged pipe or by localised lining. Localised replacement is now effected by removal of the damaged section back to a clean-cut end of pipe and insertion of a new section of pipe jointed with suitable repair couplings.

■ Increasing hydraulic capacity: Where it is necessary to increase hydraulic capacity this can be done in several ways.

- Removal of unwanted flow from the system can create additional capacity. It can be practical to disconnect surface water from a system by separation, connecting it to another piped surface water system or to a sustainable drainage system.
- Diversion of flow or part of the flow into a neighbouring system with available capacity can also be used to create capacity.
- Maximisation of existing capacity: Where there is available storage capacity in the system it can be practical to mobilise this additional storage in order to accommodate short-term peak flows.
- Removal of local restrictions: In some cases the flow is restricted in only a small section. Examples include a section of pipe downstream of a major junction or a pumping station. In these cases a small improvement can substantially increase the capacity. Care should be taken to ensure that such an improvement does not simply move the problem further downstream.
- Attenuation can be a practical solution where the hydraulic problems are caused by short-term peaks in the flow. Attenuation solutions can be in the form of on-line or off-line tanks constructed either as large chambers or as enlarged sections of sewer (tank sewers). Attenuation solutions are likely to be most cost-effective where it would otherwise be necessary to upsize a long length of sewer. Attenuation solutions are less effective when there are delayed responses in the system (e.g. due to infiltration or land drainage connections).
- Reinforcement: Additional carrying capacity can be provided within the system by replacing a sewer with a larger one (replacement) or by laying an additional sewer in parallel (reinforcement). In either case this will increase peak flows downstream and the effect of this will need to be considered.

10.5. UK procedures supporting asset management

Drainage Area Plans (DAPs) or Sewerage Management Plans (SMPs) have provided the basis for water companies' investment planning for sewer networks since the publication of the first edition of the *Sewerage Rehabilitation Manual* (SRM) in 1983 (WAA/WRc, 1983). The SRM emphasises the importance of an integrated approach to sewerage planning, in which all the hydraulic, environmental, structural and operational problems are considered together to find the most cost-effective solutions. A key aspect of the SRM procedure is to improve capital efficiency by the developing integrated solutions that take account of all aspects of performance. The SRM procedure has been used in conjunction with the Urban Pollution Management (UPM) procedure for investigating the environmental performance of sewer networks. The UPM provides a process for the investigation of urban wet weather water quality issues and identification of cost-effective solutions for continuous and intermittent discharges. More recently, Drainage and Wastewater Management Plans have introduced the wider catchment flooding aspects in collaboration with other stakeholders.

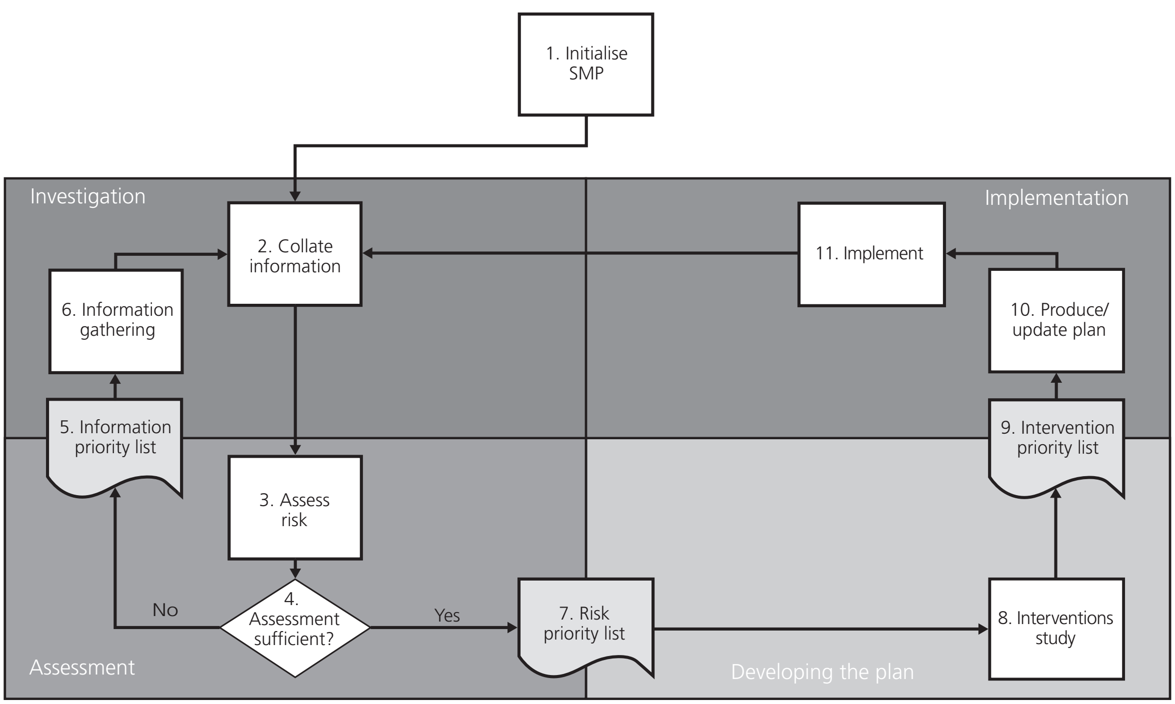
Pressures from customers and regulators to improve the water environment, particularly through the implementation of various EU environmental directives and customer and regulatory pressures to reduce sewer flooding, led to a series of major work-streams that dominated water company capital programmes. The pressures to complete these very large capital programmes in very short timescales made taking the integrated approach very difficult, particularly as water companies and regulators are responding to different deadlines. Recognising the need for a longer-term strategic approach to water company planning, Ofwat and the Environment Agency commissioned a Drainage Strategy Framework (Halcrow, 2013). This has led to the development of drainage and wastewater management planning (Water UK, 2018).

10.5.1 The SRM procedure

The SRM is an 11-step, risk-based procedure for the planning of sewer systems. It can be used for planning at different scales, from major capital investment right down to maintenance activities. The procedure is a development from the procedure in previous editions of the SRM (WRc, 2001). The procedure is illustrated in Figure 10.6.

The four quadrants of the procedure are aligned with the four stages of the BS EN 752 integrated sewer system management planning process (see Figure 10.1), the procedure working in an anti-clockwise direction. Whereas previous editions of the SRM were applied largely at a single level, the drainage area, the current SRM procedure can be applied at different scales to suit the nature of the problem or the type of sewerage asset being considered. For example, hydraulic and structural problems in sewers might continue to be considered at the level of the drainage area, but a water quality problem in a large urban area might need to be considered on a larger scale, incorporating several drainage areas. Equally, in the application of the procedure to an asset that has no influence on other aspects of the performance of

Figure 10.6 The Sewerage Rehabilitation Manual (SRM) procedure (WRc, 2009)



the system, such as manhole covers, it may be better to set the area as the whole area covered by the sewerage utility. The 11 steps are as follows.

Step 1 – Initiate SMP
Step 2 – Collate data
Step 3 – Assess risk
Step 4 – Assessment sufficient
Step 5 – Information priority list
Step 6 – Information gathering
Step 7 – Risk priority list
Step 8 – Interventions study
Step 9 – Intervention priority list
Step 10 – Produce/update Sewerage Management Plan
Step 11 – Implementation.

After setting the objectives, performance requirements and planning horizons in step 1, an initial assessment of current and future risks is undertaken using existing data. This risk assessment is then reviewed and if necessary further investigations are undertaken to refine the risk assessment until it is adequate for the purpose. After that a priority list of performance deficiencies is collated (step 7) and interventions are developed to deal with these deficiencies, which are then subject to economic appraisal. Finally, a priority list of interventions is produced and an SMP prepared and implemented.

There is no explicit monitoring and review stage as the intention is that the whole procedure is cyclic; so the first repeat of steps 2 and 3 in the next round of the procedure form the monitoring and review stages.

10.5.2 Capital maintenance planning common framework

In the UK, the capital maintenance planning common framework (CMPCF) (UKWIR, 2002) describes the water industry's risk-based approach to investment appraisal. This was developed in conjunction with, and approved by, the economic regulator Ofwat. The CMPCF uses an appraisal system based on the assessment of current and forecast future service failure risk, with and without investment. However, Ofwat is now focusing on asset management maturity improve understanding of how companies manage risks from assets and to consider its approach to regulation in light of that understanding (Ofwat, 2021).

CMPCF uses a cost–benefit approach to investment appraisal (Ofwat, 2008) and in the assessment of flood and coastal erosion risk management (Defra, 2009). Risk-based cost–benefit approaches can be applied to investment decisions regarding planned periodic maintenance activities such as sewer cleaning as well as the construction of sewer upgrading schemes.

The CMPCF (UKWIR, 2002) has three principal stages.

- A historical analysis of maintenance expenditure and serviceability indicators.
- A forward-looking analysis to identify future maintenance expenditure to meet regulatory objectives.
- A conclusion which takes the results of the first two stages and makes the case for future maintenance.

These principles have been incorporated into the recent editions of the SRM procedure.

10.5.3 *Urban Pollution Management Manual*

The *Urban Pollution Management Manual* (FWR, 1998) was developed as a procedure for planning works to reduce the impact of sewer systems, including wastewater treatment plants, on surface receiving waters. It complements the SRM procedure, providing more detailed guidance on these aspects.

Following publication of the *Urban Pollution Manual* in 1998, there were significant changes in legislation, including the implementation of the Water Framework Directive (EU, 2000), with its new water quality and ecological standards. There were also significant improvements in computing power and software development, resulting in new enhanced modelling tools for urban drainage planning. In response to these changes, a third edition of the manual was published in 2012 (FWR, 2012), updated to reflect the new priorities for a range of environmental issues, such as the impact of climate change and adaptation.

10.5.4 Drainage and Wastewater Management Plan procedure

The institutional arrangements for the water cycle in the UK present some challenges to the effective implementation of asset management principles across the whole water cycle. To achieve this, collaboration is required between a number of institutions.

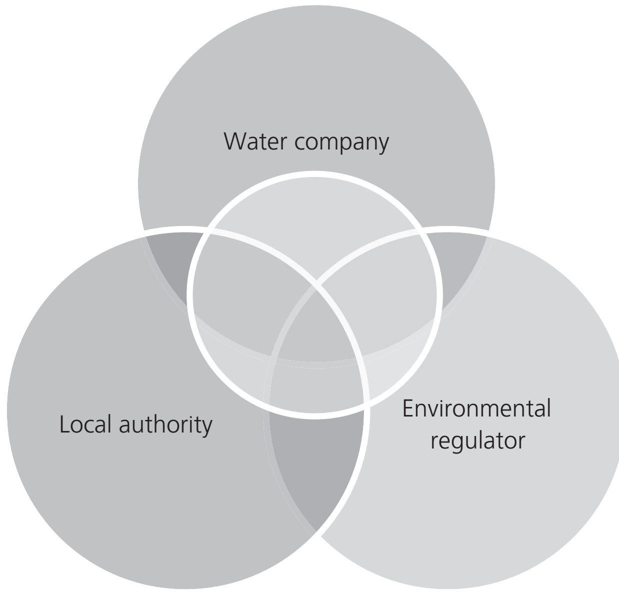
In 2018, a collaboration between the water industry, regulators and local government developed a framework for producing Drainage and Wastewater Management Plans (DWMPs) (Water UK, 2018, 2021) covering planning for surface water management, including flood risk and water quality. DWMPs concentrate on the hydraulic and environmental performance of sewer systems, but do not address structural and operational issues. However, operational issues also need to be considered as they can be vital to the environmental and hydraulic performance of networks.

DWMPs set out how water and sewerage companies intend to extend and maintain a robust and resilient drainage and wastewater system. A DWMP takes a long-term view, setting out a planning period that is appropriate to the risks faced, but with a minimum period of 25 years (Water UK, 2021). The plan is developed in collaboration with relevant stakeholders and involves working at least three different levels: level 1 (company), level 2 (catchment) and level 3 (tactical).

The issues and difficulties that surround engagement with others are not confined to flooding. Frequent CSO activity can exert a chronic polluting effect, but CSO load is only part of the load that water companies need to control. Addressing water company commitments under the Urban Wastewater Treatment Directive for continuous and intermittent discharges plus compliance with the Water Framework Directive requires a collaborative approach to understand both the contribution of the sewer system and that of others.

Water quality is not just a water company issue. Local highway authorities discharge surface water both to sewers and direct to watercourses. Local planning authorities now regulate surface water discharges from new developments and must consider both the flood risk and water quality impacts of these discharges.

Figure 10.7 Collaborative core for integrated planning for the major stakeholders



The key stakeholders are the water companies, environmental regulations and local authorities, but other stakeholders may also need to be involved. The ‘systems thinking’ philosophy encourages wider collaboration between these stakeholders (Figure 10.7); for example, with the regulator to maintain sustainable environmental flows within some watercourses through the discharge of good quality final effluent, and with water supply companies to balance the need for adequate assimilative capacity for dilution of discharges against the abstraction requirements for supply. Collaborative opportunities exist to explore the potential for demand efficiencies to offset growth impacts at wastewater treatment plants and to understand whether this would lead to a possible commensurate increase in blockages.

10.5.4.1 Managing uncertainties

Long-term planning will always include uncertainties. The rate and magnitude of climate change is a major uncertainty, but uncertainties also include the location and timing of new developments and new infrastructure. In the past, decisions have often been made only when the uncertainties have been resolved, leading to short-term sub-optimal decisions. Collaborative solutions bring further uncertainties with the availability and timing of funds to deliver those solutions.

The DWMP procedure proposes the use of an adaptive pathway approach, as set out in BS 8631:2021 Adaptation to climate change. Using adaptation pathways for decision making (BSI, 2021b), to manage the uncertainties, particularly those associated with climate change.

There need to be economic tools to provide a basis for deciding between pathways that provide flexibility. One such approach is real options analysis which applies probabilities to the costs and benefits of different pathways. It has been used in making decisions on climate change adaptation.

10.5.5 Fitting it all together

10.5.5.1 Linking DWMPs to other stakeholders' planning activities

DWMPs require companies to collaborate with other stakeholders during the process. However, each stakeholder still needs to produce plans to meet its objectives.

For a water company, its planning activities must provide for the following.

- Tactical operation and management of the wastewater system.
- Management of its capital programme to meet regulatory requirements in a cost-effective way.
- Providing the basis for its business plan, as part of the periodic review process that is a component of the economic regulation of water companies.
- Providing input to other stakeholders' plans.

This must apply equally for both the foul and the surface water sewer networks and wastewater treatment.

Other stakeholders who own or manage flood risk assets, such as highway authorities, need to have asset management plans for their respective drainage assets. The area for collaboration is only part of their planning activities (see Figure 10.7).

The processes used by each stakeholder to produce their own plans should be aligned to minimise any additional work required for DWMPs.

REFERENCES

Ashley RM, Bertrand-Krajewski JL, Hvitved-Jacobsen T and Verbanck M (2004) *Solids in Sewers*. IWA Publishing, London, UK.

BSI (British Standards Institution) (2012) BS EN 13508-1:2012. Investigation and assessment of drain and sewer systems outside buildings – General requirements. BSI, London, UK.

BSI (2014) BS ISO 55000:2014. Asset management – Overview, principles and terminology. BSI, London, UK.

BSI (2017a) BS EN 752:2017. Drain and sewer systems outside buildings – Sewer system management. BSI, London, UK.

BSI (2017b) BS ISO 24516-3:2017. Guidelines for the management of assets of water supply and wastewater systems – Wastewater collection networks. BSI, London, UK.

BSI (2018) BS EN 15885:2018. Classification and characteristics of techniques for renovation, repair and replacement of drains and sewers. BSI, London, UK.

BSI (2021a) BS EN 14654-1:2021. Drain and sewer systems outside buildings – Management and control of activities – General requirements. BSI, London, UK.

BSI (2021b) BS 8631:2021. Adaptation to climate change. Using adaptation pathways for decision making. Guide. BSI, London, UK.

Clemens F, Stanić N, Van der Schoot W, Langeveld J and Lepot M (2015) Uncertainties associated with laser profiling of concrete sewer pipes for the quantification of the interior geometry. *Structure and Infrastructure Engineering* **11(9)**: 1218–1239.

Defra (Department for Environment, Food and Rural Affairs) (2009) *Appraisal of Flood and Coastal Erosion Risk Management. A Defra Policy Statement*. Defra, London, UK. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69419/pb13278-erosion-manage-090619.pdf (accessed 09/08/2023).

Dirksen J, Clemens FHLR, Korving H *et al.* (2013) The consistency of visual sewer inspection data. *Structure and Infrastructure Engineering* **9**: 214–228.

EC (European Community) (2000) Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* **L327**. See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0060 (accessed 09/08/2023).

EC (2007) Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. *Official Journal of the European Communities* **L288**. See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32007L0060 (accessed 09/08/2023).

Ellis JB and Butler D (2015) Surface water sewer misconnections in England and Wales: pollution sources and impacts. *Science of the Total Environment* **526**: 98–109, 10.1016/j.scitotenv.2015.04.042.

Environment Agency (2022) Flood risk assessments: climate change allowances. https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances#peak-rainfall-intensity-allowance

FWR (Foundation for Water Research) (1998) *Urban Pollution Management Manual – A Planning Guide for the Management of Urban Wastewater Discharges During Wet Weather*, 2nd edn. FWR, Marlow, UK.

FWR (2012) *Urban Pollution Management Manual*, 3rd edn. Foundation for Water Research, Marlow, UK. http://www.fwr.org/UPM3/.

GFMAM (Global Forum on Maintenance and Asset Management) (2014) *The Asset Management Landscape*, 2nd edn. GFMAM. See www.gfmam.org/sites/default/files/2019-05/GFMAMLandscape_SecondEdition_English.pdf (accessed 05/08/2023).

Halcrow (2013) *Drainage Strategy Framework. Good Practice Guidance Commissioned by the Environment Agency and Ofwat*. Halcrow Group, Swindon, UK. See https://www.ofwat.gov.uk/wp-content/uploads/2015/12/rpt_com201305drainagestrategy1.pdf (accessed 21/07/2021).

IWA (International Water Association) (2003) *Performance Indicators for Wastewater Services*. IWA, London, UK.

MAFF (Ministry of Agriculture, Fisheries and Food) (2001) *Flood and Coastal Defence Project Appraisal Guidance*. MAFF, London, UK.

Moubray J (1997) *Reliability-centred Maintenance*. Butterworth-Heinemann, Oxford, UK.

Ofwat (The Water Services Regulation Authority) (2008) *Setting Price Limits for 2010–15: Framework and Approach*. Ofwat, Birmingham, UK.

Ofwat (2021) *Asset Management Maturity Assessment*. Ofwat, Birmingham, UK. See https://www.ofwat.gov.uk/wp-content/uploads/2021/03/Asset-management-maturity-assessment-March-2021.pdf (accessed 09/08/2023).

OPSI (Office of Public Sector Information) (2008) The Town and Country Planning (General Permitted Development) (Amendment) (No. 2) (England) Order 2008 SI 2008/2362.

Plihal H, Kretschmer F, Bin Ali MT *et al.* (2016) A novel method for rapid inspection of sewer networks: combining acoustic and optical means. *Urban Water Journal* **13(1)**: 3–14.

Post J, Pothof I, ten Veldhuis MC, Langeveld J and Clemens F (2016) Statistical analysis of lateral house connection failure mechanisms. *Urban Water Journal* **13(1)**: 69–80, 10.1080/1573062X.2015.1057175.

Schilperoort R, Rudelle E, Vollertsen J *et al.* (2014) CCTV versus DTS: comparison of results in the search for infiltration and inflow. In *ICUD Congress*, Kuching, Malesia.

Stützel T, Bosseler B, Bennerscheidt C and Schmiedener H (2004) *Wurzeleinwuchs in Abwasserleitungen und Kanäle*. See http://www.ikt.de/down/f0108langbericht.pdf (accessed 05/08/2023).

Syed Z and Lawryshyn U (2020) Multi-criteria decision-making considering risk and uncertainty in physical asset management. *Journal of Loss Prevention in the Process Industries* **65(2020)**: 104064, 10.1016/j.jlp.2020.104064.

Tuccilo ME, Wilmut C, Feeney C, Martelk K and Selvakumar A (2011) Field demonstration of electro-scan defect location technology for condition assessment of wastewater collection systems. *Proceedings of the Water Environment Federation* **2011(5)**: 265–281.

UKWIR (UK Water Industry Research) (2002) *Capital Maintenance Planning: A Common Framework*. UK Water Industry Research Ltd, London, UK. See https://ukwir.org/eng/reports/02-RG-05-3/66808/Capital-Maintenance-Planning-A-Common-Framework-Volume-1-Overview (accessed 09/08/2023).

UKWIR (2005) *Capital Maintenance Planning Common Framework: Review of Current Practice*. Report Ref 05/RG/05/14. UK Water Industry Research Ltd, London, UK. See https://ukwir.org/eng/reports/05-RG-05-14/66813/Capital-Maintenance-Planning-Common-Framework-Review-of-Current-Practice (accessed 09/08/2023).

WAA/WRc (Water Authorities Association/Water Research Centre) (1983) *Sewerage Rehabilitation Manual*, 1st edn. Water Research Centre, Swindon, UK.

Water UK (2018) *A Framework for the Production of Drainage and Wastewater Management Plans*. Water UK, London, UK. See https://www.water.org.uk/wp-content/uploads/2018/12/Water-UK-DWMP-Framework-Report-Main-Document.pdf (accessed 09/08/2023).

Water UK (2021) *A Framework for the Production of Drainage and Wastewater Management Plans*, revised edn. Water UK, London, UK. See https://www.water.org.uk/wp-content/uploads/2021/10/DWMP_Framework_Report_Main_Report_September_2021.pdf.

WRc (Water Research Centre) (2001) *Sewerage Rehabilitation Manual*, 4th edn. WRc Publications, Helsby, UK.

WRc (2009) *Sewerage Risk Management*. Water Research Centre, Helsby, UK. See http:/srm.wrcplc.co.uk.