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UN declares access to water and sanitation a 'human right'

A host of organisations have welcomed the United Nation's (UN) declaration of water and sanitation as a fundamental human right, with some key reservations. A non-binding resolution was passed with 122 nations in favour, none against and 41 abstentions.

Abstaining countries claimed the resolution could undermine a process in the UN's Human Rights Council to build a consensus on water rights. The text 'declares the right to safe and clean drinking water and sanitation as a human right that is essential for the full enjoyment of the right to life'.

Canada, the US, the UK, Australia and Botswana were among those that abstained from voting. China, Russia, Germany, France, Spain and Brazil were among its supporters.

World Water Council president Loic Fauchon welcomed the declaration, saying: 'This right is an essential brick in the wall we want to build against ignorance, injustice, poverty and thirst.'

The private water operators federation, AquaFed, also praised the move, saying that 'private water operators have consistently supported the right to water and sanitation' and calling the declaration 'an important milestone'. The federation added that 'this resolution must be used to turn the right into a reality for the billions of people who do not enjoy proper water services'.

Some caution has been expressed: a press spokesperson for Canada's Foreign Affairs Minister Lawrence Cannon, said that the country's sovereignty over its own natural water supply is a key issue for government. She said: 'We continue to assert that international human rights obligations in no way limit our sovereign right to manage our own resources.'

Founding President Mikhail Gorbachev of Green Cross International (GCI) said that 'the actions and voices of millions of citizens have brought the global movement for the right to water this far. I hope that more people will join us to help bring us closer to the ultimate goal – a world where everyone's right to safe water and sanitation is not just recognised but is also fulfilled.'

Amnesty International called on all UN members to uphold the rights to water and sanitation after the UN resolution was passed. ●

Water utility risk and resilience standard released

The American Society of Mechanical Engineers (ASME) and the American Water Works Association (AWWA) have unveiled the first risk and resilience management standard designed specifically for water utilities.

The J100 standard, which was created in response to the terrorist attacks on September 11, 2001, Hurricane Katrina and other recent disasters, was released at the beginning of July.

The Risk Analysis and Management for Critical Asset Protection (RAMCAP) method is designed to help water and wastewater utilities to identify potential threats to US water infrastructure and prepare for or mitigate any damage.

Reese Meisinger, president of the ASME Innovative Technologies Institute (ASME-ITI), said: 'This partnership leverages several years of development across multiple industry sectors, resulting in the only multi-sector, quantitative risk / resilience method available. Tailoring this method into an American National Standard reflects the far-sighted leadership in infrastructure security and resilience shown by AWWA and the water sector.'

AWWA executive director David LaFrance added: 'The J100 standard provides the water sector with a critically needed methodology to support risk and resilience decision making, especially in an already resource constrained economy.'

The manual addresses hazards ranging from terrorist attacks to natural disasters with the new RAMCAP methodology, which differs from others by guiding utilities in calculating the probability of a malevolent attack using an approach based on actual incidents, calculating the probability of a specific natural hazard occurring at a facility, and calculating asset and utility resilience capacity.

An expert committee representing water utilities, risk assessment practitioners and government agencies spent 18 months ensuring the standard considered specific water sector needs.

AWWA and ASME-ITI have also partnered to develop a training programme for the standard that will provide utilities and practitioners with a functional understanding of the all-hazards RAMCAP method and how it applies to the water sector. The training was launched in late July through AWWA's E-Learning platform. ●

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EDITORIAL

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EIB provides funding to Madrid water utility

The European Investment Bank (EIB) has agreed a loan of €100 million ($122 million) to Canal de Isabel II, the utility responsible for water distribution in the community of Madrid, Spain to finance investment in the Spanish capital's water supply and wastewater treatment systems.

The loan will finance a range of works on the supply, sewerage and wastewater treatment infrastructure that are included in the utility's 2009-2013 investment programme.

The programme's aim is to improve the reliability and efficiency of the water supply and wastewater management services by rehabilitating, constructing and extending wastewater and water treatment plants, constructing and expanding water mains and refurbishing the distribution network.

The project will also help to develop water reuse by investing in water treatment and distribution networks for recycled water intended for irrigation and industrial use. ●

Africa summit sees launch of new infrastructure development vehicle

A new African infrastructure development vehicle was launched recently on the sidelines of the 15th African Union heads of state and government summit. The Programme for Infrastructure Development in Africa (PIDA) is a joint initiative of the African Union Commission (AUC), the New Partnership for Africa's Development (NEPAD) secretariat and the African Development Bank (AfDB) Group.

'PIDA's objective is to merge all continental infrastructure initiatives into a single coherent programme for the entire continent. The programme will merge the 'NEPAD Short-Term Action Plan, the NEPAD Medium-to-Long-Term Strategic Framework' (MLTSF) and the African Union Infrastructure Master Plan Initiative,' the AfDB programme coordinator, Amadou Oumarou, said. Through its regional integration department (ONRI), the AfDB is the execution agency for PIDA.

'African leaders were unanimous in their call for greater regional integration in Africa,' the AfDB president, Donald Kaberuka, said. 'Our role as a development institution is to support this expressed ambition by providing realistic and achievable steps in order to attain this objective.' ●

El Salvador to improve water services with Spanish grant and IDB support

The Inter-American Development Bank (IADB) has approved a $44 million programme for water and sanitation in El Salvador, backed by a $20 million loan from the IADB and a $24 million grant from the Spanish Cooperation Fund for Water and Sanitation in Latin America and the Caribbean.

The project's main goal is to improve living conditions in El Salvador through the provision of adequate water and sanitation services. It will finance the expansion of coverage in rural areas with high levels of extreme poverty, the sustainable management of water resources and improvements in efficiency and sustainability of services provided by ANDA, the leading water utility.

Under the Rural Water and Sanitation Program, 85 water systems will be built, benefiting more than 6000 households in poor areas. The programme will help the Salvadorian government make progress toward its goal of increasing water service coverage to 80 percent in the country's 100 poorest townships, according to its 2010–2014 development plan.

The five-year programme will have three executing agencies: the Social Investment Fund for Local Development, the Ministry of the Environment and Natural Resources, and ANDA. ●

JICA provides funds for wastewater system work

The Japan International Cooperation Agency (JICA) has signed a Japanese official development assistance loan agreement with the Government of the Republic of Mauritius in Port Louis, the nation's capital, to finance up to Y7012 million ($81 million) for the 'Grand Baie Sewerage Project'.

The purpose of this project is to connect households to the existing sewerage plant in the Grand Baie region, the northern part of the country, thereby increasing the sewerage coverage ratio across the region and contributing to enhancement of environmental conservation and public health. The loan will be allocated to the construction of sewer pipes and pump stations.

The region has a wastewater treatment plant but only 10% (about 1600 households) of potential households to be covered in the region are currently connected to the plant. Therefore, there is an urgent need to increase the sewerage coverage ratio in the region and this project plans to connect about 4400 households to the plant.

This project also intends to strengthen a water quality monitoring system and improve the capacity of wastewater treatment facilities across the region in collaboration with Agence Française de Développement. ●

The WERF SAM challenge: research into remaining asset life

The provision of wastewater services involves numerous assets of many types with design / service lives, and extending the life of these assets by even a small proportion has the potential for saving significant amounts of money. In recognition of this, Water Environment Research Foundation (WERF) developed a research programme referred to as 'Strategic Asset Management Communication and Implementation'. In this paper, David Marlow, Stewart Burn and Anthony Urquhart present initial findings from Track 4 of this research programme, which addressed 'remaining asset life' concepts, and provided a state of the art review of approaches that can be used to manage, assess and model remaining asset life.

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The provision of wastewater services involves numerous assets of many types with design / service lives that range from very short to very long life (from a matter of years, to hundreds of years). The life of many of these assets could potentially be extended if we were able to gain a better understanding of what influences asset life; for example, through better knowledge of economic and risk factors, or through improved operational and maintenance practices. Extending the life of assets by even a small proportion has the potential for saving significant amounts of money, and to allow these savings to be used elsewhere to the benefit of customers and the environment. Management of remaining asset life is thus a key component of the overall asset management challenge.

The need to gain a better understanding of remaining life was outlined in the US Environmental Protection Agency's (EPA's) study of investment gaps in the US water sector [1]. In recognition of this need and, more broadly, to facilitate asset management practices through targeted research, WERF (Water Environment Research Foundation) developed a research programme referred to as 'Strategic Asset Management Communication and Implementation' (WERF ref: 06-SAM-1 CO). The general challenge statement for this research programme was to: 'Develop guidance and decision support tools for communicating and implementing a strategic asset management programme (SAM) for wastewater (and possibly water) facilities and estimating assets performance and their residual economic life.'

This paper presents initial findings from Track 4 of WERF's overall research programme, which addresses 'remaining asset life' concepts. The initial research effort within Track 4 had the goal of conceptually mapping the broad range of factors that influence remaining asset life, as well as providing a state of the art review of the science and practice of 'end of life' assessment and prediction. As such, this paper presents an overview of asset remaining life concepts, including a review of its conceptual importance to strategic asset management.

Various views of asset remaining life are also discussed, and a taxonomy and working definition presented, along with an examination of the importance of risk concepts. A summary of the approaches to assessment and modelling of remaining asset life is also given, along with a conceptual model that illustrates how a water authority might develop its approaches to the analysis of remaining asset life as it develops its asset management capacity. Recommendations for future work arising from the review stage of the research are also outlined.

Remaining asset life as a concept

What is remaining asset life?

The concept of end of life is relatively clear for living organisms – death occurs when an organism's biological functions cease and we define end of life in these terms. The situation is less well defined when the end of an asset's life is considered. For example, many assets are repairable, so complete loss of function does not imply end of asset life. At the other extreme, an asset can be considered at the end of its life well before any failures actually occur, due to the relative balance between risk and replacement or rehabilitation costs.

Maintenance is an important determinant in any consideration of asset life. The term maintenance covers a broad range of planned or unplanned activities for preserving asset condition and extending asset life [2, 3]. Figure 1 shows schematically the deterioration in asset condition over time, when the deterioration is regularly addressed by maintenance. As shown, periodic maintenance has the effect of restoring condition, but the level of condition achieved is often below that of a new asset. More extensive refurbishment and upgrading are undertaken during the life of many complex assets to replace components and to change the asset's functionality and accommodate changed service requirements. Through such periodic maintenance and capital expenditure, the life of an asset is thus extended and modified [4].

The issue of whether an asset can be repaired after failure also has a significant influence on the concept of remaining asset life. Economic considerations can, however, effectively blur the distinction between repairable and non-repairable assets. For example, it might be technically possible to repair a small and inexpensive pump but, due to the cost of repair being greater than the cost of purchase, it would probably be discarded and replaced [5]. Similarly, Elliot et al. [6] noted that prior to initiating test procedures on electric motors, it is necessary to compare the cost of replacing the motor to the cost of the testing. Assets that can be replaced at a cost less than that of the repair can be considered non-repairable for all intents and purposes.

A taxonomy of remaining asset life

As discussed in the previous section, remaining asset life is not a simple concept. One implication of this is that the term 'remaining asset life' is imprecise and will mean different things in different contexts. In an attempt to rationalize terminology, a review of asset life terms was thus undertaken, building on the experience of the research team. The following taxonomy of terms is considered to provide useful insights

Category	Description
Service failures	Operational impacts such as service interruptions, quality or quantity variations, poor customer service, etc.
Customer impacts	Impacts of interruption and customer dissatisfaction
Direct costs	Including damage to property and infrastructure, operational impacts, increased maintenance costs (associated with repair, excavation, material and equipment, traffic management, and other costs), business interruption, fines, and compensation for flooding (internal and external) etc.
Environmental impacts	Unacceptable environmental impacts considering natural and constructed environments
Externalities	Traffic disruptions, third party discomfort, aesthetic impacts, health impacts
Health and safety impacts	Possible death or injury to water authority staff and members of the public
Public relations impacts	Public relation issues arising from asset failures

Table 1 Categories of failure consequence [10]

into different views of asset life:

- Design life: the period of time over which the asset is designed to be available for use and able to provide the required level of service at an acceptable cost and level of risk. As noted in the International Infrastructure Management Manual [7], the anticipated life of an asset or component can be measured in various ways, including time, number of cycles and distance intervals. Lillie et al. [8] refer to the concept of 'design service life', and note that this is the life that was expected when the asset and system was designed, considering expected loading regimes, environmental protection and deterioration. In practice, many assets can operate well past the end of their design life due to fundamental redundancies built in at the design stage.
- Service life: the period of time over which the asset is actually available for use and able to provide the required level of service at an acceptable risk; e.g. without unforeseen costs of disruption for maintenance and repair.
- Operational life: some assets may be operated past the point where they provide the required level of service at an acceptable risk (i.e. operated past the asset's service life). As such, the operational life is taken to be the time over which the asset remains operational irrespective of performance, risk or cost considerations.

Similarly, various definitions relevant to the end of asset life can be compiled, and the following taxonomy of terms is considered to provide useful insights:

- End of physical asset life: when the asset is physically derelict and non-functioning; for example a sewer that has collapsed to the extent that function is no longer being provided and repair is not an option.
- End of technical service life: when the asset is failing to provide required functionality, service levels and / or reliability.
- End of economic asset life: when the asset is physically able to provide a service, but ceases to be the lowest cost alternative to satisfy a particular level of service [7]. In practice, this often reduces the time when the perceived or actual risk / cost associated with retaining an asset exceeds the cost of rehabilitating the asset.
- End of financial life: when the asset's initial capital value is fully depreciated.
- Obsolescence: when the asset is obsolete for some reason.

Remaining asset life is simply the time remaining until one of these end of life criteria are reached.

A holistic definition of remaining asset life

While various definitions of remaining asset life can be identified, as outlined above, for the purposes of the ongoing research it was desirable to have a single holistic definition. To this end, it was noted that whatever the definitions used to define end of asset life, the outcome is often that there is a significant level of investment made in the asset; either to rehabilitate or to replace it. As indicated in Figure 1, it can be reasonably argued that if renovation of the asset occurs, the original asset life has been extended. However, after renovation the asset will have a new design life that commences from the completion of the intervention. It thus seemed reasonable to define end of asset life in terms of when an asset will need a significant (capital, rather than operational) investment. As such, for the purposes of the research, end of asset life and remaining life was defined in the following way: 'The time at which a significant (capital rather than operational) investment is made. Remaining life is then the time left before a significant capital intervention is required.'

This definition is somewhat similar to the concept of 'phase of service life' used by Li et al. [9], who define a 'phase of service life' as a time period within the whole service life at the end of which maintenance such as repairs, strengthening, or rehabilitation is required. The definition of end of life adopted in the WERF project differs from this concept only in that the asset must be undergoing a significant (capital rather than operational) intervention before it is deemed to be at the end of its life. This definition aligns with the needs of asset managers, who must determine when an asset is reaching the end of its life because investment is then necessary and must be catered for. The exception is where an asset is no longer needed, in which case the lack of ongoing need drives the consideration of end of asset life.

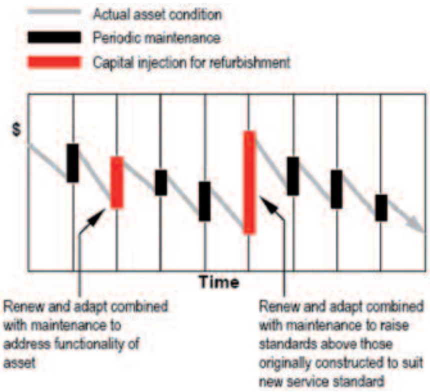

Figure 1 The impact of maintenance on the life of a complex asset [4]

The importance of risk

An attempt was made in the research to document the range of factors that influence asset life for the broad range of asset classes involved in the delivery of wastewater services, both above and below ground – see the WERF research report for details [10]. Many of the factors identified related to asset failure, the likelihood of failure, or the cost and other consequences associated with failure. As such, the influence of these factors can be considered within a risk-based management framework. Risk is therefore an important consideration in determining remaining asset life.

Risk is often considered to occur when two or more outcomes are possible and at least one of the possibilities is undesirable. Hence, risk involves both uncertainty (if an outcome is certain or has already occurred there is no risk) and the potential for an adverse consequence (though it should be noted that risk concepts can also be used to consider positive consequences). In asset management, risk is often defined as the product of the likelihood of a failure or other event that will cause loss, and the severity of the consequence, i.e. the magnitude of the loss [e.g. 7, 11, 12]. Hence, risk is expressed as:

Risk = Likelihood (either probability or frequency) x Consequence.

From this relationship, it can be seen that risk is decreased by either reducing the likelihood of failure and / or limiting the potential consequences of an incident / event. Asset managers thus need to understand both the likelihood side and consequence side of risk.

Table 2
Conceptual model of tool use according to development of asset management [10]

Stage of asset management development	Characteristics of asset management function	Assessment and analysis of remaining life
No formal systems	No specific asset management function, much of the maintenance and planning is undertaken reactively and is not optimized to any degree.	Where remaining life estimates are used, expert opinion driven approaches are adopted in conjunction with assumed asset lives (e.g. based on manufacturer's estimates). Condition assessment and risk assessment may be applied to specific assets, but their use is ad hoc rather than systematic. Deterministic models can be applied as part of these assessments. Analysis of interventions tends to focus on financial issues (internal costs).
Initial stages – understanding what assets are owned and what state they are in	Developed inventory of assets with associated data, but still generally reactive approach to asset maintenance and planning, but with some proactive management of specific 'key assets' – basic asset management plans for main asset types exist.	Expert opinion driven approaches used in conjunction with assumed asset lives. Condition and performance grading techniques used as the basis for long term planning. Condition assessment and risk assessment may be applied to specific assets, but their use is ad hoc rather than systematic. Deterministic models can be applied as part of these assessments Cohort based approaches possible for pipes (but expert opinion used to develop survival curves or similar). Probabilistic models possible but likely to be viewed as overly sophisticated. Fuzzy logic approaches could be used, but this is unlikely. Analysis of interventions tends to focus on financial issues (internal costs)
Basic asset management function	Basic maintenance management system now in place, some additional supporting asset management functions with respect medium to long term planning. General focus on management of condition and performance, but some ability to optimize maintenance and planning on the basis of cost.	Expert opinion driven approaches still used in conjunction with assumed asset lives, but now supplemented through analysis of asset-specific data. Condition and performance grading techniques still used within planning, but the scope of the analysis is now broadened to take into consideration risk grades. Condition assessment and risk assessment of specific assets or asset types used in response to specific drivers. Deterministic models can be applied as part of these assessments. Cohort based approaches possible for pipes (survival curves and similar may be developed through expert opinion and / or analysis of works orders). Basic statistical analysis of failure data possible, especially for M&E assets. Use of probabilistic models possible, but perhaps still seen as overly complex. Some optimization of maintenance costs through appropriate strategy (preventative, reactive, proactive as needed). Fuzzy logic approaches could be used, but this is unlikely. Analysis of interventions tends to focus on financial issues (internal costs).

Stage of asset management development	Characteristics of asset management function	Assessment and analysis of remaining life
Advanced asset management function	Advanced maintenance management with GIS capability, well developed business processes for tactical and strategic asset management, well defined key performance indicators and focus on risk in planning and maintenance. Able to optimize spending according to service levels and risk.	Expert opinion driven approaches are supplemented through analysis of asset-specific data and embedded in consistent business rules. Condition and risk grading techniques used for prioritization processes only, rather than planning. Condition assessment and risk assessment of specific assets or asset types used within a systematic framework. Deterministic models can be applied as part of these assessments. Cohort based and asset-level approaches used for long term planning (survival curves and similar developed through analysis of failure and other supplementary data). Refined statistical analysis of failure data and service levels possible for all assets with appropriate levels of failure data. Use of probabilistic models possible to interpret inspection data and provide better insights into economic life. Fuzzy logic approaches can be used to integrate expert opinion. ANN techniques can be used to interpret extensive asset related data. Optimization of maintenance costs through adoption of techniques such as reliability centred maintenance (RCM). Analysis of interventions still tends to be driven by financial considerations, but more emphasis is given to triple bottom line issues.
Whole of business strategy	Fully integrated data systems and whole of business approach to asset management with supporting functions. Focus on service and risk extended to consider broader definitions of 'added value' considering TBL outputs; key performance indicators refined to support this approach. Able to optimize spending accordingly to meet broader business and societal values, as well as cost etc.	Expert opinion-driven approaches only used as a feed in to appropriate analytical techniques. Condition and risk grading techniques used for prioritization processes only. Condition assessment and risk assessment of specific assets or asset types used within a systematic business performance management framework. Cohort-based and asset level approached used for long-term planning (survival curves and similar developed through analysis of failure and other suplementary data. Refined statistical analysis of failure data and service levels undertaken to understand condition assessment data, and provide better insights into economic life. Fuzzy logic approaches are used to integrate expert opinion. ANN techniques are used to interpret extensive asset related data. Optimization of maintenance costs through adoption of techniques such as RCM. Full economic analysis undertaken of all strategies and interventions, considering TBL elements (including intangible costs and externalities).

Likelihood side of risk

In general, it is possible to categorize factors that influence likelihood of failure into those that determine or influence the capacity of an asset to resist loads and those that determine or influence the load imposed on the asset. For example, De Silva et al. [13] note that ferrous pipes (such as cast iron) can fail in service due to pitting corrosion (which reduces structural capacity) and excessive in-service loading. For such assets, in-service loads can be split into contributions from internal pressure (if any) and external soil loading attributed to seasonal ground movement and traffic loads. It follows that failure will occur when these loads combine to exceed a critical property (i.e. capacity) of the corroded pipeline, such as its yield strength or critical strain energy.

More generally, 'load' can be taken to be any measure of demand imposed on an asset or system, and 'capacity' taken as the ability of the asset to function under the imposed demand. With these generalisations in mind, it can be asserted that for successful operation or provision of service, the load (L) imposed on an asset (or system) must be within its capacity (C). As discussed by Elishakoff [14], a common engineering approach for expressing the capacity of an asset to resist imposed loads is in terms of safety factors (SF). A safety factor can be defined as the ratio between some measure of load and an equivalent measure of capacity (e.g. the ratio between asset strength and an equivalent measure of imposed load or stress). At any time in its life cycle, an asset's safety factor can thus be expressed in terms of the ratio of capacity (C) to load (L), i.e.:

$$SF = C/L$$

The likelihood of failure can then be written as:

$$\text{Likelihood of failure} = \text{Probability } (SF<1) = \text{Probability } (C\text{-}L< 0)$$

In other words, the asset fails when the load exceeds its capacity, which implies that the factor of safety is less than unity (i.e. $SF<1$). The expression $C\text{-}L<0$ is a form of function referred to as a 'limit state function' [e.g. 15, 16, 17]. In terms of remaining asset life, as a limit state function approaches zero (which is equivalent to the safety factor approaching 1), an asset can be considered to be approaching failure, and this in turn could be taken as an indication that the asset is approaching the end of its life. A safety factor less than 1 implies the asset is in an unacceptable state. By implication, and depending on the measure of load used (e.g. peak or average load), the asset has either failed or the probability of failure is unacceptably high. In reality, final failure is often associated with a particular over-loading event, and failure probability can be considered in terms of the probability of the overloading event occurring.

Consequence side of risk

By definition, the likelihood of failure dictates how probable it is that an asset will fail, or how often the asset fails. The other aspect of risk is the analysis of failure consequence. From the perspective of service provision, important aspects of this analysis include:

- Tangible and intangible consequences of asset and service failure.
- The extent of impacts (for example, number of customers effected).
- The severity (whether service loss is total or partial).
- The duration of service disruption (how long customers feel the impact).
- Table 1 categorizes important aspects of failure consequences in more detail.

Many of the consequences given in Table 1 are, or can be considered to be, a financial cost. Some of these costs are tangible in that they have a market value and can be easily expressed in financial terms, while others are intangible. Intangible costs do not have a market value and / or are associated with less tangible aspects of failure such as image loss, social impacts and environmental damage, etc. [18]. While intangible costs do not have an explicit market value, it can still be possible to attribute a monetary value to them [e.g. 19, 20].

Linking risk to remaining life concepts

As shown above, the likelihood side of risk can be expressed either as the probability of an event occurring or the frequency with which the event occurs (or is expected to occur). Using frequency as a measure of likelihood leads to a useful conceptualization of risk. If frequency is expressed in units of 'per annum' and consequence in dollar terms, then the expected cost of risk is given in units of \$/yr and can be considered in the same way as any other annualized cost. In particular, the expected cost of risk can be used in cost-benefit analysis of different asset management strategies. The expected cost of risk can be referred to as 'risk cost'. For example, the International Infrastructure Manual [7] defines a 'risk cost' as the assessed annual cost to the consequence of a [risk] event; risk cost being equal to the costs relating to the event multiplied by the likelihood of the event occurring (as per the definition of risk given above).

Since risk can be considered in dollar terms and therefore treated as an annualized cost in the same way as other capital and operational expenditure items, analysis can be undertaken to determine when an asset will reach the end of its life, i.e. to assess when it is more economic to renew an asset in some way. This presupposes an ability to predict the time-dependent deterioration and failure of an asset, and to quantify the consequences that are incurred upon failure – in other words, to calculate the time-dependent risk [21]. It may, however, be more practical to attempt to maximize the likelihood of successful future performance at reasonable cost, rather than minimize costs explicitly [22].

Whether implicitly or explicitly, decisions concerning the retention or replacement of an asset involve consideration of the costs and the benefits associated with each available option. From this perspective, the aim of a successful asset management methodology is to achieve an optimal (or at least acceptable) balance between intervention costs (including inspection, analysis and replacement), the cost of asset maintenance and operation, and the benefits accrued by different intervention strategies. In terms of the taxonomy presented above, this reduces to an attempt to determine the end of asset economic life. In practice, a systems view of service provision must be taken in this analysis.

Since for many infrastructure assets the service provided must be maintained into the future, the benefits associated with service provision (including the revenue generated) are often approximately the same for the old and new asset. However, replacing an asset can accrue additional benefits associated with avoidance of future asset and service failures. This concept is illustrated in Figure 2, which shows a timeline from the current time (τ) to some future time (TMAX) when the asset would be considered derelict and have to be replaced (i.e. end of physical life is reached at TMAX). At any time between these extremes, the asset could be replaced through a scheduled intervention. As shown, replacing an asset at any time later than τ implies that the risk-costs associated with potential failures (the star shapes in Figure 2) would be incurred up until the time of replacement (time t). In contrast, replacing the asset earlier than TMAX means that risk-costs associated with potential failures occurring after the time of replacement will be avoided. These avoided risk-costs can be considered benefits of replacement. As shown by Davis & Marlow [23], such concepts can be used to calculate the most economic time for scheduling an intervention.

Assessing and modelling remaining asset life

Assessment of remaining asset life

As well as addressing the conceptual aspects of remaining life, the researchers also reviewed the different ways in which remaining life of wastewater assets can be assessed using data related to the current state of an asset (see the WERF report for details [10]). While considered overly simplistic, one approach is to use the age of the asset in combination with an estimate of the expected service life. For example, if the age of an asset is known and its expected service life is relatively well defined, then the remaining asset life can be calculated simply by determining the difference between these two figures; that is:

Remaining asset life = (Expected service life) – (Asset current age)

Alternatively, since an asset passes through a range of condition and / or performance states as it deteriorates, condition and performance assessments can be used to understand remaining asset life. In particular, acceptable asset condition states can be defined that characterize the threshold above which risk is deemed to be unacceptable. Condition assessment can then be used to determine whether the current state of an asset is acceptable. An engineer or maintenance practitioner with an appropriate level of knowledge and experience can often make a fair assessment of whether an asset is in an acceptable state. It is also possible for the assessor to estimate remaining service life directly from information on asset condition, when the assessor has knowledge of the asset age and how the asset deteriorates over time.

However, such estimates are only subjective. To provide more consistency, there is a need for standard guidance on what constitutes a significant defect for a range of asset types in a range of operational contexts and / or standard methods for utilizing expert opinion. Condition and performance grading approaches have been developed to facilitate this process. For a broad range of assets, it is also possible to specify a critical defect size that represents the limit of acceptable condition. The issue of determining acceptable asset state is then reduced to the need to assess whether such critical defects exist, or to make an assessment of the time until such defects would be expected.

Since asset condition and performance-failure can be considered as a 'cause' and 'effect' respectively, ongoing assessment of asset performance with respect to acceptability thresholds provides another means of determining if an asset is in an acceptable state. Performance monitoring also provides a measure of the impact of asset deterioration, and thus helps to determine the need for maintenance and / or replacement.

Modelling of remaining asset life

Given the asset intensive nature of the sector, effective strategic and tactical planning requires a capacity not only to assess the remaining life of an asset or group of assets, but also to predict when assets will reach the end of their life. To set the scene for future research, a state of the art review of modelling techniques was therefore undertaken to illustrate the various techniques that can be used to predict remaining asset life.

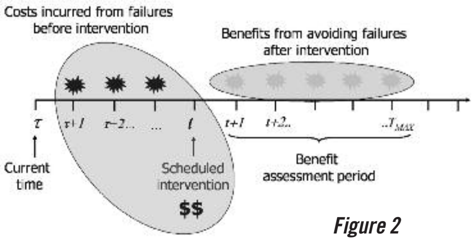

Figure 2
Illustration of intervention costs and benefits [23]

Various modelling methodologies were described in terms of the theoretical background, practical considerations and examples of application. Presenting these details is beyond the scope of this paper, and the interested reader is again referred to the WERF research report and references therein [10]. It is, however, considered worthwhile to provide a summary of the modelling techniques reviewed, which were broadly grouped into:

- Deterministic models: where relationships between external factors and asset performance are assumed to be certain.
- Statistical models: based on analysis of historical failure rate or service lifetime and other data.
- Physical probabilistic models: based on an understanding of the physical processes that lead to asset failure while accounting for realistic uncertainty.
- Soft computing (artificial intelligence) models: model structure is determined by the data and no prior relationships are assumed.

Deterministic type models are relatively simple to develop and apply. However, they usually rely on a number of simplifying assumptions. Furthermore, deterministic models do not account for the uncertainty that is associated with asset deterioration and failure. In contrast, statistical models attempt to capture this inherent uncertainty and use historical data describing failure rates or service lifetimes in asset cohorts. Statistical models work for assets where historical data is readily available for analysis. Bayesian analysis is a robust way of supplementing historical data with beliefs (or opinions) concerning asset failure rates or lifetimes, which are based on engineering knowledge or related observations.

Physical probabilistic models are useful in those cases where no historical data is available. They are underpinned by a robust understanding of the degradation and failure processes that occur for an asset in service (i.e. corrosion, fracture etc.). However, they also attempt to account for realistic uncertainty by using appropriate probability distributions for model variables. However, they can be data intensive and, in the event that insufficient data exists to describe model variables adequately, simplifying assumptions are required.

Soft-computing or artificial intelligence-based approaches are data-driven rather than model driven. Artificial Neural Networks (ANNs) predict output from input information in a manner that simulates the operation of the human central nervous system. ANNs consist of layers of nodes that provide a functional relationship between input information and predicted output. They are trained on historical data sets, which demonstrate the actual relationship between input and output information, followed by testing on independent data. While the use of ANNs to solve complex problems is increasing, they are also often considered as 'black box' solutions. Data pre-processing, methods for determining adequate model inputs and the internal workings of ANNs are seldom considered during their application. Ideally, both expertise concerning the problem at hand, and background knowledge in ANN development should be a pre-requisite for use.

Fuzzy logic-based approaches are able to incorporate engineering judgment and experience in the model development process. Specifically, they are proposed to be well-suited to infrastructure problems in which data are scarce and cause-effect knowledge is imprecise. Observations and model criteria are based on vague (linguistic) terms such as 'poor', 'average' 'good' condition etc. Fuzzy logic-based techniques allow the propagation of these attributes through a model, therefore yielding realistic results. As part of the artificial intelligence / soft computing modeling category, fuzzy logic-based approaches also risk being treated as 'black-box' solutions. Without a thorough grounding in the background fuzzy set theory, models can be developed that are unrealistic.

Technique application as a function of asset management capacity

It is interesting to consider how a water authority might develop its approaches to the analysis of remaining asset life as it develops its asset management capacity. While this can be anticipated to be a path dependent process to a degree, it is still informative to illustrate conceptually how this development might occur. To this end, Table 2 details a view of asset management development, along with the approaches to assessment and analysis of remaining life that could be used at each stage. For example, as can be seen from Table 2, it is assumed that a more sophisticated approach to asset management gives rise to more data availability, and consequently the possibility of more approaches to modelling remaining asset life.

It should be noted that the level of asset management sophistication attained does not necessarily relate to the size of company, since relatively small companies can develop sophisticated approaches for some asset classes. In fact, the level of sophistication that adds value to a particular water authority will depend on the nature of its asset stock, its business environment (in particular, the requirements of stakeholders), resource constraints and technical capacity. For example, the research team has previously worked with a company that operates an extensive pipe network but only one treatment plant. This company had a relatively sophisticated approach to the management of its pipe network, but a relatively unsophisticated approach to its management of treatment assets, since this was all that was considered necessary to meet its asset management needs. Interestingly, a change in requirements from a regulator eventually drove the company in question to adopt a more sophisticated approach to management of its treatment assets.

It is also noteworthy that water authorities need to focus on the stages of asset management that are most relevant to their business. For example, companies with relatively new and still expanding asset stocks (e.g. due to new developments) need to develop good practice in the early life cycle stages of asset management, whereas those that are managing ageing asset stocks need to focus more on rehabilitation planning and delivery. The latter would require more sophistication in the evaluation and prediction of remaining asset life than the former.

Conclusion

This paper has presented initial findings from Track 4 of WERF's 'Strategic Asset Management Communication and Implementation' research programme. The initial research effort within Track 4 had the goal of conceptually mapping the broad range of factors that influence remaining asset life, as well as providing a state of the art review of the science and practice of 'end of life' assessment and prediction. This paper summarizes initial findings in relation to the concept of remaining asset life, the importance of risk concepts and the range of modelling and assessment approaches that can be used.

While the reported findings represent a starting point, numerous areas for further research and development were identified during the review stage of the project. For example, there remains a need for industry standardization of terms and definitions, as well as a way to determine how to account for obsolescence in the consideration of remaining life. The use of risk-based techniques also needs further development, including the collection of life cycle cost data, the specification of analysis approaches for a range of asset classes, and dealing with associated uncertainty in decision-making. In particular, there is a need for guidelines and standardization on the treatment of external costs and externalities in asset management decision-making, including methods to place a monetary value on these costs [e.g. 20].

From the perspective of operational procedures such as condition assessment and monitoring, there is a need to develop standard guidance on what constitutes a significant defect for a range of asset types in a range of operational contexts, as well as development of protocols for quickly 'screening' equipment or structures to identify those that are approaching the end of their life. Since much data collected in relation to this is qualitative, subjective or descriptive, protocols are also needed to help ensure consistent assessments are made that are free of bias. To this end, common condition, performance and risk grading procedures and specifications would be useful, especially if they were developed across the sector and applied consistently over time.

Recommendations related to modelling of remaining asset life reflected the need to develop protocols that align the different available techniques to different asset types and scenarios. In particular:

- There needs to be more emphasis placed on identifying the optimum data requirements for model calibration as they relate to statistical models.
- For physical probabilistic models, there is a need to link condition assessment processes to the modelling technique for all pipe materials, as well as for the development of protocols and tools to aid model use.
- There should also be further exploration of the use of soft-computing / artificial intelligence-based approaches for asset life time prediction, as they appear to fill some gaps left by other approaches, especially for more subjective data.
- Methods to incorporate useful, and readily available engineering expertise into the model development should be pursued.
- Comparative benchmarking of available modeling approaches is also desirable.

The progression of asset management development presented in this paper provides one view of how water authorities could align the use of different tools and techniques with their level asset management sophistication. With this model in mind, a key requirement in terms of the overall WERF research programme is to provide water authorities with guidance on how to identify and attain an appropriate level of asset management sophistication in light of their business environment and operational constraints. A key recommendation in this regard is to produce a practitioner's guide to economic decision methodology and illustrate the practical application of different tools to meet specific asset management processes. This has been proposed as the area of research for Track 4 in the remainder of the research programme. ●

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**Paper presented at LESAM 2009 –
3rd IWA Leading-Edge Conference on
Strategic Asset Management**

Optimal asset management planning: advances in water mains and sewers analysis within a new modelling environment

A state-of-the-art integrated asset management planning modelling environment, known as PIONEER, has been implemented within the UK's United Utilities, covering all above and below ground assets. The system, developed by Tynemarch, operates on the United Utilities intranet. An advanced suite of models allows the user to forecast customer service measures and costs, as well as producing an optimal set of investments that achieve the specified service objectives at least cost. In this paper, Jeremy Lumbers, Tony Conway, Tim Fynn and George Heywood outline the key functionality of PIONEER and the water distribution and sewerage models included.

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The UK water industry has adopted a forward-looking risk-based approach to assessing the requirements for capital maintenance expenditure, known as the Common Framework for Capital Maintenance Planning (CMPCF) or 'Common Framework' (UKWIR, 2002). The development of the CMPCF was prompted by a general agreement by both the water companies and regulatory bodies that there was a need to improve the basis for estimating the expenditure required for asset maintenance as a component of the regular price review process.

The Common Framework is based on the analysis of risk (specifically the probability and consequences of asset failure to customers and the environment) and encompasses an economic approach that allows the trade-off between capital and operational cost options to be considered, i.e. whole-life costing. The Common Framework builds on the economic regulator Ofwat requirements for economic levels of capital maintenance to be demonstrated as outlined in MD161, Maintaining Serviceability to Customers (Ofwat, 2000). The Common Framework approach enables capital maintenance requirements to be identified with due regard to the costs associated with asset failure and (where appropriate) the value placed by customers on service improvements.

A number of key concepts form the basis of the CMPCF. Firstly, capital maintenance should normally be justified on the basis of current and forecast probability and consequences of asset failure, with and without interventions. The consequences of failure include the direct and / or indirect impact on the level of service to customers and the environment, as well as costs to the water undertaking. Where appropriate, the CMPCF requires an evaluation of the trade-offs

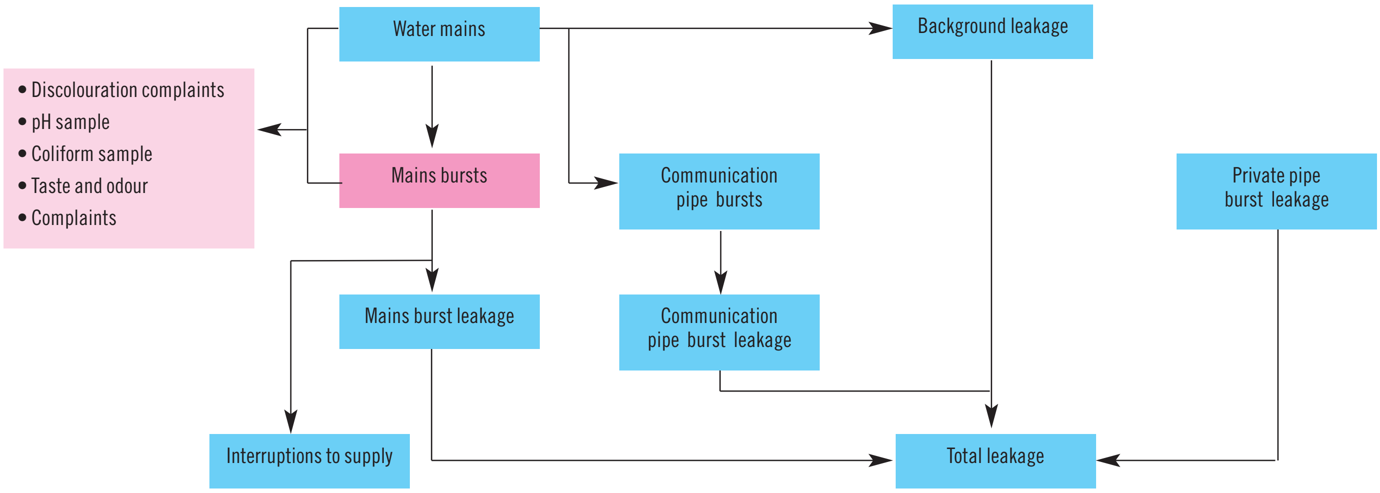


Figure 1 Integrated approach to water distribution mains analysis

between operating costs and capital costs so that the optimal balance can be determined. The analysis should recognise the integrated nature of both the water and wastewater systems.

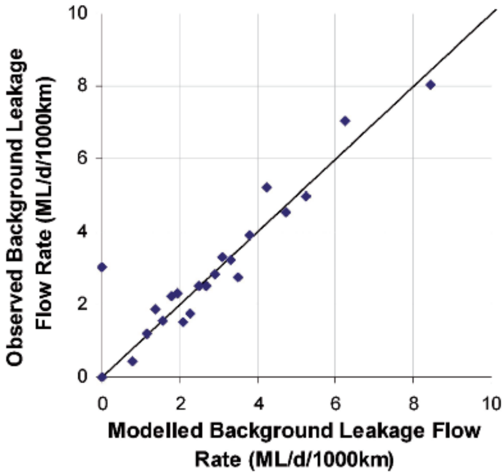


Figure 2 Observed versus predicted background leakage

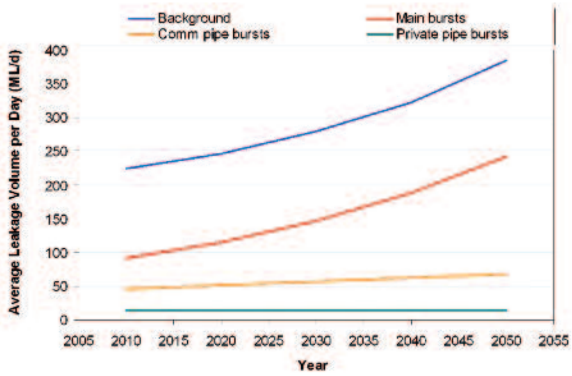
Serviceability indicators, which define the expected levels of customer service and in some cases specific asset performance, are used by the regulators to assess the justification for investment and the outcomes of investments (known as 'interventions').

Serviceability indicators may be environmental, such as pollution, or service, such as poor water taste and odour, or asset performance, such as pipe bursts. Social and environmental costs are included in the cost-benefit analysis.

The Common Framework was fully endorsed by Ofwat and the recommendations of an assessment of its use in the 2004 Price Review were included in subsequent regulatory guidance – MD212, Asset Management Planning To Maintain Serviceability (Ofwat, 2006) and the 2009 Price Review Information Requirements (Ofwat, 2008).

To support the Common Framework adoption within United Utilities, an integrated asset management planning modelling environment, known as PIONEER, has been implemented, covering all above and below ground assets. The system, developed by Tynemarch, operates on the United Utilities intranet and is accessed via a web browser. An advanced suite of models is incorporated that forecast customer service measures and costs, as well as producing an optimal set of interventions that achieve the specified levels of service objectives at least cost.

Figure 3 Forecast interruptions with and without selected interventions



Key functionality

The principal components of PIONEER are as follows. An asset data store that provides a repository for data from a number of sources for use in serviceability forecasts and optimisations, and a serviceability and cost forecaster, which stores models for estimating future values of serviceability indicators and costs, with and without interventions. The user is able to configure intervention options to be considered for specific assets, as well as the models to be used to estimate their costs and benefits. An advanced optimiser is an integral component and is used to select the interventions required to meet a user-defined planning objective. The system includes job scheduling facilities for the user to set up and run a series of forecasts and optimisations.

The analysis is based on the principle that future serviceability indicators are related to the likelihood of assets to fail and the extent to which they are improved through capital maintenance. The manner in which an asset can fail and the characteristics of the failure are known in the system as a failure mode.

Failure modes have associated serviceability consequences and costs. Failure modes have a user-defined likelihood of occurrence and a set of consequences. These are combined in the analysis to produce a measure of risk for each serviceability indicator for each failure mode applied to each relevant unit. Although not a requirement, failure occurrence likelihood is often age-related so that likelihood of failure increases over time without other intervention.

A wide variety of model types can be created in the system including: calculation trees; decision trees; external function; look-up tables; user tabulated likelihoods and distributions.

Water distribution systems analysis

The water mains analysis integrated a number of sub-models covering forecasting of bursts, interruptions to supply, leakage, discolouration and water quality. The links between the network performance measures are illustrated in Figure 1.

The burst forecasting sub-model was an enhancement of that developed through a UK-wide National Mains Deterioration Modelling project funded by UKWIR (2005).

The data used to identify and calibrate the sub-models included mains attribute data such as age, material, diameter, length, hydraulic characteristics, connectivity, connection density and network configuration. Environmental data used included soil corrosivity, soil fracture potential, temperature variations, water pH, socio-economic data and surface use. The integration of leakage with other measures of service is an important development that explicitly takes into account the over-lapping benefits of interventions.

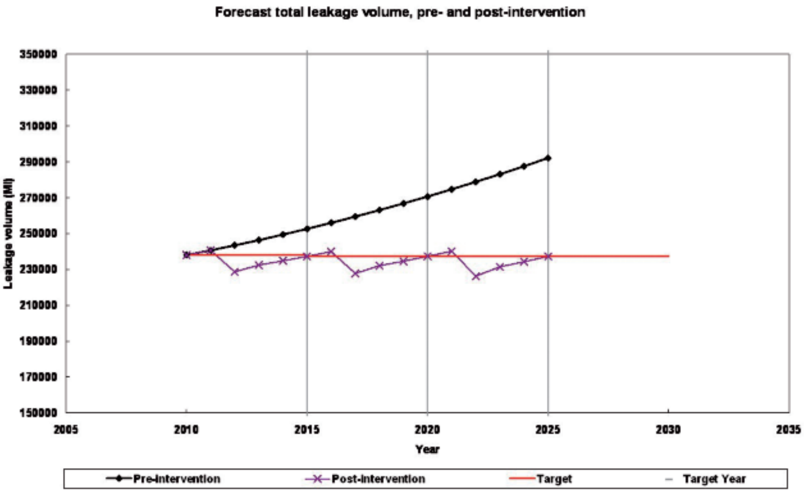


Figure 4
Forecasts of total leakage with and without interventions

Service areas modelled

The service areas selected for consideration were as follows:

- Bursts – as defined for Ofwat June return reporting.
- Interruptions to supply in each of the DG3 duration bands.
- Leakage – including burst-related leakage and background leakage within the distribution system, from both mains and services.

The models were identified from data on the mains attributes, failure records, operating environment and service history burst records, dated and geo-referenced to allow environmental variables (such as weather conditions and soil types) to be taken into account. Leakage data, recorded in the form of net night flow for each district metered area (DMA) was used with average customer allowances and hour to day factors to calculate average night flow loss values for each DMA. Supply interruptions records linked to address, including the duration of the interruption and the dates over which it occurred was taken into account, together with the recorded reason for the interruption (e.g. mains failure, maintenance, third party). Data on communication pipe (CP) repairs was used with recorded dates of the repair and a geographical reference as per mains bursts. Repairs to leaking supply pipes, meters and stop taps were recorded as per communication pipes. The annual numbers of supply pipe, stop tap and meter repairs carried out in each DMA were used in leakage modelling.

Model form

The models are in a general multiplicative form given below, which is the product of a series of individual functions, one for each explanatory factor. This was one of the best performing model forms for burst rate models in the National Deterioration Models project (UKWIR, 2005) and has been found to perform well for a range of model types. The failure rate *F(t)* is given by:

$$F(t) = C_0 \cdot f(\mathrm{A}) \cdot f(\mathrm{B}) \cdot \ldots \cdot C_1 \cdot C_2 \cdot \ldots$$

where *f*(A), *f*(B),… are individual functions for continuous variables such as age, diameter etc. The parameters C_1, C_2,… are included to take advantage of categorical variables such as pipe material, surface type etc. C_0 is a model-dependent constant. The individual functions, with the exception of weather, are in a common form as below. With careful choice of coefficients, the function can fit either linear, power, exponential or more complex non-monotonic curves.

$$f(\mathrm{var}) = \mathrm{Max}(1 + A_{\mathrm{var}} \cdot \mathrm{Exp}(B_{\mathrm{var}} \cdot \mathrm{Var}) + K_{\mathrm{var}} \cdot \mathrm{Var}^{N_{\mathrm{var}}}\ ,\ 0)$$

The weather function used in the burst rate model is in a simplified linear form as below, with the benefit that the monthly models can be used with an annual weather index for future forecasting.

$$f(\mathrm{weather}) = \mathrm{Max}(1 + K_{\mathrm{AF}} \cdot \mathrm{AF} + K_{\mathrm{R}} \cdot \mathrm{R} + K_{\mathrm{SMD}} \cdot \mathrm{SMD}\ ,\ 0)$$

AF, R and SMD are the monthly days of air frost, monthly rainfall and monthly mean of soil moisture deficit respectively.

Significance tests were carried out on all explanatory factors for each sub-model using Wald and p-value statistics for each factor.

The burst models assume that the observations (bursts) follow a Poisson distribution and were calibrated using the maximum likelihood estimation (MLE) approach. This involves finding the combination of model parameters that maximises the probability of observing a set of historical records identical to that used for model calibration. For other models, a normal distribution was assumed, and least-squares methods were applied. Where sufficient data were available (i.e. where material groups had a sufficient length of mains and total number of historical bursts), the burst model was calibrated using half of the mains in that group, randomly selected to avoid bias. The model was then applied to the remainder of the data set, and the results compared with historical burst records for these mains. Figure 2 shows a comparison between the observed and the predicted background leakage.

Intervention options

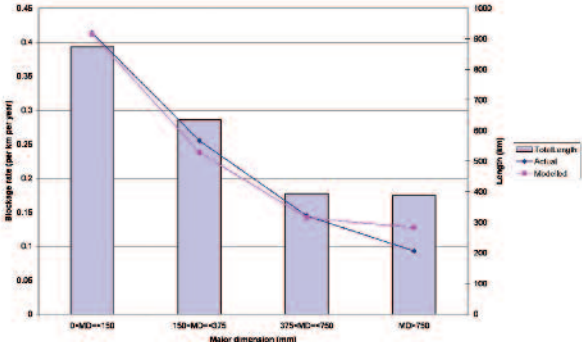
The intervention options considered were mains renewal and mains renewal combined with communication pipe renewal. Interventions can also be linked to material, for example the inclusion of communication pipe renewal in the second intervention type may be defined as being dependent upon the communication pipe material. The renewal materials applied were polyethylene for mains with a diameter up to and including 300mm, and ductile iron for larger mains.

Results

The optimiser selects the least whole-life cost set of pipe-level interventions required to maintain target levels of serviceability over a defined horizon, taking into account the costs of failure (repairs, complaint handling, customer compensation). Cost benefit optimisation can also be undertaken using the results of surveys indicating customer willingness to pay for service improvements.

Forecasts of average leakage volumes

Figure 5
Blockage rate versus major pipe dimension



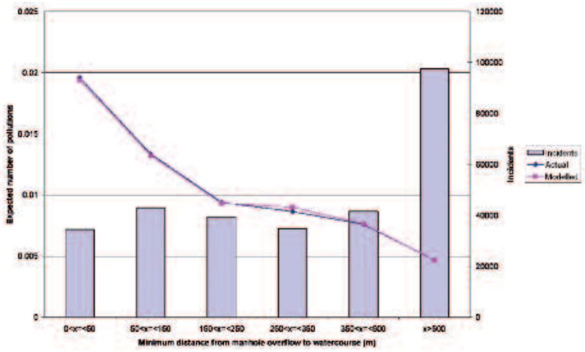


Figure 6
Probability of pollution given a blockage by minimum distance from manhole to watercourse

per day associated with different categories of mains and pipes are shown in Figure 3. Figure 4 shows the forecast of total leakage with and without optimal interventions.

Sewerage systems analysis

Models of sewer condition deterioration, collapse rate, blockage rate and flooding and pollution consequences have been developed. The models were identified from data and validated against a separate data set. The data used included: defect data obtained from CCTV surveys; sewer attribute data such as estimated age, material, depth, hydraulic characteristics, connectivity, type and manhole locations; digital terrain data to calculate overland flow distance to assess pollution and flooding risk; historical maps to estimate age of sewers where unknown; environmental data such as soil type, depth and surface type; socio-economic data including housing type, income and occupancy; and hydraulic model outputs.

Deterioration models have been derived from detailed sewer defect data from CCTV surveys, utilising both the density and severity of defects recorded. The deterioration modelling has made use of improved estimates of the dates at which sewers were laid, based on a unique approach to the automated analysis of historical maps.

All models have been developed using data recorded at the pipe level, and may be applied to individual pipes or to cohort groups of sewers as required.

The digital terrain, address point and watercourse data were used to derive several attributes of potential use in estimating the consequences of a failure. For each pipe, the upstream manhole that would flood in the event of a failure was found from consideration of static hydraulics. Manhole overflows were then simulated and a simple overland flow routing algorithm was used to trace the route of the flow. The algorithm followed the steepest downhill slope between grid points until a flat or sunken area was reached. Various attributes were then calculated including: flow distance – the longest path of the overflow from the manhole before a flat or sunken area is reached (to a maximum of 500m from the manhole); the minimum distance of flow to property – the minimum distance between the path of the overflow and any property; the minimum distance of pool to property; and the minimum distance of flow to watercourse or pond.

These attributes were made available for inclusion in the models.

Model form

The approach for the estimation of failure rates is as follows. For each attribute, pipes were divided into groups based on the value of the attribute. The mean failure rates or consequence probabilities and 95% confidence intervals around the mean were calculated. The difference between the highest lower confidence interval boundary and the lowest upper confidence interval boundary was then calculated for each attribute. This gave an indication of the spread of the mean failure rates or consequence probabilities for each attribute. The attribute with the largest spread was identified.

The means and confidence intervals for the values of the selected attribute were then examined. Groups with similar mean values were merged. Groups were defined as having similar mean failure rates if the 95% confidence intervals around the means overlapped.

Constraints were placed on the minimum total length of pipe and the minimum number of incidents within each group. Groups not conforming to these rules were merged as appropriate. If, after merging, the mean failure rates of all groups were similar (i.e. the confidence intervals overlapped), the attribute was discarded and the one with the next largest spread was examined.

Two condition indices are used. One index characterises condition in relation to the estimation of collapse rate (the collapse-related condition index, or 'collapse index'), the other characterises condition in relation to the estimation of blockage rate (the blockage-related condition index, or 'blockage index'). The indices comprise linear weighted combinations of defect densities and severities.

During model calibration, the defect types and weightings are identified to maximise the usefulness of each index in estimating failure rates. As different defect types are significant with regard to the collapse and blockage failure modes, one index characterises condition in relation to the estimation of collapse rate (the collapse-related condition index); the other characterises condition in relation to the estimation of blockage rate (the blockage-related condition index).

Intervention options

The interventions considered in the optimisation included:

- Structural rehabilitation: cured in place pipe, cured in place patch, dig-down repair and whole pipe replacement
- Major cleansing including jetting and root cutting

Results

A comparison of modelling and predicted blockage for pipes for different diameters is shown in Figure 5. The importance of proximity to watercourses regarding the potential for causing pollution incidents is shown in Figure 6, which compares the modelled versus the observed.

Conclusions

A modelling environment has been developed and implemented that allows a wide variety of model types to be included in an integrated analysis across different asset types, above and below ground. The below ground asset models included were identified from data and apply at the pipe level. Multiple customer service and asset performance measures can be considered simultaneously to enable an optimal set of interventions to be determined. For example, the integration of leakage with other measures of service explicitly takes into account the over-lapping benefits of interventions.

The results of the models have been used for strategic asset management planning and as an input to short-term investment prioritisation. The modelling environment, PIONEER, is live on the United Utilities intranet and has become part of the company's routine asset management processes. ●

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Visualization and analysis of medical ultrasound processing applied to Ground Penetrating Radar

Ground Penetrating Radar (GPR) is used in asset management to survey the state of buried pipelines, but analysis of the resulting radargrams can be difficult, subjective and time consuming. Thomas Deserno, Karsten Müller, Markus Reiss, Gael Pentang, Daniela Hofmann and Jürgen Niessen in this paper discuss the application of medical ultrasound processing techniques to GPR data in order to make the evaluation of radargrams faster and more accurate.

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Ground Penetrating Radar (GPR) is a technique for non-destructive detection and illustration of buried objects and cavities as well as soil layers and water table. GPR is based on actively emitting electromagnetic waves in a medium, usually in form of impulses. Along its path, the radar signal is scattered, reflected and diffracted at discontinuities, as well as attenuated through absorption. The running time of the signal is a measure for the spatial depth of objects. The reflection data is registered and edited to form a so-called radargram.

The major problem facing the GPR technique is the difficulty associated with the visualization and interpretation of the radargrams. Currently, this is still done manually and, therefore, is subjective and time consuming. Available software packages support only basic manipulation of the image data, which includes background removal, noise filters, and edge enhancement. The interpretation of a radargram is difficult and requires an expert's experience (see Figure 1). Therefore, improving the processing of GPR data is still a major field of research. Contrarily, medical three-dimensional (3D) ultrasound is likewise based on reflection signals, but automated analysis, visualization, segmentation and interpretation of such data has already been well established. Figure 2 exemplifies the developments that have been achieved in medical applications.

In this paper, we aim at interfacing GPR data to medical ultrasound and applying medical image visualization and processing techniques to GPR data for improved asset management (Figure 3). This paper introduces a converter software that aims to interface medical ultrasound with GPR data, allowing the application of medical image visualization and processing techniques to GPR data. From the GPR radargrams stored in DZT format, corresponding ultrasound files conformant with the Digital Imaging and Communications in Medicine (DICOM) standard are generated and rendered into volumes with ImageJ and the Medical Imaging and Interaction Toolkit (MITK).

As a result, hybrid visualization is obtained where direct volume rendering is combined with model-based surface reconstruction of cylindrical pipes, pipe systems, cavities, and other basic structures. Furthermore, the interface allows the application of medical image processing and analysis to GRP data.

Ground Penetrating Radar (GPR)

GPR is based on actively emitting electromagnetic waves in a medium, mostly in the form of impulses with dominant frequencies in the range of approximately 20 MHz to 2 GHz. The frequencies used for investigating the subsoil are between 400 and 1000 MHz.

Along its path, the radar signal is scattered, reflected and diffracted at discontinuities, as well as attenuated through absorption. The dielectricity constant $\varepsilon = \varepsilon 0 \star \varepsilon r$ is the relevant physical magnitude. Since ground material components are not uniform, εr is continuously subject to fluctuations. Decisive for a reflection is a transition from one medium with a low εr into one with a high εr or vice-versa. As a result, the dielectric conditions in the ground are imaged. During the propagation in the medium, the signal experiences a material-dependent attenuation. The higher the conductivity σ, the lower the penetration depth. Since conductivity is dependent upon frequency, the penetration is depth attainable. The running time of the signal is a measure for the positional depth of objects [1]. The reflection data is registered and edited to form a radargram (Figure 4) [2].

The soil consists of different materials, which form a layer of different dielectricity. Radar waves emitting from the transmitter are partly transmitted and reflected, and from the runtime of the signal, spatial position is computed. Foundations, pipes, water, and other embossed structures result in full reflection, which is clearly observed in the radargram by its sinusoid pattern.

Objects in the underground can be detected with this method regardless of their material, provided that the contrast of dielectrical constants of the discovered structure and the surrounding material is sufficiently high. The lateral position of any object can be determined, usually with the help of radargrams, with an accuracy of 10cm. The error in depth determination is within 5% to 10% [2]. Considering a mostly homogeneous soil, anomalies of existing cavities or dispersions in the soil can be derived directly from the results of GPR measurements [4].

Because GPR data interpretation needs co-location with external information like geologic data, geo-referencing has been established [5]. Using a GPS (Global Positioning System) (Figure 5) GPR data is arranged in a geospatial coordinate system.

The result of geo-referencing is visualized in Figure 6. From a large field, several scans have been obtained, which may partly overlap and usually incompletely represent the areal. Using Georail-Sprinter, each scan is composed of 14 measurements per row. After geo-referencing, the individual scans can be combined to represent a larger volume of ground surface.

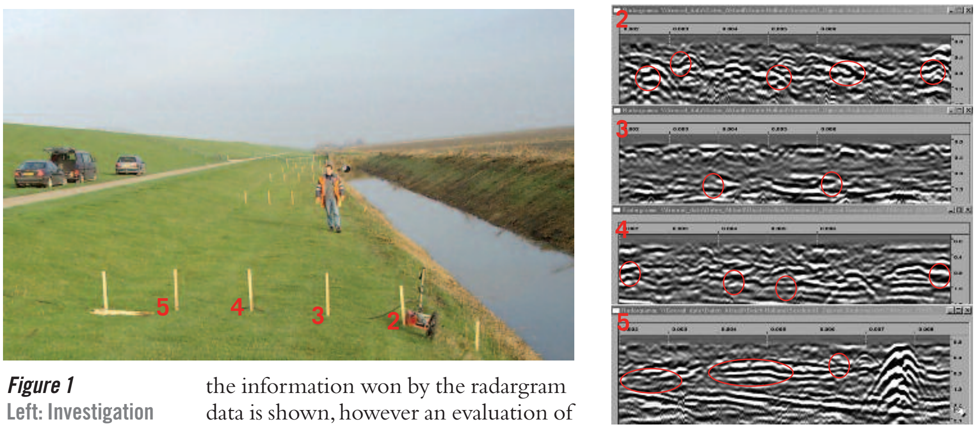


Figure 1
Left: Investigation of embankment with GPR.
Right: Resulting radargrams with cavity signatures from muskrats highlighted.

Visualization of GPR data

Currently, a small number of visualization techniques are available to display GPR data. In the following, these techniques are briefly reviewed.

2D standard data visualization

The easiest way of showing a radargram to the inspector is directly displaying the raw data. Each scan of each antenna is shown individually, and pseudo-colouring is usually applied to support manual interpretation and analysis. In addition, artifacts and noise may be removed automatically or semi-automatically by digital filtering of the raw data. In the radargram, suspicious signatures manually are marked and commented by the user. For example, Figure 7 shows a radargram with three manual annotations indicating soil infiltration of water from a crossing pipe, loose soil, and a crossing line without any finding for annotations A, B, and C, respectively.

Figure 2
Medical ultrasound. A 3D surface extraction allows applying rendering techniques

3D geo-referenced data visualization

The individual scans of each antenna array can be combined using the geo-references from the GPS signal. A 3D radargram is formed, and usually displayed again using pseudo-colouring. The 3D visualization software supports browsing individual slices, and – beside filtering and noise removal – thresholding can be applied to extract structures of high signal amplitude (Figure 8).

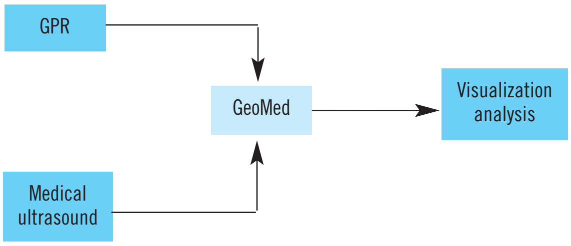
Despite its high resolution and that the complex 3D information is visualized at a glance, this display option has disadvantages as well. Only the information won by the radargram data is shown, however an evaluation of the signatures on the radargram is difficult. For instance, an evaluation of a radargram from an investigation of three conduits where metal plats, breakdown bodies and tanks filled with air and water were inserted, does not give precise information about the structures. Manly because volume rendering techniques, as used in the medical area, have not yet been included.

2D geo-referenced model visuals

Visualization of models rather than raw or pre-processed radar data has also been suggested [5]. In contrast to 3D geo-referenced visualization, the GPR information is now used for co-location of structures into existing plans. In this way, an overview is quickly provided to the inspector using a well-known representational form (Figure 9).

Technically, the radargram data is transferred into a 2D geo-referenced representation and symbols, which are related to different structures of interest manually located in the radargram, and are overlaid or merged into existing plans. In Figure 9, for instance, circular objects are displayed to visualize suspicious structures from the GPR signal. This type of visualization is based on geographic information systems (GIS) and tools for computer-aided design (CAD) [6]. However, this feature of 2D models is also their drawback. For many applications, model visualization might be too abstract, because the information displayed no longer corresponds to the signal measured, since too many details are disregarded. In particular, the sinusoid reflection patterns are lost.

Figure 3
The GeoMed project aims at merging GPR data with medical ultrasound techniques for improved visualization and data analysis



Medical 3D data visualization and processing

A couple of commercial systems for developing medical image processing and visualization exist. However, we focus on packages in the public domain since these frameworks usually allow user specific extensions and adaption.

ImageJ

ImageJ is a Java-based image processing programme developed by Wayne Rasband at the National Institute of Mental Health (NIH) in the US [7]. It was designed with an open architecture that provides extensibility via a lot of powerful Java plug-ins and recordable macros. It is therefore completely platform independent and runs under Windows, Linux and MacOS [8]. Custom acquisition, analysis and processing plug-ins can be developed using ImageJ's built-in editor and a Java compiler. Together with user-written plug-ins, ImageJ makes it possible to solve standard and specific image processing and analysis problems, particularly in the medical domain. It can display, edit, analyse, process, save and print any common 8-bit, 16-bit and 32-bit image format, including digital imaging and communication in medicine (DICOM) files and raw data, as well as series of images. The latest version of ImageJ updates documentation test images and a growing collection of provided plug-ins can be downloaded from the ImageJ homepage [9]. The complete software source code is available online and details about its simple installation can be found in the ImageJ tutorial at the ImageJ homepage.

The programme can import 'stacks', e.g. a series of DICOM images of the same size and type in a folder, and display them in the same window [9]. The loaded stack can be rendered in a volume with the volume viewer plug-in. The object is displayed in a side window in three different views. Depending on the chosen view, a section plane can be selected and modified by shifting the object in the main window. The resulting representation can be rotated in all three dimensions and each layer can be shown according to the alignment of the sectional planes.

MITK

The Medical Imaging Interaction Toolkit (MITK) is a free C++ open source software system for development of interactive medical image processing software that can handle non-medical data as well [10]. It was originally developed as a common framework in the Division of Medical and Biological Informatics (MBI) at the German Cancer Research Centre (DKFZ).

MITK is a class library based on and extending the Insight Toolkit (ITK), that forms the algorithmic basis for data registration, interpolation and segmentation, and the Visualization Toolkit (VTK), providing powerful visualization capabilities. So, the main purposes of MITK are to reduce the effort required to construct specifically tailored, interactive applications for medical image analysis (segmentation, registration) and supporting easy combination of algorithms, which have been developed by ITK, with visualizations that have been created by VTK for the development of interactive medical imaging software [11, 12]. MITK is able to process different 2D and 3D data. Among these are DICOM files, point sets, sets of 2D slices, and surface files.

Re-using the design principles of ITK and VTK, MITK is an object-oriented, cross-platform library with classes that are derived from top level classes of ITK. It uses a data-centred approach in which the central elements representing the model are data objects and data trees. A data object represents and provides access to data. It can be created and updated by process objects connected together to a data processing pipeline. A data tree allows hierarchical organisation of multiple data objects. Objects within the data tree are created and updated by process objects. A pipeline may be constructed, automatically affecting all references to the constituents of the pipelines. Optionally, properties like colour, opacity, visibility, etc. can be added to data objects. These properties apply to all views of the data, rendered into different windows, by default, but may be changed for each view if required. For example, a data object may be visible in all but one view.

In particular, MITK allows joint visualization of 3D data, which is directly rendered, and data segments as well as artificial models, which are represented by their triangulated surface. Figure 10 exemplifies this type of combined visualization. Maximum intensity projection is used for volume rendering, and the orbital areas are displayed using surface rendering.

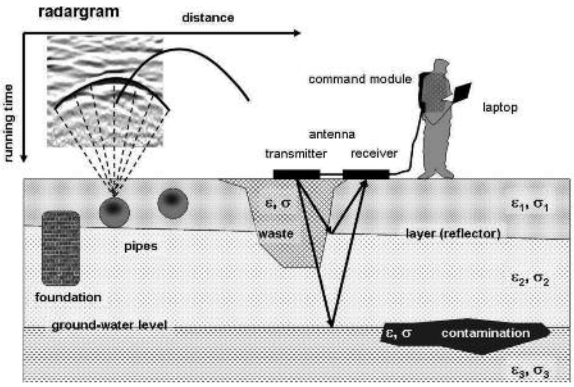


Figure 4
Measuring principle of GPR data [3]

GPR imaging and data handling

All measurements were done using the 'Georail Sprinter' device by GBM Wiebe Ltd. (see Figure 5), which is based on a TerraVision array of 14 bi-static 400 MHz turnstile dipole antennas (see Figure 6). They are installed in parallel on a trailer with a distance to the surface of 2-3cm. Due to the arrangement of the antennas, it is possible to detect objects like pipes in the ground. The array is about 2.2 m wide, so that a lane can be ascertained entirely at a single pass. GPS recording and geo-referencing of the radargrams is performed.

The database contained a total of 117 GPR files recorded in the German cities of Cologne, Detmold, Nuremberg, Otzenrath and Rosslau. These files resulted from road as well as from embankment inspection. Typical image resolutions are 14 x 512 x L, where L denotes the length of the measured section. In our data, L_{min} = 503 and L_{max} = 17,831.

All data is stored in DZT format containing all the 14 measurement profiles (so called passes). The DZT file format corresponds to the Radan format for geophysical survey system interface (GSSI). GSSI files have either a 512-byte (old style) or 1024-byte (current style) header [13], sequentially followed by the proper image data (Figure 11).

The header gives information about the data type used to code the image, the image identification, an offset that indicates where the pass data begins and the dimensions of each pass. In addition, important metadata on system characteristics, as well as GPS coordinates, can also be found in the header of the georadar file (Figure 12).

DICOM standard in medical imaging

DICOM is a common standard for exchanging medical image data and diagnostic information between image acquisition systems, such as x-ray, ultrasound, computed tomography (CT), magnetic resonance imaging (MRI), viewing stations, and the archive to form picture archiving and communication systems (PACS). For these purposes, DICOM defines:

- Objects such as images and all kind of meta data including patient, study, and pathology data,
- Syntax and semantic of commands needed for information transmission, and
- The protocols for transmission.

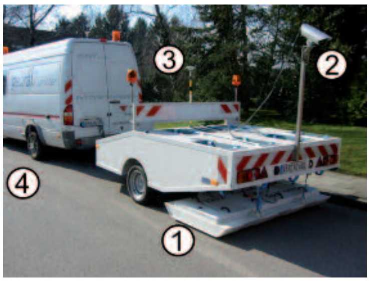
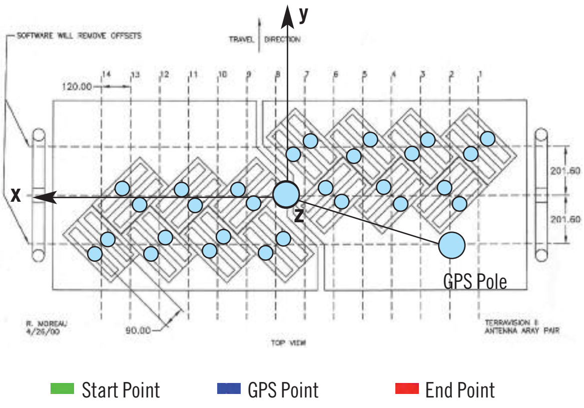
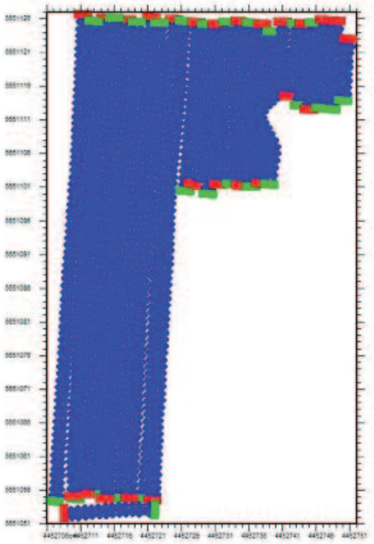


Figure 5
GPR Imaging Device (Georail Sprinter). The vehicle for road analysis consists of (1) an array of 14 radar antennas, (2) optical camera, (3) GPS module, and (4) distance measurement unit

The DICOM standard is based on a tag value representation. A tag uniquely labels an information element. The basic element (tag, value representation, value length, and value field) is called attribute. Many attributes form an information object. An information object is an abstraction of a real world entity (e.g., a CT image, a study, etc.) which is acted upon by one or more service classes and is member of

Figure 6
Left: Geometry of TerraVision antenna array and GPS pole. Right: Reconstructed acquisition field.





an information object class with a particular information object 0definition (IOD). A service class represents a structured description of services which are supported by cooperating DICOM application entities acting on a specific class of information objects. An important element within the DICOM object model is the service object pair (SOP) which combines an information object with an applicable service class (Figure 13). This is the fundamental unit, which allows interoperability with the DICOM standard.

A single DICOM file consists of an introductory header followed by a stream of DICOM object (Figure 14). The DICOM header includes a 128-bytes preamble and a 4-byte prefix 'DICM' directly followed by metafile information [14]. By this nature, DICOM is easily extensible, and can be adapted to future modalities that may be introduced in clinical use. In this case, several information objects may be re-used and referring to the attributes and the data dictionary defining almost 30 value representations, application specific information can be modelled, too [15]. However, to ensure interoperability, we are not aiming at defining new GPR information objects but use existing ultrasound objects to host the relevant meta information (see Figure 12).

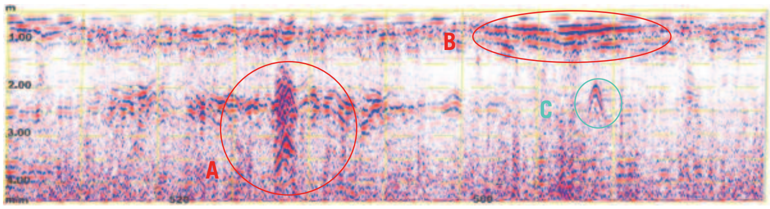
Data conversion

Data conversion is not implemented from scratch but refers to existing toolboxes. In particular, we use the DICOM toolkit and DICOM3Tools, which are briefly introduced before our conversion algorithm is presented.

The DICOM toolkit (DCMTK) was developed at the Research and Development Institute for Information Technology Tools and Systems in Oldenburg [16]. It implements a large part of the DICOM standard in C++ programming language. The toolkit is platform-independent and a variety of libraries and resulting programmes are freely available. It is continuously developed according to the DICOM standard and is used both for testing and commercial development.

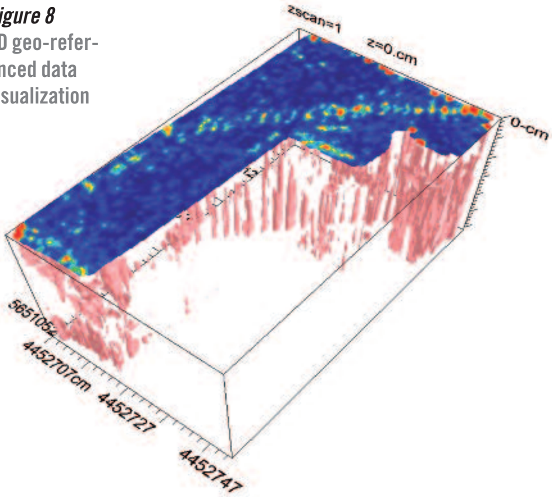
The official version of DCMTK includes modules for standard library functions (ofstd), network communication (dcmnet), worklist management (dcmwlm), images (dcmimage), JPEG compression (dcmjpeg), digital signatures (dcmsignl), data sets and files (dcmdata), simple image archives (dcmqrdb), image data (dcmimgle), presentation states (dcmpstat), secured transfer (dcmtls), and structured reporting (dcmsr).

Figure 7
2D standard data visualization (pseudo-coloured radargram with manual annotations)



The dcmdata module offers for example a class library for reading, processing and storing of DICOM files. These functions can read and write DICOM files in different transfer syntaxes and are relatively error-tolerant for false coded files. Additionally, a complete electronic DICOM data dictionary is available. Practical example applications include displaying a DICOM file in textual form on the console with dcmdump and creating a DICOMDIR index file for DICOM disc with dcmgpdir. DCMTK also contains the dcmodify function used in the programme to insert, modify and delete individual DICOM attributes. This function is globally installed and can be accessed from the command line with the corresponding parameters (day, optional: value, path to the DICOM file).

Figure 8
3D geo-referenced data visualization



The Dicom3Tools of David Clunie is an extension of the DCMTK package with practical examples and new functionalities. The rawtodc function included in the Dicom3Tools is used to convert RAW files into DICOM files. It requires as input parameters the RAW data, its height and width, the number of bits per pixel, the number of samples, and the photometric interpretation to generate the corresponding file in DICOM format.

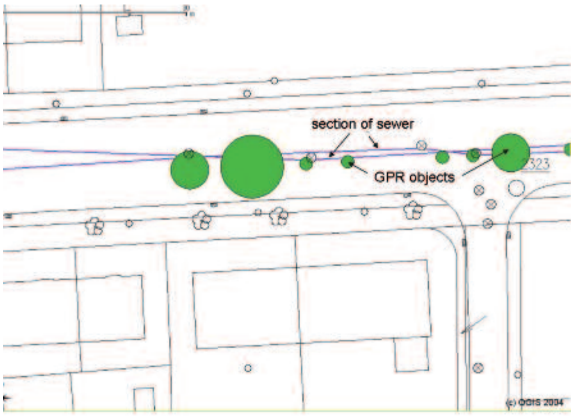
Based on these tools, a script was developed that converts a 2D georadar file with several passes into a series of DICOM images. The script is based on a predefined folder structure in which the source files are stored together with an empty log file in a folder and the resulting DICOM files are written in another folder. These folders can be specified by the user as input parameters at script execution. The necessary input parameters are:

- The georadar file to be converted,
- The input folder for temporary files, and
- The output folder for storage of the resulting DICOM files.

After setting and exporting the PATH- and the DCMDICTPATH-environment variables conveniently, the DICOM dictionary can be loaded to execute the script for file conversion. The conversion process includes the decomposition of the georadar scan into individual PNG slices, and the header information is stored in a log file. Then, a standard LINUX function is used to generate corresponding RAW files from the PNG format. The conversion of image files from RAW format to DICOM format is done with a predefined method of the DICOM toolkit. Finally, the dcmodify function of the Dicom3Tools is used to configure the obtained DICOM files into 2D DICOM conform ultrasound images. All the attributes with the tag group number '0002' are determined by the DCMTK and their values are assigned so that subsequent modification of these attributes is not possible. All other attributes can be modified manually to change their default values. Some examples on the information transfer table are given below:

- The image type is constant and has the predefined value 'DERIVED PRIMARY' since the DICOM series results from the conversion of a georadar file. In this context, constant means that this attribute has the same value for all the converted

Figure 9
2D geo-referenced model visualization [6]



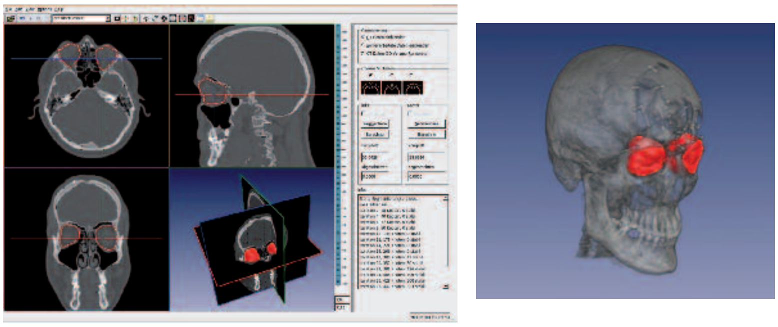
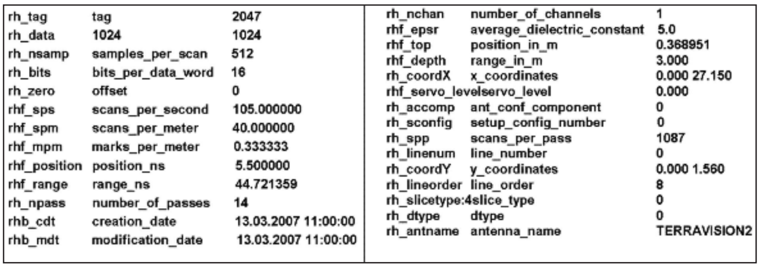


Figure 10
Medical volume data visualization. Left: The MITK application has four coupled viewing windows for axial, sagittal, coronar and combined view, where the corresponding reticles are shown. Right: The fourth window may also be used to display joint volume / surface renderings.

Figure 11
DZT file format structure



rh_tag	tag	2047
rh_data	1024	1024
rh_nsamp	samples_per_scan	512
rh_bits	bits_per_data_word	16
rh_zero	offset	0
rhf_sps	scans_per_second	105.000000
rhf_spm	scans_per_meter	40.000000
rhf_mpm	marks_per_meter	0.333333
rhf_position	position_ns	5.500000
rhf_range	range_ns	44.721359
rh_npass	number_of_passes	14
rhb_cdt	creation_date	13.03.2007 11:00:00
rhb_mdt	modification_date	13.03.2007 11:00:00
rh_nchan	number_of_channels	1
rhf_epsr	average_dielectric_constant	5.0
rhf_top	position_in_m	0.368951
rhf_depth	range_in_m	3.000
rh_coordX	x_coordinates	0.000 27.150
rhf_servo_levelservo_level		0.000
rh_accomp	ant_conf_component	0
rh_sconfig	setup_config_number	0
rh_spp	scans_per_pass	1087
rh_linenum	line_number	0
rh_coordY	y_coordinates	0.000 1.560
rh_lineorder	line_order	8
rh_slicetype:4slice_type		0
rh_dtype	dtype	0
rh_antname	antenna_name	TERRAVISION2

Figure 12
Exerpt of metadata in DZT header

georadar files of this study. It should be noted that this value should be specified explicitly by the user.

- The attributes 'instance creation time' and 'instance creation date' are automatically set by the script to the current date and time of the DICOM file creation.
- The SOP Class UID and the SOP Instance UID are set from the toolkit.
- The values for the attributes 'study date' and 'time study' are taken from the variables rhb_cdt of the georadar file (see Figure 12). These values vary for different files.
- The modality is set manually to ultrasound for ultrasound imaging. This value is constant for all the DICOM series generated in scope of this work.
- The conversion type WSD is set automatically. It describes the type of image conversion for generating a DICOM file. In this case, a workstation is used. The values of manufacturer of the computer for data collection as well as the company doing the data generation are constant and should be modified manually.
- Referenced SOP Class UID and SOP Instance UID Referenced generate a connection of the individual images of a series of pictures with each other. These referenced images have the same SOP Class UID as that of the current image. The referenced SOP Instance UID is the same.
- The name of the image series is taken from the GPR tag rh_name and stored in the DICOM attribute patient name.
- The value of the DICOM attribute patientID is composed from the study time and study date and is automatically set by the script.
- The value of the DICOM attribute 'patient's sex' is constant and set to 0.
- The image number is set from a counter variable that is incremented during image formation. In georadar files, no indication of the number of samples per pixel is given, so it is automatically assigned to the default value of 1 and is not modified.
- The photometric interpretation is set constantly to the value of 'MONOCHROME 2' because the data only contains gray values. By default, the number of frame is set to 1, but this is modified according to the variable rh_npass and set constant to 14.
- The values of the DICOM attribute rows and columns are respectively taken from the variables rh_nsamp and rh_spp. These values vary depending on the GPR data.
- The pixel spacing cannot be deduced from the GPR data. Therefore, it is set constantly to a ration of one.
- The value of the attributes bits allocated, bits stored and high bit result from the photometric interpretation. This data also is constant. The data format manually based on the pixel representation is set to an unsigned Int type 000H.
- Since the images undergo a compression during the processing, the attribute 'lossy compression' takes the value 01.

After setting all these DICOM attributes, the conversion in a 2D DICOM ultrasound series is performed and GPR data can be read, displayed and further processed by any medical software compliant with the DICOM standard.

Models to visualize

However, we do not only aim at visualizing the GPR signal, but use medical software and programmes for hybrid data and model visualization. As it is commonly accepted in the medical field, such visualization essentially can simplify the understanding of complex image data such as ultrasound and GPR.

GPR surveys are now commonplace in environmental and engineering geophysics for non-destructive investigation of the shallow subsurface. Underground infrastructures that need to be investigated are channels, sewers, pipes, as well as special structures, but also cavities that are present on defect pipes. The investigation of cavities is also interesting for embankment inspection since it can help to detect damages of the sandy underground construction that might become crucial on floodwater conditions. In terms of abstract visualization models, GPR data portions of sewers and drainage systems can be simply visualized by a series of geometric objects (Table 1).

Results

The primary goal when processing GPR data is to detect relevant information for interpretation and analysis to support appropriate asset management. Using the developed converter software, GPR data can be transformed into a series of medical ultrasound images for DICOM compliant volume visualization. Currently, the header of GPR data is composed of more than 40 parameters that are used to encode the radar signals. These parameters include the number of channels, distance of antennas, creation date and time, GPS information and other electrical parameters. They are mapped to DICOM image object definitions. Basically, image modules such as 'general image', 'image pixel', 'device', 'US region calibration', 'US image',

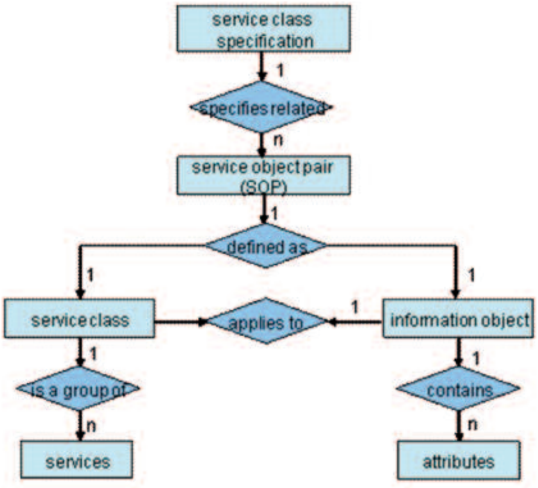


Figure 13
Entity relationship model of DICOM elements

and 'palette color lookup table' are used to embed the relevant tags.

As result, direct volume rendering of GPR is possible. Figure 15 shows an example of GPR data visualized as medical ultrasound in ImageJ. The volume illustrates a GPR measurement carried out on a portion of road. A suspicious area that shows a cavity can be seen. A relevant structure is also marked on the picture.

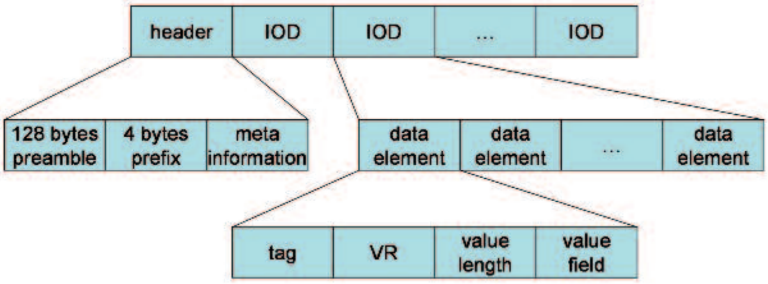
Hybrid visualization of volume data and abstract models is supported using the MITK toolkit. Figure 16 shows the same data as displayed in Figure 15. MITK, however, additionally allows user-guided exploration of 3D data, segmentation and visualization of hierarchically organized surface models and volume data [17]. Therefore, MITK is suitable to combine GPR data volume rendering with model-based surface reconstruction of models representing the relevant structure (pipe) and the suspicious region (cuboid). Figure 17 presents different views of hybrid visualization.

In summary, medical image processing and visualization becomes available for GPR data. Direct volume rendering techniques with the ImageJ software as well as combined volume surface visualization modes with MIT allow simplified analysis and interpretation of GPR radargrams after conversion into the DICOM US format.

Discussion and conclusion

In this paper, our goal was to prove the concept that image visualization, processing and recognition algorithms developed and tested for medical ultrasound are adaptable to GPR data and make the evaluation of radargrams faster and more accurate.

Figure 14
The DICOM image file structure



In particular, the illustration of GPR data with precious visualization programmes is extensive and offers frequently just the data representation, and interpretation still is difficult for communal decision makers. To obtain a better visualization, GPR data was transformed in DICOM format, which is already established in the medicine sector. Thus, the illustration of GPR data is possible by means of medicine image processing programmes. To relieve the interpretation of radargrams, it has been analysed, if the algorithms, which are already used for medicine ultrasound, are adapted for GPR information. The visualization of buried objects and soil layers can be enabled with simple symbols and their combinations in 3D presentations. In medical research, these techniques are used already successfully. For illustration of subterranean infrastructure and layers, however, it still has to be tested.

To acquire GPR data, it is reasonable in the first step to operate in a less complex environment (for instance a levee). There are less disturbing objects like unknown fragments, boulders or layers, which complicate the identification of the located objects. In normal case, levees have exact interfaces (e.g. seal, gravel, compact soil), and if applicable a common sewer and cable system (e.g. drainage, pipes, cables). Thus, cavities can be identified more easily. In a following project, this basis shall be used to illustrate the internal structure of an embankment as a 3D model through using geo-referenced GPR data integrated into GIS by means of a bidirectional interface.

GPR is also applied to investigate complex environments. Here, the next step after illustrating a 3D model of the internal structure of an embankment is to picture the internal structure of a more complex environment. The identification and visualization of a subterranean infrastructure with complex cable and pipe systems, as well as unknown buried objects and constructions, will be enabled. ●

Acknowledgements

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Table 1
Idealized models for hybrid visualization

Buried objects and soil layers	Idealized illustration	Buried objects and soil layers	Idealized illustration
Pipe section		Cavities evolved from leaks in sewer e.g.	
Cavities, buried constructions of sewer		Soil layers, water table	
Sewer, drainage systems and cables		Cavities by means of muskrats (investigation of embankment systems)	
Sewer constructions, inspection points		Sewer in different soil layers	

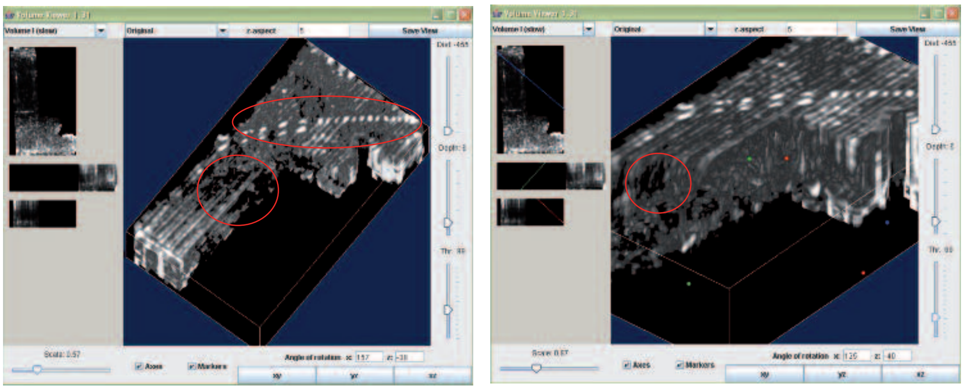

Figure 15
GPR data as used in Figure 8 is visualized in ImageJ. Left: Complete data set, the relevant structure and a suspicious cavity are marked. Right: Zoomed view of the suspicious cavity.

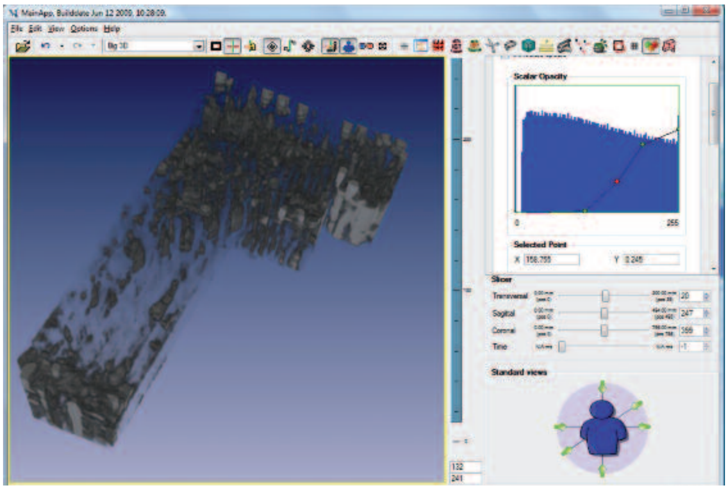

Figure 16
GPR data as used in Figure 8 is visualized in ImageJ

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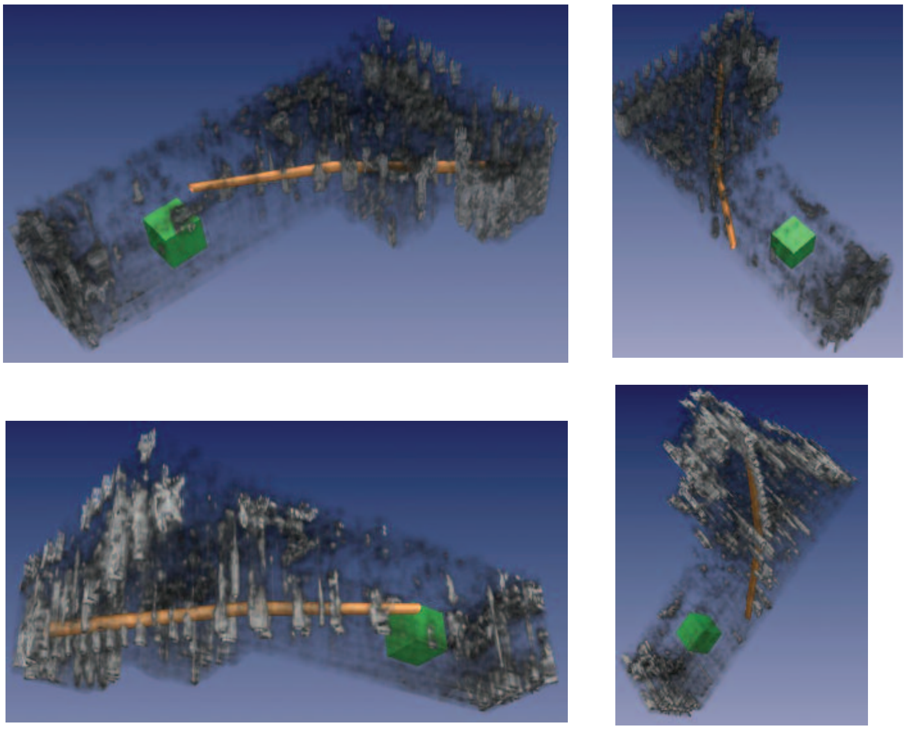

Figure 17
Hybrid GPR data visualization is interactively explored using MITK

Paper presented at LESAM 2009 – 3rd IWA Leading-Edge Conference on Strategic Asset Management

Linking asset management to sustainability though risk concepts: the role of externalities

Emerging national and international trends like climate change, population growth, damage to ecosystems and a carbon constrained future are imposing new challenges on the urban water sector. Sustainability principles, aligned with the concept of sustainable development, have the potential for allowing asset management and other business processes to be evolved in a way that helps water authorities meet these complex challenges. Given the development of asset management to date, it is desirable that sustainability principles be linked to existing approaches and frameworks, rather than necessitating a new 'sustainability' framework to be developed. Since risk is a fundamental principle in asset management, if a link is made between risk and sustainability, this will also align asset management with sustainability. Part of this challenge is to effectively integrate the consideration of externalities into risk analysis and decision making, which is the main focus of this paper. David Marlow, Leonie Person, Stuart Whitten, Darla Hatton MacDonald and Stewart Burn consider the concept of externalities from an economic perspective, as well as the practical implications to a water authority and asset managers. A framework for the inclusion of externalities in asset management decision making is also presented. The application of the framework is highlighted through a brief consideration of its use in assessing the timing of replacement for a large diameter water main.

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The supply of high quality potable water and removal of wastewater is an integral part of a healthy modern society. In urban areas, water services are delivered through a diverse range of physical assets, which have a high capital value and cost a significant amount to operate and maintain. Since the water sector is so capital-intensive, effective management of assets is a cornerstone of delivering service. In reflection of this, the urban water sector across the globe has over the last decade or so expended significant effort to raise the standard of asset management. Notwithstanding the achievements made to date, there are emerging national and international trends that are today imposing new challenges. For example, at a global level, there are numerous issues associated with climate change, population growth, damage to ecosystems and a carbon constrained future (due to reduction in oil reserves and attempts to curb greenhouse gas emissions). At a more local level, changing community attitudes and increasing pressure on water resources present additional challenges.

The convergence of these and other similar trends is likely to have an increasing impact on the business environment within which water authorities must operate, and provides a driver towards re-evaluating many of the paradigms that have underpinned the design of systems and service provision in the past [e.g.1]. In turn, this influences the way in which services are provided, the adoption of new asset types to deliver this service, and the way in which these assets are operated and maintained into the future. At the same time, the sector must maintain and operate its existing asset stocks in an effective manner, and meeting these demands in a changing environment represents its own challenge. All these changes mean that the current approaches to asset management also need to be evolved so as to provide the sector with the capacity to meet upcoming challenges.

Sustainability principles have the potential to allow asset management and other business processes to evolve in a way that helps water authorities meet these emerging challenges. This in turn requires asset management tools and procedures to be evolved so as to reflect these principles [2, 3]. With this potential in mind, this paper examines some of the conceptual links between asset management and sustainability. Amongst other things, it is asserted that risk concepts, in conjunction with appropriate life cycle costing techniques, provide one means through which asset management can be evolved so as to align with sustainability principles. To achieve this, however, the consideration of cost and benefit needs to be extended to address those impacts that are currently not captured by the market; the so called 'externalities' associated with the provision of water services. This paper therefore discusses the various perspectives that can be taken when considering externalities, as well as the role and importance of externalities to asset management. An outline of a 'common framework' for the inclusions of externalities in asset management decision making is also presented, along with a brief discussion of its application to a specific asset management issue; the replacement of a large diameter pressure pipe.

Asset management and sustainability

The concept of sustainability

Before addressing the issue of externalities in more detail, it is considered worthwhile to highlight the conceptual linkages between asset management and sustainability. As discussed previously by Marlow [2,4], at a basic level the terms 'sustainable' or 'sustainability' merely imply the ability to continue to do something indefinitely. A focus on a long-term view is thus always implicit within any use, but after that the term can be (and is) used in a myriad of ways. For example, with respect to the water sector, 'sustainable' can be used to refer to the financial longevity required to deliver water services into the future [e.g. 5,6]. However, sustainability is often taken to mean much more than this, since it is (or is becoming) synonymous with the concept of 'sustainable development', a widely quoted definition of which is given in the report from the Brundtland Commission [7]: 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'

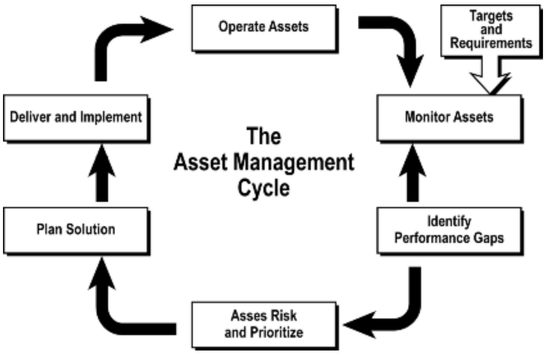
In the authors' opinion, it is this kind of sustainability that is required to meet the emerging challenges referred to in the introduction. However, at its broadest level, sustainable development is inherently a societal outcome associated with the aggregate impact of different sectors and activities. The question then arises as to how the water sector can align with such a broad and aspirational concept. With this question in mind, Marlow & Humphries [8] proposed the following operational definition for sustainability in relation to a water business: 'For a water utility, sustainability is practically achieved when all its activities, both internal to the business and across its supply chain, achieve net added value when assessed across each of the triple bottom line outcomes (financial, social and environmental) over the medium to long timescales, considering all costs and benefits, including externalities.'

The reference to externalities in this definition is considered in more detail in the later parts of this paper. It is also noteworthy that the term 'triple bottom line' (TBL) used in this definition is becoming synonymous with the term sustainability [e.g. 9], and expands on the concept of the 'single bottom line' of financial performance (i.e. profitability). Advocates of the TBL concept argue that business continuity requires a broader focus than just financial performance alone, and that businesses need to give appropriate focus to social and environmental output measures [e.g. 10].

Linking asset management to sustainability

Having developed out of the need for public health and environmental improvements [e.g. 11], and with an increasing need to operate in a financially efficient manner [e.g. 12] while meeting a broad range of legislative requirements, the water sector is intrinsically engaged with achieving TBL outputs. It can therefore be inferred that asset management within the water sector has, to some extent at least, always been undertaken with consideration given to TBL issues. The question is; does this mean that water sector asset management is undertaken in a manner that is aligned with sustainability concepts? To answer this question, consider the asset management process conceptualised in terms of an on-going cycle, as shown in Figure 1.

Figure 1
The asset management cycle [13]



Asset managers make decisions at various levels within this cycle. For example, with respect to planning new assets, asset managers need to determine:

- What option will provide the best solution (extending an existing centralised network, or adopting something different like a decentralised solution)? and then
- Given the option selected, which assets represent best value and acceptable risk?

With respect to existing assets, managers face a different set of questions:

- Should I leave an asset or replace it?
- If I replace it, should I replace it with the same type of asset or something different?
- If something different, then what will be the impacts on my existing assets and thus service, what about service provided by the new assets?
- If I cannot afford to replace it, should I do something else like change service (e.g. pressure management)?

Asset managers may or may not be required to consider issues associated with sustainability in either type of decision making. This is implicit in Figure 1 because while assets (and thus levels of service provided) are managed in light of targets and requirements, setting these targets and requirements is not part of the asset management cycle per se. Instead, they are set in relation to the strategic objectives of the authority, which should in turn reflect the needs of all relevant stakeholders [13]. Hence, if stakeholders require sustainability principles to be considered, the asset management cycle will be undertaken in light of these requirements. Conversely, assets can be managed to deliver non-sustainable goals if that is the requirement of stakeholders.

The decision to operate in a more or less sustainable fashion is thus outside the scope of asset management, residing instead in the domain of environmental, socio-political, and business ethics [14]. Nevertheless, if adopted, many activities undertaken in light of sustainability goals will be subsequently directed through asset management. In this respect, asset management is a vehicle for delivering against sustainability objectives of a water authority, as long as there is a way of considering sustainability concepts in associated decision making. As will be discussed in the remainder of this paper, the concept of externalities embedded within a risk-based decision making framework provide one means of achieving this link.

The role of externalities in achieving sustainability

In accordance with the operational definition of sustainability presented above, for a water authority to be assured of contributing to sustainable development at a societal level, its operations must deliver net added value when assessed across all costs and benefits, including externalities. The question then arises as to what an externality is and why they are important in the context of asset management and sustainability.

Externalities: an economic definition

From the perspective of economics, there are a variety of definitions of externalities as they relate to water; for example:

- An externality is any impact caused

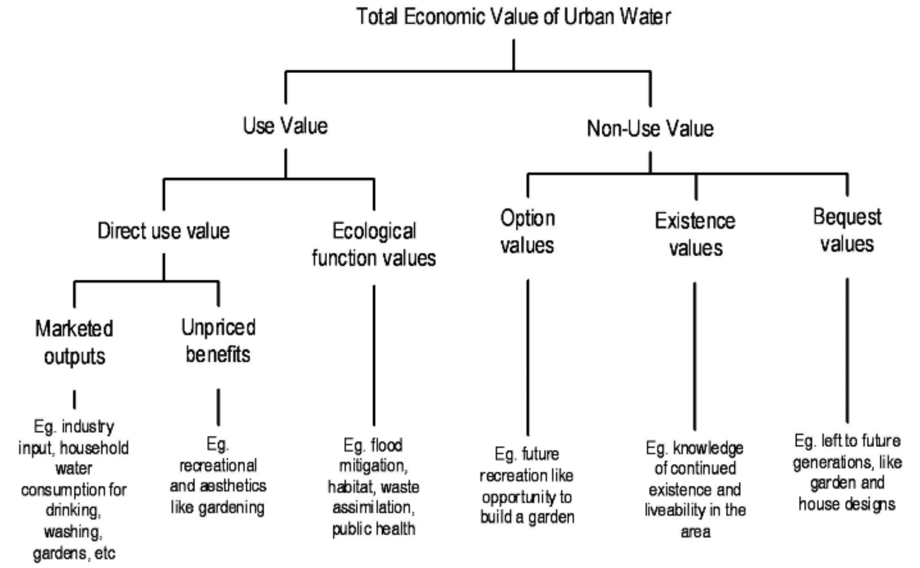


Figure 2
The total economic value of urban water

by human activity whose costs (or benefits) are not factored into the decisions of the economic agents involved in the transactions [15].

- A legitimate action by one economic unit that impacts on the welfare of another economic unit that does not take place through markets [16].
- A cost or benefit that arises from an economic transaction that falls on people who do not participate in the transaction [17].

There is, however, necessarily a commonality between all such definitions, since any economic consideration will generally reflect the fact that externalities. They all have direct impacts on the physical characteristics or attributes of the environment and people, which in turn generate indirect impacts on ecosystem functions and human wellbeing [15], occur when those impacted are not involved in a transaction, can be positive (i.e. provide a benefit to others) or negative (i.e. create a cost to others), are measured as a change in welfare or social wellbeing, sometimes termed social cost and social benefit [18], and have specific boundary conditions that relate to people, environment, governance, time, space, measurement unit and event (e.g. not every pollution spill has the same impacts), therefore estimation of externalities is specific.

While externalities are case specific, depending on issues like the context of the economic activity, property rights and social expectations, the likely range of externalities arising from urban water service provision can be considered to fall into five groups: pollution / contamination (e.g. land contamination and greenhouse gas pollution); environmental impacts (e.g. habitat loss / generation); public health and safety (e.g. safety of general public and vulnerable groups); social disruption (e.g. noise, dust and odour nuisances); and non-compensated financial loss (e.g. opportunity cost of land and property value).

Linking externalities to economic value

Measures of economic value are based on what people want; their preferences. Hence, the theory of economic valuation is based on individual preferences and choices [19]. The economic value of a particular externality is measured by the maximum amount of other things that a person is willing to give up to avoid it occurring. In a market economy, dollars (or some other currency) are a universally accepted measure of economic value, because the number of dollars that a person is willing to pay for something indicates how much of all other goods and services they are willing to give up to get that item. As will be discussed later in the paper, viewing an externality as being equivalent to a monetary cost is a useful approach in asset management, since externalities can then be treated in the same way as any other cost. More broadly, however, the concept of total economic value (TEV), which encompasses all potential values (both positive and negative), can be applied to externalities.

The components of total economic value are well established in the environmental economics literature [e.g. 20] and are illustrated in Figure 2. In practice, however, the analysis of TEV is largely irrelevant because the focus of most economic decisions is the incremental or marginal change in TEV associated with different scenarios; i.e. 'with' and 'without' some change. This invariably means that for a particular project or scenario only a subset of the components of TEV, as shown in Figure 2, may be affected and hence require investigation. Importantly, the change in TEV should be assessed in 'net' terms (benefits net of costs), since total expenditure or gross revenue does not provide the relevant marginal magnitude and direction of change necessary to understand total changes in TEV.

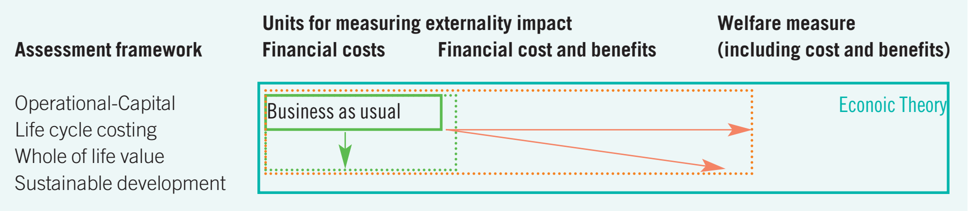
Externalities associated with the provision of urban water services influence the TEV derived by users and delivered to the community, and are thus relevant to economic decisions. For example, changes in the structure, type, function and management of urban water assets will influence the externalities generated and hence the TEV derived. The specific type of externalities generated will be case specific, depending on issues like the context of other economic activity, property rights and social expectations. However, the likely range of externalities arising from urban water service provision can be considered to fall into four groups:

- Environmental impacts: e.g. land and water contamination / pollution; greenhouse gas emissions; habitat loss / generation; biodiversity impacts.
- Public health and safety: e.g. safety of general public and vulnerable groups
- Social disruption: e.g. noise, dust and odour nuisances; traffic disruption, etc.
- Non-compensated financial loss: e.g. opportunity cost of land and property value.

The impact of externalities on asset management decisions

Historical experience has shown that ignoring externalities like pollution and greenhouse gas emissions in decision making can skew decisions towards short-term solutions that result in unsustainable practices and industry outcomes. Legislative requirements can and do compel asset managers to address such issues, but approaches are still needed to assess tradeoffs between allowable impacts associated with

Table 1
Typology of costing and economic assessment frameworks



Assessment framework	Units for measuring externality impact Financial costs	Financial cost and benefits	Welfare measure (including cost and benefits)
Operational-Capital			
Life cycle costing			
Whole of life value			
Sustainable development			

Table 2
Potential economic approaches for externality estimation

Externality	Cost estimate method
Land contamination	Mitigation cost
Greenhouse gas pollution	Proxy good
Habitat loss / generation	Mitigation cost
Safety of general public and vulnerable groups	Choice modelling
Noise and odour nuisances	Contingent valuation
Opportunity cost of land	Replacement cost
Property value	Hedonic price

different interventions; this is the aim of integrating externalities into decision support approaches for asset management.

By taking into account all of the impacts associated with a management option that are valued by society, irrespective of whether they are captured by the market, or whether or not there is a reasonable expectation of compensation, available interventions would be judged from the perspective of total cost imposed on society. This may change the type of service provision strategy (e.g. decentralised solutions), the management strategy adopted (e.g. level of maintenance provided), the type of intervention selected (e.g. trenchless technology versus trenched replacement) or the type of incentive to stimulate a response (e.g. price rebates on low water use). Clearly for this to be the case, the relative magnitude of the externalities involved need to be significant enough to influence the decision making.

Burn et al. [12] presented conceptual arguments to show that, at least when viewed from the perspective of the community, the tendency of water authorities to ignore externalities in their analysis can also mean the economic value of asset replacement is underestimated, and this in turn could lead to insufficient levels of capital maintenance (renewals spend). In contrast, the inclusion of externalities in the analysis provides a truer reflection of the cost of service provision to the community across the TBL of economic, social and environmental performance, and allows a higher expenditure in activities such as renewal to be justified, though affordability and (more usually) customer willingness to pay issues must still be considered.

It is noteworthy that while there are often welfare losses to the community relating to unplanned asset and service failures, if such failures are within industry standards, these losses are not strictly considered externalities due to their concurrence with customer service level agreements. Nevertheless, such losses still have a significant role to play in asset management and, for the purpose of analysis, can be treated in the same way as true externalities.

Internalising externalities

The process of taking account of externalities within decision making is called 'internalising externalities'. Internalising externalities generally means that the producer of the externality modifies the decision process to take account of the welfare impact of the externality or is 'charged' for the externality provision. This 'charging' can include: being informed of the externality; providing payment to those affected or to remediate the environment; or requiring a change in production outputs or processes. Of most interest to asset managers is the last option, i.e. the change in production or process, but all of these 'charges' are dependant on the nature and extent of the externality, who holds the initial property rights and what a socially efficient solution would be. For a water utility internalising externalities into their asset management strategies there are two possible results:

- No change in current planning outcomes but the utility is more informed of impacts and may take this into account in the future; or
- Change in planning outcomes that are based on the incorporation of the externalities (and impacts on social welfare associated with asset and service failures); for example, a change in timing of a decision or change in technology options.

It is interesting to note that asset managers may perceive and value externalities differently to the community because they are considering business decisions in light of stakeholder requirements, interpreted with respect to their own understanding of these requirements and their perception of and attitude to risk. These two perspectives can be summarised as follows.

From the community perspective, externalities are associated with welfare change (generally a loss of welfare) imposed on communities, where this is contrary to community expectations, and is associated with the actions of a water authority. The value placed on the externality from this perspective is a true economic consideration; it is concerned with the degree of net change expressed in terms that reflect the value placed on the externality by society. This perspective assumes that there is a 'social license to operate' which establishes communities expectations and requirements within the urban water industry. The community then considers any deviation from these expectations (resulting in change in welfare) to be an externality.

From the water authority perspective, externalities (including external costs and other welfare changes) are associated with consequences that arise due to asset failures but are un-costed. These asset failures impact the community and are not financially compensated, although they are potentially all within the 'legislated' agreements established for the authority to operate. In general, these will be local considerations and the value placed on avoiding these consequences will reflect the willingness of the water authority to avoid negative impacts on stakeholder relationships (stakeholders implying customers, community, regulators, etc., and impact implying negative publicity or relationship).

The key point is that in a true economic sense, externalities are assessed from the perspective of society. Water authorities may, however, place a different valuation on the externality and, indeed, be willing to pay more to avoid a given externality impact than would otherwise be justified from a societal perspective; for example, to avoid negative publicity associated with a high profile failure that disrupts a sporting or cultural event.

Taking account of externalities in asset management

Life cycle concepts

As noted by Marlow & Burn [21], externalities arise due to decisions made in each part of the asset life cycle, so it is natural to take account of externalities using asset life cycle concepts. To align with sustainability principles the approaches adopted must account for all the costs and benefits accrued across the whole life of an asset (and systems of assets), including externalities. Various approaches have been developed to analyse asset life cycle costs that can be used to achieve this end [e.g. 22, 23]. A typology that illustrates the evolution of costing and economic assessment concepts toward sustainability is shown in Table 1.

As shown, the typology includes four frameworks for assessing the value of service provision and three 'units' for measuring externality consequences. Table 1 is intended to illustrate that economic theory captures the broadest range of externalities and measurement approaches, whilst the urban water industry's current 'business as usual' financial practices have a narrower scope. The arrows indicate the conceptual shifts that must occur if the sector is to fully address the sustainability challenge. Implicitly, asset management must align more with economic theory if sustainability aspirations are to be met. It is noteworthy that each of the dimensions in Figure 3 can be considered nested; i.e. welfare measures necessarily include financial cost and benefits, and that planning for sustainable development necessarily includes understanding life cycle costing and operational-capital assessments.

The role of risk

Figure 3 shows a traditional view of asset management's role in providing asset capability; i.e. provide necessary service at least life cycle cost. A key component of any consideration of life cycle costs is the cost of risk. As indicated in Figure 3, 'risk costs' can arise from each stage of the asset life cycle, and asset solutions should be selected in light of these and other costs, balanced against the necessary asset capability. At the design stage, life cycle costing in conjunction with risk analysis techniques can be used to select an appropriate solution, taking into account the expected failures over an asset's life [24, 25]. Once constructed, the management of risk requires water authorities to make on-going assessments to determine an appropriate risk management strategy that represents the balance between the assessed level of risk and other life cycle costs, including the cost of rehabilitation or replacement [26]. For existing assets, risk is generally considered to be the product of the probability of asset failure and the expected consequence.

Sustainability principles can be incorporated into risk assessments through a more comprehensive assessment of failure consequences, undertaken in terms of the overall potential impacts that could be imposed on customers, communities, and the environment across the asset life cycle, along with the probability that these consequential impacts will be realised [12]. As noted previously, alignment with sustainability principles requires a consideration of externalities in this assessment. There is also a need to widen the scope of risk assessments to cover other domains outside the technical / engineering system, for example, including the human-technology interface, inter-generational issues, and the ecological, socioeconomic, cultural and political domains [14].

From the perspective of asset management, integrating sustainability into decision making through risk concepts is a particularly attractive proposition because risk is already a fundamental component of existing asset management frameworks and practices. As such, if a coherent and robust link can be made between risk and sustainability, this would represent a key step in the attempt to operationalising sustainability within asset management functions, not least because a separate 'sustainability' framework for asset management would not be required, which would simplify and promote uptake.

A framework for assessment of externalities

Issues to be considered in assessing externalities

While a desirable end from the perspective of sustainability, taking externalities into account in asset management represents a significant challenge. In practical terms, the first step is to identify the types of externalities that are created by the intervention under consideration. The type of externalities will be related to a combination of factors, for example:

- Existing network and system conditions (including climate impacts and contingencies, built environment characteristics, and management capacity);
- Characteristics of potential failure events (e.g. magnitude of collapse, depth of the flood, volume and duration of effluent discharge to a river channel);
- Environmental factors, including type of land-use (e.g. business, residential, rural, etc.); and
- Social factors (e.g. demographic and socio-economic population characteristics, risk perceptions and protective behaviours).

Once identified, there is then a need to prioritise externalities by an initial screening assessment to determine whether any are likely to be negligible (and by inference identify those that could be significant) given the context of the decision in hand. Prior to assessing a significant negative externality in any more detail, it is prudent to assess if this can be managed through an alternative intervention; i.e. determine if there is an affordable option available that does not impose a significant negative externality. Where this is

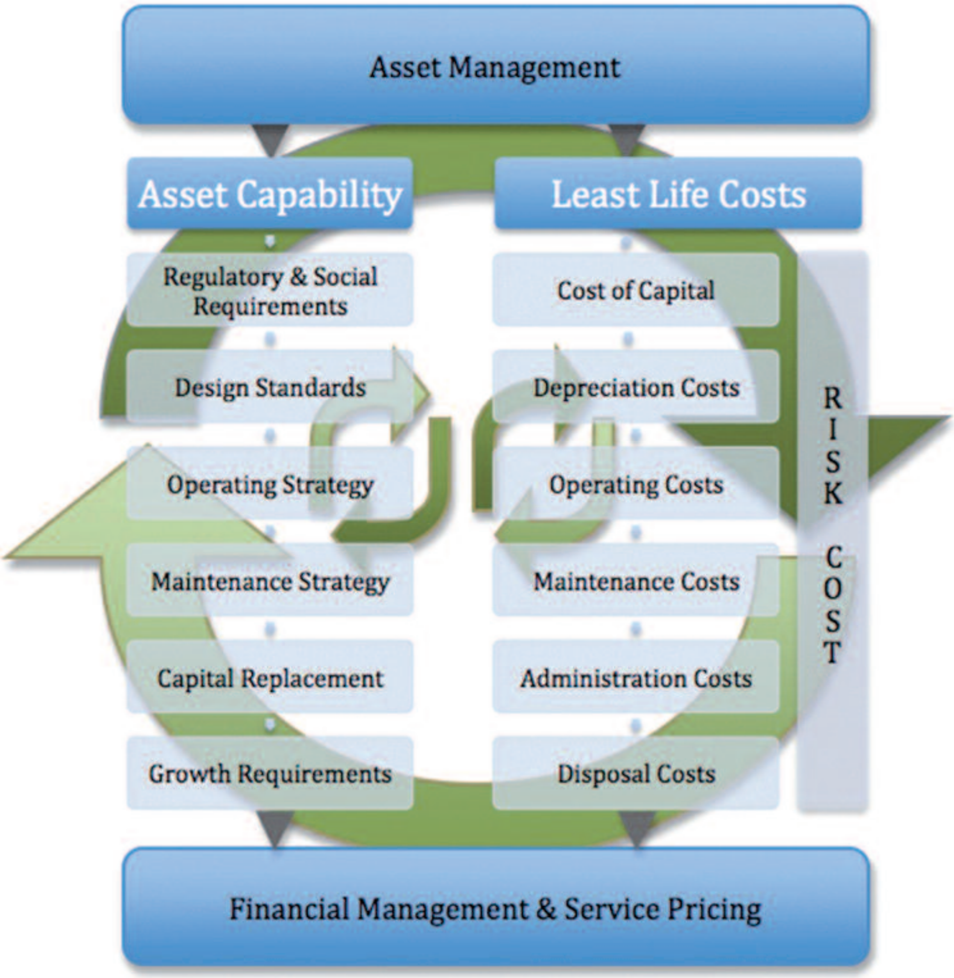


Figure 3
A life cycle view of asset capability and risk [27]

Step	**Critical issues**
Pragmatic scoping	Water authorities should first consider: Which impacts to include? Are these impacts really externalities? Are they likely to have a negligible impact in the context of the decision? Is there an economic / affordable option available that does not impose a specific and significant negative externality?
Define externalities for consideration	Identify who is affected in the transaction, i.e. the 'others' Identify if positive (i.e. provide a benefit to others) or negative (i.e. create a cost to others) externality Clarify the link between the urban water asset and people, which in turn generates indirect impacts on ecosystem functions and human wellbeing Identify what 'value' is appropriate for inclusion, i.e. financial, costs and benefits or welfare Determine specific boundary conditions that relate to; people, environment, governance, time, space, measurement unit and event
Quantifying impacts	Identify the physical magnitude of each externality Determine who is affected Determine what magnitude of physical impact is expected Determine what direction (positive or negative) of physical impact is expected
Value externalities	Determine the preferred and pragmatic method and data for value estimate; e.g. market price, surrogate markets, survey based and benefit transfer Undertake analysis
Evaluation	Determine appropriateness of valuation to current decisions and context (socio-political, management and environmental); and Undertake sensitivity analysis across all relevant externalities to asses the robustness of available options, across a range of values

Table 3
Framework approach for evaluation of externalities

not the case, and different options allow a trade off to be made across a range of externalities, or even one significant negative externality, work is then needed to evaluate the externality for the range of options available. As noted in Marlow & Burn [21], this is a two stage approach that involves evaluating both the magnitude and economic value of the impact.

While outside the scope of this paper, a range of economic techniques are available to place a value on externalities, including market-based methods (e.g. mitigation or replacement costs), surrogate market methods (e.g. proxy good and hedonic price techniques) and survey based methods (e.g. techniques like choice modelling and contingent valuation, which are used to understand 'stated preferences' and place a value on an externality from a community / societal perspectives) [28]. Table 2 provides a first pass estimate of methods that could be used to estimate the value of externalities associated with urban water asset management. The methods shown are related to primary research approaches, and an alternative is to use benefit transfer for all costs, although this will be less accurate.

The benefit transfer approach estimates the 'value' of an externality based on transferring a function, amount or relationship from previous primary research (study) to the case study site. In economic analysis, this approach is normally only appropriate for desk-based or policy work where there is insufficient time or it is too costly to undertake primary research, information is limited and the decision environment is sufficiently similar to a previous study. However, in asset management, the benefit transfer approach may be a pragmatic step for taking into account externalities; e.g. for developing generic values for use in decision making. Other pragmatic approaches that could be used include subjective pairwise ranking, which allows monetary values to be placed against non-financial consequences with a minimum of data [21]. However, a disadvantage is that the prioritisation is subjective, being based solely on the views of the participants involved in the ranking. In practice, this approach is more suited to obtaining an insight into the values placed on externalities from the perspective of the water authority, and thereby determine the willingness to 'pay to avoid' an impact, as discussed previously.

While there may be a driver towards application of pragmatic approaches, it is important that the value assigned to an externality reflects the context specific and dynamic preferences of individuals and the community. Since outcomes will merely reflect a snapshot in time, it is also essential that the robustness of a decision be tested by undertaking sensitivity analysis across the range of minimum and maximum values for externalities that can be anticipated.

A framework for the evaluation of externalities

A framework approach to the evaluation of externalities has been developed to provide water authorities with a systematic process for addressing relevant issues. The framework was developed by drawing on previous work [18, 21, 29, 30] and is summarised in Table 3. For the most part, it is assumed the focus will be on negative externalities that can not be engineered out of a given solution. However, there may be situations where a water authority wishes to consider whether a significant positive externality makes one option more value adding compared to another. In both cases, the decision making process essentially reduces to making an informed economic trade off, taking into account all significant costs and benefits, irrespective of whether these are normally captured by the market.

As all values for externalities will be estimates, it is critical that the value assigned to an externality reflects the context specific and dynamic preferences of individual and the community. Since outcomes will merely reflect a snapshot in time, it is also essential that the robustness of a decision be tested by undertaking sensitivity analysis across the range of minimum and maximum values for externalities that can be anticipated.

Application of framework

Detailed application of this framework is beyond the scope of this paper. However, it is informative to provide an outline of how the framework would be applied in practice. To this end, consider the case where a decision must be made over the replacement of an ageing large diameter cast iron main, the failure of which could result in significant social and environmental disruption. The asset management decision under consideration is then the optimum time to replace the pipe. For such cases, analysis of risk can be undertaken using physical probabilistic modelling combined with risk-cost-benefit analysis, as detailed in Davis & Marlow [26]. The process used is summarised in Table 3 (left column). An interesting aspect of this approach is that the replacement decision is evaluated in terms of the net present value of an intervention, so it is necessary to understand not only the costs associated with failure, but also the benefits of intervention, including benefits from avoiding failures after the intervention, as shown in Figure 5. The inclusion of externalities in this analysis could change the time at which intervention is most cost-effective. For example, a significant externality related to a delayed

Table 4
Linkage between risk assessment and evaluation of externalities

Risk assessment steps	Evaluation of externalities
Identify asset(s) for analysis (prioritize risks)	Pragmatic scoping (this should form part of the process for identifying assets to inspect)
Inspect target asset: obtain raw data for condition assessment	
Convert raw condition data to corrosion rate and estimate probability of failure using physical probabilistic models	
Determine the types of consequences associated with expected damages and intervention options	Definition of externalities of interest
Determine data required; and design and deliver projects on estimating consequences for different interventions (values, scale, costs and likely outcomes)	Quantifying impacts associated with failure and intervention options Value externalities
Use failure probability and cost consequence in combination to inform future interventions	Evaluation, including sensitivity analysis

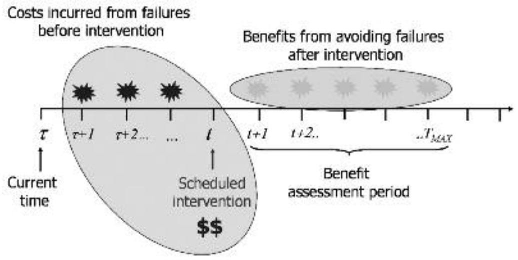
intervention would bring the time of intervention earlier in the planning horizon; the reverse would also be true.

Table 3 (right column) also shows how the externality framework (detailed in Table 2) would be applied in this kind of risk assessment. As shown, the analysis of externalities will be principally included in the final steps of the risk analysis, following on from the condition assessment work. However, in a more general sense, the consideration of externalities will inform the prioritisation of assets for inspection and risk assessment.

For this type of decision, there are a range of possible externalities associated with failure, inspection and replacement of the pipe using a range of options (e.g. full / partial like for like replacement; trenched and trenchless techniques). For the purposes of the current discussion, a good example is the impact on traffic and social activity. Disruptions will occur during a failure of the pipe and also during the planned replacement of the pipe. In fact, the length of time over which disruptions occur may well be longer for replacement of a pipe in comparison to those associated with a failure. Nevertheless, externalities associated with failures could still be more significant. The difference is that customers and the wider community may be more accepting of planned events, as they can in turn plan around the known disruption, so the impact on welfare is relatively lower. In addition to this consideration, planning an intervention provides adequate opportunity for ensuring appropriate environment and health and safety controls are in place, again, indicating that the range of externalities could be lower (e.g. planning provides greater opportunity for minimising environmental impacts and public health & safety issues).

In considering the impact of potential interventions, there is thus a need to consider the difference in value placed on the impacts of a planned interruption (i.e. inspection and replacement) when compared to an unplanned interruption (i.e. failure). Inclusion of externalities into analysis of unplanned failure events is thus warranted, but it may also be necessary to undertake work to confirm some of the assumptions for planned work, given the context of the particular intervention. Further details of approaches to the analysis of externalities for this kind of asset management decision can be found in Marlow & Burn [21].

Figure 4
Cost-benefits associated with pipe replacement decisions [26]



Conclusion

This paper has considered the role externalities will play in an enlightened view of asset management aligned with the concepts of sustainable development. As discussed in the paper, sustainability principles have the potential for allowing asset management and other business processes to be evolved in a way that helps water authorities meet complex challenges like climate change. Given the development of asset management to date, it is desirable that sustainability principles be linked to existing approaches and frameworks, rather than necessitating a new and separate 'sustainability' framework to be developed. Since risk is a fundamental principle in asset management, if a robust link is made between risk and sustainability, this will also help align asset management with sustainability. Part of this challenge is to effectively integrate the consideration of externalities into risk analysis and decision making. However, while the inclusion of externalities in decision making is an important step towards aligning asset management and sustainability, it must still be acknowledged that for asset management to become a real tool for the delivery of sustainability objectives, decisions must be made within a broader sustainability framework. In particular, stakeholders must be fully engaged with the need for change, and systems of regulation and incentives put in place to drive business aspirations in a sustainable direction.

Notwithstanding the importance of these broader societal issues, if analysis can be undertaken to represent externality issues in a consistent manner and thereby provide, at the very least, a relative measure of the economic value of different management options, water authorities can select solutions that are aligned with sustainability objectives, and provide justification to stakeholders for budget levels that take into account the wider impact of their activities. Consistency in the treatment of externalities (between water authorities and even individuals within a given authority) can, however, only be achieved if appropriate guidelines are set and used.

Development of such guidelines is an important challenge that still needs to be addressed by the water sector. The research detailed in this paper has been undertaken to help address this issue, but a great deal of further work is required, including the application of the framework to a range of asset management problems at different scales, and the integration of concepts into asset management tools and processes. Such tools and processes should be designed to facilitate asset managers to make robust decisions that are aligned, as far as is practicable, with the sustainability aspirations of their water authority. While consistency in approach is important to this aim, the costs generated in the analysis of externalities will often be non-market (or based on proxy or surrogate markets). As such, it is likely that the efficacy or otherwise of externality calculations will always be open to challenge. With this and robustness of decision making in mind, a capacity to undertake sensitivity analysis should be considered an essential feature of any tool or process developed. ●

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Web: www.marketforce.eu.com/water

2nd WaterLoss Asia 2010 Conference and Exhibition
14-15 October 2010, Kuala Lumpur, Malaysia
Tel: (603) 6140 6666
Web: www.waterlossasia.com

6th International Conference on Sewer Processes and Networks
7-10 November 2010, Surfers Paradise, Australia
Contact: Zhiguo Yuan
Email: zhiguo@uq.edu.au
Web: www.spn6.net

International No-Dig 2010
8-11 November 2010, Singapore
Tel: +44 (0) 845 0948066
Email: trenchless@westrade.co.uk
Web: www.nodigsingapore.com

Vietwater 2010 Water and Wastewater Industry Show
10-12 November 2010, Saigon Exhibition and Convention Centre, Ho Chi Minh City, Vietnam
Tel : +603 40454993
(Malaysia Office),
+84 4 62872679
(Vietnam Office)
Email: richard@ambexpo.com / support@ambexpo.com
Web: www.vietwater.com

Sustainable Infrastructure and Asset Management National Conference
23-14 November 2010, Sydney, Australia
Web: www.awa.asn.au/events/siam10

Infrastructure Asset Management
6-7 December 2010, London, UK
Web: www.marketforce.eu.com/calendar

Aquatech India
2-4 March 2011, Mumbai, India
Web: www.india.aquatechtrade.com/in/en/Pages/default.aspx

Cities of the Future
22-25 May 2011, Stockholm, Sweden
Email: frida.pettersson@cit.chalmers.se
Web:www.cof2011stockholm.org