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PAPERS

IADB approves loan for Jamaica capital water improvements

Jamaica's National Water Commission has announced it is embarking on a project worth J$100 billion (€0.9 billion) that will extend its potable water network to reach 85% of the island, compared to a current 73% coverage.

The project will involve rehabilitation, expansion and construction of water treatment facilities across the island, including piping water from the north coast, where water is abundant, to the south.

The Inter-American Development Bank has also approved a $133 million loan for Jamaica to improve the water supply specifically in the capital of the country - Kingston.

The work will improve the efficiency, quality and sustainability of the potable water services provided by the Kingston metropolitan area and increase access to water in selected urban centres of Jamaica.

The programme will optimise water infrastructure performance, reduce non-revenue water levels and strengthen the National Water Commission, which is in charge of the initiative.

The rehabilitation of Kingston's potable water supply will include financing the completion of works in selected water treatment and production facilities, reduction of commercial and physical losses, installation of customer water meters, leak detection equipment and repair.

Improvements in the chosen urban centres will consist of design, construction and implementation of water production, treatment and distribution systems for Old Harbour, St Catherine; May Pen, Clarendon; and Mandeville, Manchester. ●

UN-HABITAT announces expanded water and sanitation project for Lake Victoria

UN-HABITAT has announced it is to expand its Lake Victoria water and sanitation initiative to 15 more cities in Kenya, Tanzania, Rwanda, Uganda and Burundi, supported by a $4.2 million loan from the African Development Bank.

Speaking during a visit to existing projects in Kenya, UN undersecretary general and executive director of UN-HABITAT, Dr Joan Clos, said: 'With support of our donors and partners, we are excited to be able to expand our invaluable work in water and sanitation provision in this region.

'The lake provides a livelihood for nearly one-third of the populations of Kenya, Uganda and Tanzania combined, and the majority of these people are living without adequate water and sanitation. By providing these basic services we are paving the way for improved health and faster development in the region.'

The Lake Victoria water and sanitation initiative currently covers 11 cities in Kenya, Uganda and Tanzania. Phase II will expand water and sanitation provision is extended to nearly one million people.

The funds will support project implementation by providing hygiene training in schools and other public institutions and by extending the capacity of facilities upgraded in Phase I. ●

Land experts raise millions from redundant water assets

UK utility Scottish Water has received a multi-million pound boost to its operations from sales of its redundant assets, with help from experts at Bell Ingram, a UK land agent.

Bell Ingram has already helped dispose of 1500 sites and assets across Scotland, which the utility giant no longer needs, generating £4.3 million ($6.7 million) in revenues to re-invest in Scottish Water's operations.

Those sites were among a total of 2500 redundant assets identified across Scotland, including large water treatment works, assorted properties, disused land and water storage facilities.

Graham Lumby, director at Bell Ingram, said: 'A total of 575 sites have been auctioned, raising more than £4.3 million, which Scottish Water has re-invested in its networks and services. Equally as important is the work we have carried out to successfully transfer or sell another 175 sites to adjacent landowners. Those transfers mean Scottish Water has no future costs or future liabilities for those sites, so it can re-invest savings back into its ongoing operations.' ●

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Canada's Water Monitoring Agency installs Aquatic Informatics' AQUARIUS software

Aquatic Informatics Inc. has announced the successful implementation and launch of its AQUARIUS data management system at the Water Survey of Canada's Thunder Bay office in Ontario, Canada.

The deployment of AQUARIUS will increase the agency's efficiency in acquiring, processing, and publishing hydrometric data from its entire national monitoring network, says the company. The system will also provide business productivity tools for Water Survey's hydrologists and field technicians allowing them to work with larger volumes of data with greater ease.

'Capabilities such as workflow automation and quick and easy access to a new centralized data storage centre are but two of the new benefits that the AQUARIUS system brings to Canada's largest water agency,' states Edward Quilty, Founder and CEO of Aquatic Informatics.

Aquatic Informatics' Australian partner, Greenspan, developed the environmental telemetry solution EnviroSCADA. The large-scale deployment of the AQUARIUS system is integrated with Greenspan's automated data acquisition system for over 2400 of Water Survey's continuous water monitoring stations across Canada.

Mark Wolf, Principal Consultant of Greenspan, added: 'Our EnviroSCADA framework leverages the unmatched power, flexibility, and robustness of ClearSCADA, one of the most widely used Supervisory Control and Data Acquisition (SCADA) systems in the world.' The data that is collected by EnviroSCADA is then made available through AQUARIUS to over 200 Water Survey technicians and scientists in real-time across Canada.

The Regina Water Survey office will be the next in line to roll out AQUARIUS where its real-time data analysis solutions will be put to through the rigors during the next flood season. From there AQUARIUS will be rolled out to the remaining offices throughout the remainder of 2011. ●

Officials announce complete revamp of Delhi's water system

City officials have announced that Delhi's water management and distribution system will be completely revamped, under ambitious reform measures for the sector.

In the first phase, government will devolve certain aspects of the management system to private entities and construct a number of wastewater treatment works, as well as increasing the tariffs. A regulatory body will also be created, and the government is considering legislation to fine users heavily for excessive water waste. ●

Leak detection equipment helps save water in US town

The town of Mooresville in North Carolina (USA) has been using HWM leak detection equipment to save time, money and water in its 240 miles (384km) of water mains, complying with new state regulations in the process. With the new equipment, Mooresville Public Services Department has found itself able to identify and repair leaks in the distribution network as and when they occur, minimising disruption to both the service and during the maintenance process.

Mooresville is a town of 33,000 people that provides an average daily flow of 12.2 million litres of water to 13,000 homes and businesses. In the summer of 2008, officials at the town's Public Services Department were recording a 10% non-metered water rate, and underground water leaks were damaging the road network. In addition to this, the extensive digging required to find and repair the leaks increased costs and caused further disruption and congestion. With the passage of North Carolina House Bill 2499 requiring public water services to develop and implement water conservation measures, as well as new industries moving into the area that would drastically increase water requirements, officials knew it was time to upgrade their water management programme.

Mooresville purchased acoustic leak detection equipment from HWM through Fluid Conservation Systems (HWM's sister company in the USA). Mooresville Public Services Director, John Vest, said: 'The FCS equipment was compatible with our record keeping system, and simple enough so that the guys in the field could use it and feel confident that they were collecting accurate results.'

Mr Vest contacted local distributor Carolina Meter & Supply and purchased Permalog leak detecting acoustic noise loggers, L-Mic and X-Mic ground microphones, a MicroCALL+ Digital leak noise correlator, and a Patroller II system to allow leak data to be collected from a moving patrol vehicle in 'drive-by' fashion.

Within six months of installing the equipment, Mooresville Public Services staff had located and repaired 24 leaks, saving an estimated total of $80,000 annually. Workers were pinpointing leaks accurately, allowing preventative maintenance work to be scheduled with advance public notification to avoid traffic congestion. 'The FCS equipment has really enhanced our planning capabilities. We're finding leaks before they become a problem,' said Field Operations Supervisor, WD Bumgarner. ●

Pipe breaks as key data for active asset management of pipeline inventories

Deteriorating water and wastewater assets in North America mean hundreds of billions of dollars would be needed to replace the system, with a large proportion of this relating to pipe replacement, a financial cost unmet by utilities. In order to better address these needs, there needs to be a repair and replacement strategy informed through network data, including pipe breaks.

In this article, Frank Blaha outlines some of the work the Water Research Foundation has undertaken and is currently involved with, which aims to further the knowledge of pipe breaks, and how this data can be used to allow a utility to use its resources most effectively in the ongoing management of its water network.

Frank J Blaha
PE, Senior Research Manager, Water Research Foundation

Water utilities are among the most capital intensive of all utilities (Olstein, et al, 2009). A major part of this capital investment is in the buried assets associated with the utility, especially the transmission and distribution system. In a recent US Environmental Protection Agency (EPA) study of drinking water infrastructure replacement needs, out of total water system replacement needs of $334.8 billion over the next 20 years, $200.8 billion of need (60%) is in the transmission and distribution area, much of which would be associated with pipe replacement (US EPA, 2009). This article is based on the results of a survey conducted by EPA in 2007, in which thousands of water utilities were involved (US EPA, 2009). While specific numbers differ, this EPA study is in general agreement with other studies that similarly identify a huge unmet financial need for renewal of water systems.

Figure 1
An old pipe in excellent condition. Credit: Jeff Leighton, Portland Water Bureau.

Water utilities need help in addressing this unmet need, since current rates paid for water service are not sufficient to address these identified needs.

One method of addressing this need is to better identify replacement priorities within the transmission and distribution systems. While EPA surveyed thousands of utilities, these utilities determined for themselves how best to respond to the survey questions. It is certain that many utilities based their estimate of replacement priorities on the age of their pipelines. However, age of water pipelines does not tell the whole story. Just as water utilities are very capital intensive, it also seems that water pipeline assets are among the longest-lived assets of all utilities. A few studies have identified that at current replacement rates, North American water utilities are on the order of replacing 0.5% of underground assets per year, or total replacement in approximately a 200-year timeframe (Grigg, 2007).

This seems an unreasonably long lifespan to expect of our buried pipelines, but on the other hand, if replacement need estimates are based on a pipe lifespan of 50 or 75 years, this might be an unreasonably short lifespan to expect of a water pipeline. Pipeline assets that are 75, or 100, or 125 years old are not necessarily deteriorated or failing assets in need of replacement. Figure 1 demonstrates this concept very well, showing a coupon from a pipe in excellent condition; although it was installed in Portland, Oregon in 1883 (this coupon was collected when the line was cut to install a valve). There are many examples of utilities studying the performance of their pipelines and finding that relatively youthful pipe cohorts, sometimes on the order of 40 or 50 years old, are failing at a greater rate than older pipe cohorts. Figure 2 illustrates this point, clearly showing an advanced state of deterioration of a pipe installed in 1975 – a relatively young pipe for most water utilities.

If age is not the primary criterion upon which to determine which pipeline to replace, what should be? One of the key criteria upon which decisions can be made, and which is routinely used by North American water utilities, is pipe breaks. Given the extensive piping systems in the ground, pipe breaks are inevitable. However, if breaks are not simply viewed as regrettable events, but rather as opportunities to gather data that are representative of the actual state of the piping system, then pipe breaks can become part of a robust asset management programme. Pipe break data can help utilities identify those assets performing well, and those assets performing poorly, and will help utilities focus renewal decisions on those assets most in need of attention, and not just on 'old' assets. The Water Research Foundation (Foundation) has completed, and is working on, a number of ongoing studies that help advance the science and understanding of pipe breaks, and related risk management concepts. This body of work allows for improved decisions regarding which pipes to renew. The value and application of this work on pipe breaks will be briefly reviewed to establish that pipe breaks, when viewed as data reflective of the condition of a utility's pipe assets, can be an important asset management tool for a water system, and should probably receive more attention as useful and helpful data in managing our pipeline assets.

Pipe breaks as a decision criterion

Pipe breaks are frequently a key data input considered by utilities in deciding which pipe to replace. In a key Foundation study by Gregg Kirmeyer and others (Kirmeyer, GJ et al, 1994), which is commonly cited in the literature, it was reported that 75% of utilities (15 of 20 utilities surveyed in detail) included pipe breaks as a key criterion in pipe replacement decisions. While other common factors cited by utilities in this study included pipe age (45%), low flows (40%), condition or type of materials (30%), and need for pipe size changes (30%), pipe breaks was by far the single most commonly cited criterion for deciding on pipe replacement. The occurrence of a break is useful data, but generally when the break is repaired an excavation is made, exposing the pipe so that workers can repair the pipe. This is, of course, an excellent opportunity to gather additional data on the pipe condition in that area at relatively minimal cost. A Foundation study, 'Prioritizing water main replacement and rehabilitation' (Deb, et al, 2002), identified some of the more useful and easily generated data, which a utility should consider capturing in such situations. This report also provided a decision tool for small diameter cast iron pipe that can be used to assess the pipe safety factors and thus guide the replacement decisions of a water utility.

Pipe breaks and rates

Since pipe breaks can be so important to pipe replacement decisions, a logical question to ask is: 'What is the average pipe break rate in North America?' The answer to this question is a bit fuzzy, due to the large number of water utilities and the limited data available to answer this question. 'Limited data' refers to the limited nature of the surveys done to develop a defensible number. Many surveys have been done on this specific question, and so many numbers have been presented. However, each survey is somewhat limited in its response rate when compared with the approximately 52,000 community water systems in the US, much less when you consider all of North America, including Canada and Mexico.

The Kirmeyer study mentioned above also considered the issue of the average pipe break rate in North America. This report included results of a large survey reported in an American Water Works Association (AWWA) database that has now become Water:/Stats, and also included detailed interviews by research team members of 20 utilities. The Kirmeyer report presented that the data associated with the large survey (1097 utilities reporting) indicated an average a break rate of 0.27 breaks per mile (0.17 breaks per km) of pipeline per year, while the 20 separate utilities interviewed in detail had a break rate of 0.21 breaks per mile (0.13 breaks per km) per year.

The reasons behind these differences were not explored in the Kirmeyer study, but many other reported break rate data fall within this range of average break rates (0.21 to 0.27 breaks per mile per year), with some studies giving an average break rate of 0.25 breaks per mile (0.16 breaks per km) per year (Grigg, 2007). However, it would be valuable to better understand the range of pipe breaks experienced in North America. The Foundation is funding work to provide more perspective and context on this issue.

US main break database

The Foundation has engaged Dr Neil Grigg of Colorado State University to work on a template for a North American national main break database. This database is adapted from, and is to be compatible with, a similar database done in the UK, which has proven useful to UK utilities.

This project, 'US beta testing of the UKWIR national mains failure database' (Project 4195), is also being coordinated with similar efforts by the Water Services Association of Australia (WSAA), to adapt the UK database for use in Australia. While data from an individual utility is valuable, when data are aggregated from many utilities some trends may be observed that could not be seen in data from just one utility, and the value of the aggregated data can be very powerful. When the North American and Australian databases are available and used, these databases should prove valuable tools in helping to develop better statistics on pipe failures in general, and could help

Figure 2
A new pipe in poor condition. Credit: Southern New Hampshire.

to identify good and bad cohorts of pipe, which are not otherwise known.

In addition to the database project mentioned above, the Foundation recently started another project to put pipe breaks into a broader perspective. This study will pull together into one source the many different reported numbers from different studies and surveys on pipe breaks, and then lay out a research roadmap to address any critical knowledge gaps that appear to exist. This project, 'Main breaks: current knowledge and research roadmap' (Project 4374), is a 2011-funded project expected to be completed in 2012 or 2013.

The Foundation will also be tracking work in the expansion of Partnership for Safe Water into distribution system operations. This expansion of Partnership is based on a completed Foundation study 'Criteria for optimized distribution systems' (Project 4109, Friedman, et al, 2010), which presented that breaks in a distribution system are one of three critical metrics that can be used to measure the degree of optimization in the distribution system. With regard to breaks, the study identified main breaks as being reflective of the physical integrity of the distribution system, and recommended a ten-year record of break statistics, analyzing for trends or other indications of changes in the system. Under this expansion of Partnership for Safe Water, over 70 water utilities will be moving forward to establish distribution system optimization programmes, and this work should help to establish an expanded and more detailed understanding of main break rates across North America. The Partnership for Safe Water is expected to start significant distribution system expansion work in early 2012.

Importance of break types – 'small' pipes versus 'large' pipes

The discussion above addresses pipe breaks as though they are all largely equivalent. However, each pipe break is a unique event, and many different 'types' of pipe breaks could be identified that would have different statistics associated with them. For instance, the break rates of different pipe materials would logically be different, since different pipe materials have different physical characteristics, and thus will respond differently to different manufacture, installation, and operational conditions.

The typical types of pipe materials used in North America are cement mortar lined and unlined cast iron pipe (grey iron pipe), lined and unlined ductile iron pipe, steel, asbestos cement, concrete pressure pipe, and PVC, based on the Kirmeyer study cited above. Useful statistics on break rates associated with each type of material, and size, could be developed and would be informative. Similarly, statistics could be developed on the types of breaks experienced, based on the physical location and characteristics of the break on the pipe. For instance, a break might occur longitudinally along the long axis of the pipe, or it might travel around the circumference of the pipe, resulting in a ring break, etc. However, there are two general categories of break that are important for management purposes, yet which are independent of pipe material or physical break characteristics. These are small diameter pipe breaks and large diameter pipe breaks. Figure 3 provides a quick representation of the different approaches to managing small and large diameter pipe breaks based on the different consequences of failure associated with these pipes.

Small diameter pipe breaks can be managed by counting the break rates actually experienced by a utility. This approach is acceptable due to the typically non-critical nature of the pipe, non-catastrophic nature of failures associated with such pipes, and relatively low costs associated with both repair and replacement of such pipes. Small diameter pipe is logically the most prevalent type of pipe in water utility systems, and is of a weaker construction in comparison with large diameter pipe, and so small diameter failures will be much more common than large diameter failures. Small diameter pipe is also often located in residential areas or semi-residential areas, and so these are also where breaks most commonly occur. Pipe breaks can sometimes be repaired while the system is still in operation, in which case there is minimal to no customer impact. When part of a system must be shut down to allow for a small diameter break repair, the area impacted is typically more limited than that associated with a large diameter repair. Still, there is the possibility of negative customer impacts, especially if a break occurs in the morning or early evening, when customers indicate they find services outages to be the most disruptive.

It is commonly thought that customers demand water service 100% of the time, any lower service factor being cause for complaints. However, the results of a Foundation study, 'Customer acceptance of water main structural reliability', demonstrated that customers have more resilience and tolerance for water outages, within some definable limits, than expected. In the results of a survey conducted for this study, 60% of respondents were willing to accept a service interruption of up to two hours duration, but if breaks or outages are frequent they are much less forgiving. This is demonstrated by only 10% of survey respondents being willing to accept five or more service interruptions in a five year period. The results of this study

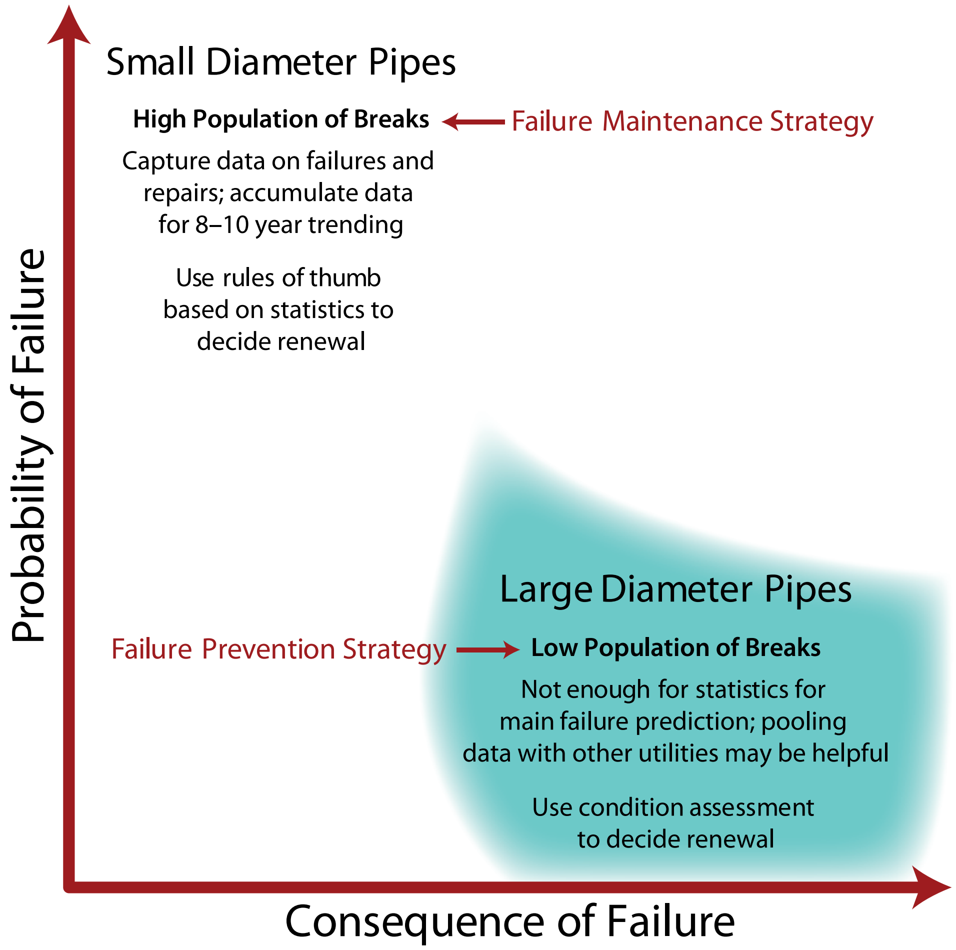

Figure 3
Small / large diameter failure management strategies

also highlighted the critical need to communicate with the customers about such issues as pipe deterioration and possible outages associated with breaks, and especially in regard to planned outages associated with distribution system renewal activities (Damodaran, 2005). On the issue of the cost of such small breaks, the total reported cost for a typical break is $10,000, with this total split into approximately $5000 in direct costs to a utility, with another $5000 in indirect costs to society (Grigg, 2007). These societal costs could include any cost not covered by the utility, for instance, traffic delays or traffic re-routing caused by the break. While these small diameter break costs are not inconsequential, they are manageable since most medium and large-sized utilities are accustomed to responding to pipe break / repair events.

The approach of counting and managing pipe breaks is presented in the report 'Criteria for optimized distribution systems' and is likewise included in the expansion of Partnership for Safe Water into distribution system excellence. While each utility will need to define for itself the maximum pipe size it considers 'small', it appears that the maximum size for 'small' pipe would typically vary from 12 inches (30cm) to 24 inches (61cm) in diameter. Almost all utilities would consider 24 inch diameter pipe to be large.

Large diameter pipe breaks, by comparison with small diameter breaks, are unacceptable to utilities, and most utilities would likely acknowledge that as a goal they desire to completely eliminate large diameter pipe breaks. A large diameter pipe break tends to be more consequential, even catastrophic, than small diameter breaks, in regards to impact and damage in the area of the break. Large diameter pipes also tend to be critical pipes in a transmission and distribution system, resulting in substantial impacts to the utility experiencing breaks in these pipes. Failures in large diameter pipes can result in cities or portions of cities being placed on boil water orders. Finally, large diameter pipe breaks can be expensive to repair. Fortunately, compared with smaller diameter failures, large diameter failures are relatively infrequent (due to less large diameter pipe in use, and due to more sturdy construction of large diameter pipe compared with small diameter pipe), yet they do occur.

Large diameter pipe breaks are often reported in newspapers and on TV since they are extremely disruptive, and, in a negative way, photogenic. We have all seen pictures or heard stories about multiple blocks of cities flooded by a broken pipe, or holes caused by a broken pipe which swallow cars or other vehicles, or rescues from homes or cars when people are stranded by flood waters from a broken large diameter pipe. A recent example of a large diameter pipe failure is the one suffered by the Massachusetts Water Resources Authority (MWRA) where a coupling ring on a ten foot (3m) diameter pipe that entered service in 2003 failed, resulting in approximately two million people being put on a boil water order. This event in Massachusetts was the subject of a Foundation co-funded study, 'Multi-agency response to a major water pipe break: a Massachusetts case study and evaluation, final report' (Stratus Consulting, Inc., 2011). While a failure on a ten foot diameter pipe is certainly a major event, the response to this event went very well, and the report identifies many positive strategies and approaches used by the Massachusetts Water Resources Authority that helped this successful response.

Total cost data on large diameter breaks have not been routinely compiled by the water community. Legal issues can follow such failures, in which case much of the related information, including but well beyond costs, is confidential. In these situations the people involved in such events are also often under strict confidentiality requirements. Lack of information clearly makes cost development difficult. Also, social costs, by their very nature, are not paid by utilities. However, in one study in which costs on 30 large diameter breaks were developed in detail, total costs varied from $6000 to $8,500,000, with an average cost of $1,700,000. Direct costs to the utilities for these 30 events were found to vary from $6000 to nearly $7,500,000, but the largest fraction of these utility costs (52%) were associated with claims paid directly by the utility and / or the utility's insurance for property damage (Water Research Foundation, 2007). Thus, over half of the direct costs borne by the utilities are avoidable by avoiding a failure, and these 'costs' could be better used in renewing the piping system, and reducing the chance of failures. These costs get into a range where utilities start to be willing to conduct condition assessment studies to prevent such high cost failures.

Condition assessment

For the purposes of this discussion, condition assessment is any direct or indirect means to try to ascertain the possible condition of your pipeline assets, and thus better determine the likelihood of failure of these assets. In general, condition assessment activities take extra time, effort, and expense over and above operation and maintenance of a utility transmission and distribution system. This additional effort, as well as the technological limitations of the assessment methods, and the cost considerations of pipeline renewal, means that most condition assessment in North America at this time is focused on large diameter pipe, and most particularly on critical large diameter pre-stressed concrete cylinder pipe (PCCP). The resulting condition assessment data are generally useful in assessing the likelihood of failure of a pipeline, although a precise estimate of remaining lifespan of the pipeline cannot be provided.

The Foundation has engaged in a number of studies of condition assessment tools and techniques. Most recently it partnered with the Water Environment Research Foundation in a comprehensive survey of condition assessment tools and techniques published in 2007. This report, 'Condition assessment strategies and protocols for water and wastewater assets', identified 85 condition assessment tools and techniques available to water and wastewater utilities to generate various types of data and applicable to various types of pipe and other assets. Condition assessment tools and techniques for the water and wastewater community are evolving rapidly, and so EPA has recently funded some related condition assessment studies, which are, or will be, available on EPA's website at www.epa.gov/nrmrl/wswrd/awi.

Some of these studies are specific to certain types of pipe or situations. For instance, the 2009 EPA report 'Condition assessment of ferrous water transmission and distribution systems, state of technology review report', EPA/600/R-09/049 is specific to ferrous pipe. These reports will include detailed results of field trials of condition assessment and leak detection tools on an in-place 24-inch diameter, centrifugally cast, grey iron pipe, cement mortar lined. This pipe was removed from potable water service shortly before the field trials, and excavated immediately after. The pipe is being analyzed in detail in a laboratory setting to better understand the true pattern of pipe thickness, corrosion pit occurrence and leakage associated with the pipe. The results of this field trial study and related laboratory assessment work are of high interest to water utilities and will be posted to the EPA website in the near future.

The Foundation has also engaged in some studies to advance condition assessment technologies or to better understand deterioration processes. Most recently it funded a project to advance acoustic monitoring data processing associated with PCCP: 'Acoustic signal processing for pipe condition assessment' (Project 4360). A premise in this study is that the wire breaks associated with deterioration of PCCP will be different from each other depending on how many wires have broken in a given segment of PCCP pipe, so if the data can be processed to make this differentiation then the next wire break experienced in a PCCP pipe could be processed to ascertain its condition.

The Foundation also recently funded a study to improve condition assessment techniques specific to bare (no polyethylene encasement) ductile iron pipe: 'Evaluating the current condition and future performance of ductile iron pipe' (Project 4361). Some Australian water utilities have used linear polarization resistance (LPR) technology and are generally pleased with the results of their work, but this study anticipates some advancement in LPR technology, which could make it more entirely field-based and thus more cost efficient and possibly more accurate as well. These two studies are both funded by, and are part of, the EPA research programme Innovation and Research for Water Infrastructure for the 21st Century, in which the Foundation and the Water Environment Research Foundation are collaborating. In terms of understanding management approaches specific to ductile iron pipe, currently the most common water distribution system pipe being installed, the Foundation recently completed (2011) a study, 'Long-term performance of ductile iron pipes', which also supported the collection and management of break and repair data, stating that: 'This type of analysis conducted periodically (say, every two to three years after having accumulated repair records for eight to ten years) can prove instructive in gauging the deterioration and thus be able to respond proactively.'

Summary

A number of studies have identified a large unmet financial need associated with the deterioration of water utility assets, especially pipeline systems. Addressing this need will require a variety of tools, possibly including new financial tools, improved communications products, and improved engineering approaches to better understand the likelihood of failure and the possible consequences of failure.

An important data input to making better decisions on what to renew is data on pipe breaks and repairs. While all utilities experience pipe breaks, some utilities may undervalue pipe break data. These data will be generated at a utility, all a utility needs to do is to capture these data and analyze them, and odds are they will gain insights into the performance of their transmission and distribution system which they would not otherwise have, especially if they analyze their break and repair data with a record of eight to ten years of similar data. Similarly, condition assessment data can prove very valuable in better understanding the likelihood of failure of critical pipelines, and thus aid in risk management decisions to help prevent such failures.

Taken together, pipe break and condition assessment data support active management of buried assets through improved risk management decisions balancing risk with service levels and minimized life cycle costs. ●

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Applying sustainability to servicing strategy

In this paper, Matthew Ferguson and David Gough describe a range of initiatives developed by the Australian utility Sydney Water to improve its sustainable infrastructure planning and servicing decisions.

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Water industry decisions can be complex, requiring balanced assessment of social, environmental, technical and financial considerations. A sustainable decision is one that weighs up all these factors in a way that is understood and accepted by key stakeholders.

To enable sustainable decisions to be made it is necessary to have an effective and transparent decision framework. It is also necessary to have consistent and comprehensive data regarding the financial, social and environmental performance of the various servicing options.

One of the key areas for improved decision making is area planning, Sydney Water's infrastructure planning framework for determining preferred water servicing strategies for new growth and infill areas. A major focus of these plans is to determine the most sustainable way of meeting water demands that do not require potable water.

To ensure the most sustainable servicing solutions are identified, the area planning process follows an options identification and evaluation framework as outlined in the Sustainability Planning Manual. The Manual and the area planning process will be supported by an Options Library that provides a repository of consistent, contemporary data and assumptions for water and wastewater related products and services. The Options Library, currently under development, will ensure that planners have the best available information to quantify and compare the impacts of various servicing options.

The Options Library also includes various tools such as a carbon estimator tool (for calculating embodied and operational energy), and an average water use model, for consistently forecasting water use based on improved efficiencies as applied to the servicing option.

The planning framework, including the interrelationship between the Sustainability Planning Manual, the area planning process and the Options Library is illustrated in Figure 1.

These aspects of the planning framework, and the Sustainability Planning Manual used in area planning are described in detail in the following sections.

Sustainability Planning Manual

The decision-making framework in Sydney Water's Sustainability Planning Manual is adopted from the Sustainability Framework[2] commissioned by the Water Services Association of Australia (WSAA). The framework consists of a six-phase process that uses multi-criteria analysis (MCA) to inform decision makers about the relative merits of various options.

Key activities addressed in the manual are how and when to engage with key stakeholders, and how to effectively use MCA to understand the relative strengths and weaknesses of various options. MCA is an approach that allows for stakeholders to make strategic decisions by optimising choices based on modelled or predicted environmental, social, technical and financial performance on a relative ranking basis.

The sustainability framework applied in this manual provides steps for engaging stakeholders, setting objectives, developing options and appropriate quantitative and qualitative criteria to measure options, assigning weights to those criteria, and using them to evaluate options and carry out sensitivity assessments.

The manual is in three parts. Section 1 describes the background to the sustainability framework. It explains how to use the manual and how it fits with Sydney Water's existing processes, policies and goals.

Section 2 explains the six phases of the framework, with a particular emphasis on MCA. Each phase lists a set of desired outcomes and objectives. Instructions are provided for required activities to achieve these outcomes, as well as examples of suggested tools and processes. The six phases are listed in Table 1.

Section 3 outlines Sydney Water-specific guidelines, resources and tools that may also be useful throughout the planning process and provides links to these.

Application to area planning

Area planning is Sydney Water's main process for evaluating and identifying preferred servicing strategies for its water or wastewater services. Area planning is undertaken at a number of levels, ranging from a strategic perspective of its overall service provision (Level 1) to plans that identify preferred water services at a local or precinct level (Level 3).

Sydney Water has applied the Sustainability Planning Manual MCA approach to several Level 3 area plans, including West Dapto, Bankstown, Warriewood, Macquarie Park and Sydney central business district. Developments in these areas range from low density residential through to high density residential and commercial uses.

While the plans consider both the provision of drinking water and wastewater services, a key focus has been to determine the most sustainable way of meeting those water demands that do not require potable water. A broad range of options have been considered in these area plans. The options considered most frequently include centralised recycled water, precinct level recycled water, sewer mining, stormwater harvesting, greywater treatment and rainwater tanks.

A key focus, and one of the fundamental changes to the planning approach by Sydney Water in recent years, has been the level of engagement of key stakeholders in the development and evaluation of alternative servicing strategies. This has been achieved primarily through a series of workshops where stakeholders participate in identification and screening of options, establishing evaluation criteria and weightings, scoring

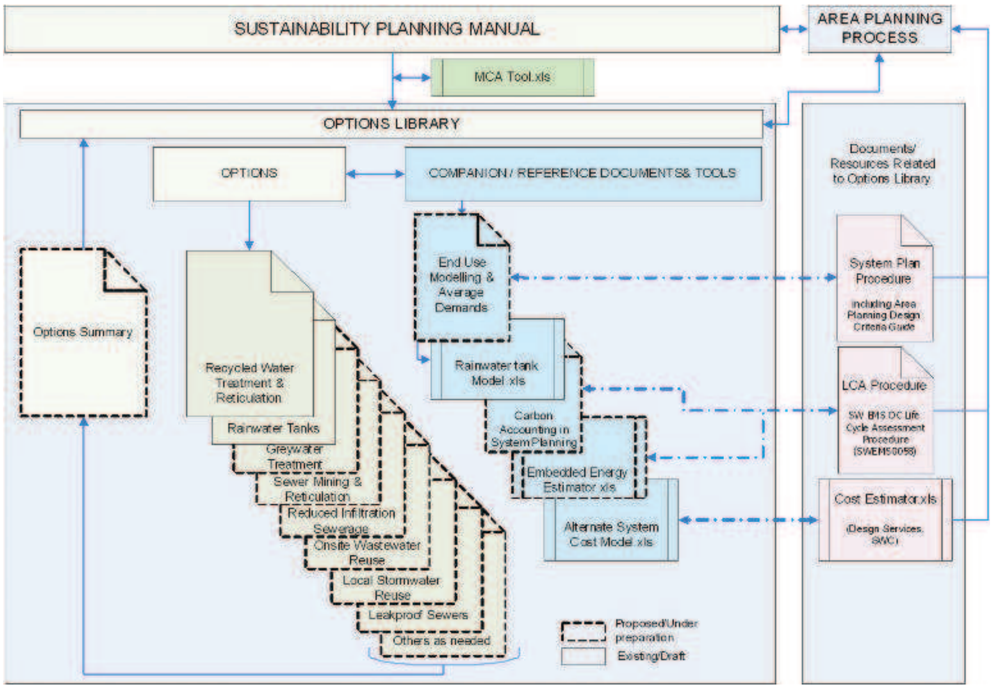

Figure 1
Planning Framework

of options and sensitivity analysis.

Depending on the complexity of the project, and the familiarity of stakeholders with the evaluation process, there is generally one to three workshops held during the options development and evaluation phase.

It is important to note that the outcome of the MCA will not always determine the approach ultimately adopted by Sydney Water for service provision. While the outcomes of the MCA are a critical consideration, the approach ultimately adopted by Sydney Water may take account of other factors such as financial risk, staging of development and funding arrangements for service provision.

Review of Sustainability Planning Manual use in area planning

Recently, the Sustainability Division of Sydney Water undertook a review of the application of the Sustainability Planning Manual in Level 3 planning, with a particular focus on the use of MCA in the evaluation of servicing options. The five area plans identified above formed the basis of the review.

The review was undertaken to establish if improvements could be made to the Manual and the application of MCA, and to provide recommendations that would enhance the transparency and consistency of options evaluation in future area planning. The scope of the review was broad and included project objectives, identification of options, evaluation criteria, weightings, documentation and reporting.

It should be noted that even though the review focused on only five area plans, numerous area plans have been prepared over the last two to three years. They have been prepared by a number of different project teams, with varying mixes of internal and external planning and resourcing. The potential for substantial variations in approach is therefore significant.

The key observations and recommendations arising from the review are discussed below.

Table 1: Phases of the Sustainability Planning Manual

Phase	Purpose
1	Defining the problem, including scope, purpose and objectives
2	Generate preliminary options
3	Select sustainability criteria
4	Screen options
5	Detailed assessment
6	Select preferred option

Options identification

The question of options identification might on face value appear straightforward. However, it is important that the options identified are realistic, and adequately recognise and account for the roles of the householder, developer and utility in operating and maintaining the water servicing option under consideration. The level of customer acceptance, and the level of effort and involvement by the customer in maintaining the required performance of local infrastructure, is an important sustainability consideration.

Performance data, such as water savings, need to be based on expected actual use, not design parameters. Design values indicate the upper expected demand from the system, which means that benefits against a base case scenario will be overestimated.

The options identified must also be realistic and implementable. For example it cannot be assumed that all new medium and high density residential development would have sufficient space or be able to accommodate large on site rainwater collection and storage. Without careful consideration of the configuration and viability of the options under consideration, any comparison and sustainability assessment will be flawed.

A base case scenario option involving extension of existing services (if available) should always be included in short-listing. Without an appropriate base case option, it is not necessarily proven that a preferred alternative servicing solution is the most sustainable.

Evaluation criteria

As expected, evaluation criteria have varied from plan to plan. Water savings, wastewater impacts, costs and energy impacts have been common quantitative criteria across all area plans but have differed in the way they have been measured. Qualitative criteria have generally concentrated on the social impacts and technical risk elements of the options.

Table 2 lists the criteria considered in three of the area plans that have been prepared to date; Botany, Warriewood / Ingleside and Macquarie Park. While some of the criteria are quite specific to the area plan under consideration, it is also apparent that in a number of instances the criteria chosen to address the goals are very similar between area plans. This strongly suggests the potential for further standardisation across area plans, especially in a similar class of urban form (e.g., infill).

Rigour in setting an appropriate set of evaluation criteria early in the process will lead to better decisions and avoid the need to gather data for non-critical measures. For example, removing criteria with weighting of 5% or less results in no change in outcome for the five area plans assessed. Removing criteria with weighting of 10% or less only affects the outcome of two out of five area plans (Warriewood and West Dapto, where the rankings between the highest scoring options were relatively close).

General guidelines for improving the selection of evaluation criteria are:

- Only include criteria that meet the defined project objectives and would realistically affect the decision of one or more stakeholders.
- Ensure data / information is available for each criterion.
- For each criterion, ensure data / information exists that will adequately differentiate the options.
- Minimise overlap of criteria to avoid complex weighting exercises.

As an example, the concept of levelised cost is frequently used by Sydney Water in comparing the water savings from a

Table 2: Evaluation criteria used in area plans

Quantitative criteria	Qualitative criteria
Botany	
Estimated total potable demand	Minimise social disruption
Estimated total potable water saved	Customer acceptability
Estimated potable top-up	Ability to integrate with activities of other water cycle managers
Estimated total wastewater flow to Malabar	Expected level of planning approval complexity
Total capital cost	Flexibility of strategy (timing, demand staging, urban design, etc)
Total operating cost	Efficient use of all infrastructure
NPV $	Reliability of non-potable solution
Levelised cost per kL	
Estimated total kW hours	
Estimated area required for infrastructure, buffers and TSC offsets	
Warriewood / Ingleside	
% saving in drinking water demand per person	Environment, flora, fauna, heritage impact
Average reduction in drinking water production (%)	Risk of over application of nutrients to the terrestrial environment through irrigation with non-drinking water
Total supply of non-drinking water for unrestricted use (recycled + storm + rain)	Expected level of customer acceptance, buy-in and participation
Average reduction in STP effluent discharged to the ocean	Supplementary capacity for bushfires
Preliminary estimates of non-drinking water cost (NPV $/ NPV kL of non-drinking water supplied)	Noise, odour and visual impact
Average greenhouse gas savings for the utility in the supply of non-drinking water	
Average greenhouse gas savings for the customer in the supply of non-drinking water	
Macquarie Park	
Minimise drinking water use	Level of acceptance by customers and community
Minimise lifecycle energy use	Property owner's acceptance of option
Minimise wastewater discharge to the environment	Integration with existing strategies, plans and works of Government and / or Council
Minimise lifecycle cost	Ability to accommodate change (growth rates / change in technology)
	Ability to contribute to Council's stormwater objectives
	Risk of scheme failing, resulting in a third party stepping in

project in relation to the cost of achieving those savings over the life cycle of the project. It is defined as the present value of the expenditure divided by the present value of the water saved (i.e. PV $/PV kL). However, it is not always an appropriate measure of cost in an MCA. First, it overlaps with the 'minimise potable water use' criterion. It also suggests that all costs are to achieve water savings. This ignores expenditure to achieve other goals, such as wastewater overflow benefits, community amenity, etc.

Evaluation criteria should be established early in the evaluation process and generally not altered throughout the assessment process. The addition of criteria to finesse the outcome will not typically improve the outcome. This is because additional criteria are usually less important than the original criteria, leading to the added criteria receiving a very small weighting. A criteria with a low weighting will not significantly change the result and will lead to the original weightings becoming less important.

Weightings

In general, weightings have been been fairly consistently applied across area plans, with some tailoring to specific project needs. Figure 2 illustrates the weightings that were applied for the main evaluation criteria across the five area plans. Not all objectives were considered for all area plans. Cost, flexibility and the degree of integration (i.e. the extent to which the proposed option can integrate with or leverage existing services), and drinking water savings have generally been the highest weighted criteria. Wastewater performance has on average been weighted highly but also shows the widest distribution of weights.

Sensitivity testing

A good idea for sensitivity testing is to use the full range of weights used in previous area plans. Comparing weights improves a decision maker's ability to better understand what is different about their area plan and its influence on results.

Sanity checking of weighting typically needs to be applied. For example, energy has been weighted relatively highly, on average over 10%. Despite the high weighting there is usually little difference between the options in terms of energy consumption and/or confidence in the energy estimates. It is therefore an important part of sensitivity testing to test how this uncertainty impacts on the outcome of the MCA.

Documentation

To improve the consistency and transparency of documentation a minimum reporting requirements reference table has been developed, based broadly on the Sustainability Planning Manual. This reference table aims to improve the ability to review the MCA supporting document, as well as acting as a checklist for the document authors to ensure their report is complete.

MCA outcomes

A detailed comparison of the individual MCAs shows that they have been largely consistently applied, but the solutions have differed between areas. Assessed residential schemes are dominated by rainwater tank servicing solutions with recycled water being viable in some areas. Local recycled water (sewer mining / on site) has been the preferred option in area plans with predominantly high-density development.

Table 3 summarises the preferred solution for each area plan based on the MCA evaluation and the key drivers for that decision.

It is interesting to note that the application of the Sustainability Planning Manual led to the identification of the lowest cost option as preferred in only two out of the five area plans. The drivers of the preferred solutions have been found to be different for each area plan, even when the same preferred option was identified. While the cost and cost risk performance differences have dominated a few area plans, other non-cost criteria have been the deciding factors in other area plans.

Review of the MCA results showed that Bankstown, Macquarie Park and Sydney CBD had clear preferred options. In Warriewood, the full range of options scored quite closely. However, in the case of West Dapto, the decision between rainwater tanks and providing recycled water is relatively close and small changes in the assessed impact of rainwater tanks on wet weather system performance may have impacted on the result.

A closely scored MCA after appropriate data checking and sensitivity testing indicates that options are equally 'sustainable'. The process should be terminated at this stage and the decision made on a business needs and risk basis.

Precinct level sewage treatment plants (i.e. distributed centrally managed sewage treatment plants) have scored poorly in area plans to date (Bankstown, West Dapto, and Sydney CBD). This has been primarily due to low weighted scores for costs, cost risk and customer acceptance.

In part such low scores (for what might be intuitively regarded as attractive options) may be due to limited knowledge and confidence regarding the various aspects of option performance. In general, scoring tends to favour those options with known performance and risks, so if there is a strong desire to promote 'innovative' responses, it may be necessary to review the evaluation criteria and reduce the dependence on proven performance, reliability etc.

The development of the Options Library will provide more data to planners on the various aspects of performance of decentralised wastewater treatment and go some way to addressing this issue.

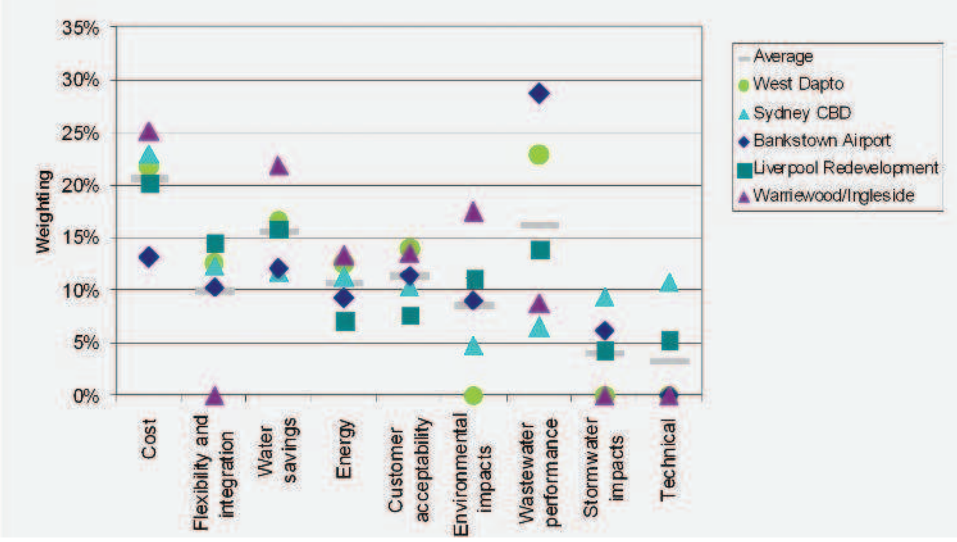

Figure 2 Criteria weighting for selected Area Plans

Options Library

To improve the consistency and efficiency of area planning an Options Library is currently under development. The Options Library is a suite of related documents that detail and summarise the major attributes of water related options (e.g. rainwater tanks, recycled water reticulation, sewer mining, decentralised wastewater systems) that should be considered for servicing urban growth or new market opportunities.

The Options Library will provide:

- Resources to assist in consistent and transparent planning.
- A repository of shared knowledge and data, kept up to date to enable efficiency and accuracy in planning.
- A structured approach to investigating and comparing alternative products and servicing options, especially emerging initiatives.

Each option document focuses generally on the areas in Table 4.

To give a more complete picture of how an option might be applied and to determine its relative strengths and weaknesses, a typical application is assumed. Some guidance may also be provided on how the option would be applied to a particular area or different development type.

This provides both the quantitative and qualitative information to cover the most crucial MCA criteria, and particularly those that can be used to distinguish between different options.

A number of tools and reference documents are included in the Options Library and provide the basis for most comparative data in the Option Documents. These are intended to not only detail the methods used to populate qualitative and quantitative information in the option documents but also to be a resource in their own right.

Documents or tools either available or under development) include:

- Average water use model: provides a method planners can follow in estimating future average water use for different residential development types, lot sizes and location, depending on the option (rainwater tanks vs greywater etc.).
- Carbon accounting in system planning: basis for and guidance on how to calculate operational and embodied energy for water systems and use in decision making.
- Carbon estimator tool: for calculating operational and embodied energy and associated greenhouse gas impact for water related options.
- Alternate system cost model: tool for calculating capital cost, operating costs and approximate sizing of different recycled network supply configurations, for a range of input variables such as demand, minimum pipe sizes, standards of service, etc.
- Cost of carbon abatement tool: Sydney Water recently developed the Cost of Carbon Abatement (CCA) Tool as part of a wider project with our energy partners (Energetics and Worley Parsons) to identify and assess opportunities to reduce carbon emissions. The CCA Tool allows comparison of the economic return for each opportunity by calculating the levelised cost per tonne of emissions reduced over a given period (e.g. 30 years). The tool then allows the information to be presented in the form of a cost of abatement curve, or graph. Scenarios can then be run on future energy and carbon prices and the extent of voluntary reduction commitments that a utility may have committed to, all of which impact the economic viability and timing of opportunities.

Conclusion

Sydney Water has made very significant efforts to enable sustainable decision making in providing water related

Table 3: The preferred solution for each area plan

Area plan	Preference	Drivers
Sydney CBD	On site recycled water	Cost, capital risk
West Dapto	Rainwater tanks	Capital risk, wet weather prformance
Warriewood	Rainwater tanks	Cost
Bankstown	Rainwater tanks	Lower environmental impact, customer acceptance
Macquarie Pk	Sewer mining	Water savings, reduced wastewater discharge

Table 4: Areas of the option documents

1. Option description	7. Customer involvement, responsibility and acceptance
2. Customer uses and service standards	8. Utility / stakeholder involvement / responsibility
3. Water use	9. Adaptability and staging
4. Cost	10. Option availability, issues and current analysis
5. Energy and greenhouse gases	
6. Environmental and community impact	

services for growth areas.

This paper illustrates that the quest for sustainable decision making involves significant effort and requires careful consideration of a number of factors. These include improved options data, applying robust and transparent processes for decision making including the application of MCA, and providing appropriate tools and other support to planners involved in identifying and evaluating serving options.

The application of the Sustainability Planning Manual and the use of MCA led to a number of different servicing solutions being identified as the most sustainable in different area plans. This is appropriate as the selection of a sustainable servicing strategy is influenced by local circumstances, the available performance data for the alternatives, the views of stakeholders, the evaluation framework, and the detailed manner in which the decision framework is applied. The outcomes highlight the risk in having preconceived views about what is or is not a sustainable servicing strategy.

The Options Library will provide a valuable resource to planners, providing them with comprehensive and contemporary data on the costs and performance of servicing alternatives. It will promote efficiency, transparency and consistency in planning across the organisation.

Sydney Water will continue to develop the data, decision making frameworks, and tools to help planners evaluate sustainable servicing options in a manner that is transparent, consistent and efficient and understood and accepted by stakeholders. ●

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Asset management of valves

Valves are an important component of drinking water distribution systems, allowing water companies to isolate pipes for maintenance or in response to incidents, amongst others. If work is undertaken in a section and a valve does not function properly, customers in an adjacent section can also be affected. Malfunctioning valves can thus influence the availability of the whole water distribution system.

Valve maintenance increases the valve reliability. Here, Mirjam Blokker, Ilse Pieterse-Quirijns, Eddy Postmus, Vera Meira Marmelo and Luis Lourenço Mendes discuss the software tool CAVLAR, that helps water companies to analyse complex networks and develop a targeted maintenance programme for valves.

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Valves in drinking water distribution networks are essential for isolating incidents, such as pipe breakage, pipe failure or contamination events, to ensure continuity of supply. The basic function of valves is to isolate a section of the distribution network to limit the effect, and therefore the risk, of an incident to the surrounding network. Valves are also used for flushing the network or creating pressure zones.

Valves are not 100% reliable and thus can influence the availability of the water distribution system as a whole. In fact, the effect of malfunctioning valves can be quite large as for every malfunctioning valve several additional valves need to be closed (Trietsch and Mesman 2006). The reliability of a valve relies on: the ability to locate the valves, to identify them, to access them, to turn the valves, and degree of closure (Rosenthal et al. 2001). An inventory of valve management in The Netherlands by van Thienen et al. (2011) showed that valve reliability is not assessed in a structured way by all Dutch water companies, and that the reliability of valves that are not being maintained can drop considerably to below 85%. The consequence is that valve maintenance increases the average valve reliability. One Dutch water company has increased the valve reliability from 91% during unstructured valve maintenance to 95% in a maintenance programme where each valve is inspected once every three years (van Thienen et al. 2011).

Some isolation or shut-off valves are more critical in the network availability, either due to the probability of use or the effect of valve failure. It may therefore be cost effective to put a more stringent maintenance programme on these critical valves than on other valves. Due to the historical development of drinking water distribution systems, many distribution networks are quite complex, and therefore understanding the reliability of the system can be difficult. In order to optimise a valve maintenance programme a method to quantify the effect of valve failure, and thus identify critical valves, is required. KWR has developed the software tool CAVLAR for this purpose. This paper shows the application of CAVLAR in two case studies on optimisation of valve maintenance: one in the Netherlands (a town in the supply zone of Water Company Groningen) and one in Portugal (an part of the Lisbon network supplied by EPAL). The case studies illustrate the effect of a targeted valve maintenance programme on cost and customers.

Performance indicator for interruption of supply

Scheduled or unscheduled work on pipes requires the isolation of a section by closing valves. This will interrupt the supply to the customers within the isolation section. In the event a valve does not function properly, customers in an adjacent isolation section can also be affected. The effect on customers can be expressed with several performance indicators (Alegre et al. 2000), of which CAVLAR computes four: the impact (the number of connections that are affected, including those in adjacent sections); the ratio between the impact and the number of connections in the section with the pipe burst; the CML (customer minutes lost, in minutes per customer per year); and CI (customer interruptions, the number of interruptions per year).

CML is registered by all Dutch water companies for asset management purposes as well as for national benchmarking. In 2009 the average CML due to both scheduled and unscheduled work was 17 minutes per customer per year (Vewin 2009). The CML is comprised of the probability of a pipe break in each isolation section, the duration of interruption and the number of customers affected. CML is defined by the following equation (Blokker et al. 2005):

$$CML = \frac{\sum_{i=1}^{N} d_i \cdot c_i}{M}$$

with *i* counting all events of supply interruption (from *1* to *N*), *di* the duration of event *i*, and *ci* the number of connections that are affected by event *i*. *M* is the total number in the connections. A connection in the Dutch definition is a billable address. The duration (in minutes) is defined by the time it takes, after the valves are closed, to repair the main and open the valves again.

EPAL has suggested its most important valves as the ones that experience the highest flows at 8.00 am and the ones needed for flushing. They have not used a performance indicator related to customer impact in their operations.

For the purpose of valve maintenance, a performance indicator is required to prioritise sections or valves. Based on the common practice in The Netherlands, CML was selected as an appropriate performance indicator for both case studies.

CAVLAR calculations

The performance indicators that CAVLAR computes are determined by the probability of a pipe burst, the duration of interruption and the number of affected customers per section. They are also determined by the probability of each shut-off valve functioning properly. CAVLAR computes the performance indicators per isolation section with a given reliability of each valve. CAVLAR considers all surrounding sections, not just the neighbouring sections.

CAVLAR imports a water distribution network model (e.g. in EPANET format) and converts it into a section and valve model. The required information per section (defined by a unique identifier) is the number of connections in that section, the section length, the pipe failure probability in the section (number of bursts per km per year) and whether the section is a feeding section or not. The required information per valve (defined by a unique identifier) is the two sections between which the valve is placed and the valve reliability (in %). In order to compute the CML information on interruption duration (in minutes) also needs to be set. Apart from the network configuration the input parameters from Table 1 are used in the case studies. Location specific values for failure rate are explained in the description of the case studies.

With the calculated performance indicators CAVLAR can identify the most critical valves. These are the valves that in case of malfunctioning would have the largest effect on the performance indicators (Trietsch and Mesman 2006). By setting the valve reliability of the most critical valves to a higher value than for the less important valves and repeat the calculations, the effect of a targeted valve maintenance programme can be determined.

Case study Winschoten

Water Company Groningen wanted to define a targeted valve maintenance programme for the town Winschoten in the north east of The Netherlands. For this purpose the water company deployed CAVLAR. First, a water distribution network model of Winschoten (Figure 1a) was constructed from SHAPE files containing information of pipes, valves and customer connections. The connection pipes with small diameters were filtered out. The network model was then imported into CAVLAR. The connections were determined with the help of the base demand. The resulting model in CAVLAR is a section diagram (Figure 1b). The section diagram immediately shows where the large sections are, which sections require many valve closures, and which sections have only one valve and thus are very vulnerable. Table 2 provides some information on the network characteristics.

The valve configuration of the Winschoten network is based on valves needed for flushing and the water company's constraints on section size (a maximum number of 200 connections per section, and a maximum section length of 2000m) and maximum number of valves needed for section isolation (five). The water company's constraints on network configuration are not always met in practice. Figure 2 shows some configuration characteristics. There are a number of dependent isolation sections. These sections are only connected to one other isolation section, with one valve. If this other section is shut off, the dependent

Table 1: Settings for the CAVLAR calculations

CAVLAR settings	Groningen	EPAL
Failure rate (# / km.year)	0.04	0.17
Interruption duration (min / interruption)	180	180
Valve reliability (%)	80 - 100	80 - 100

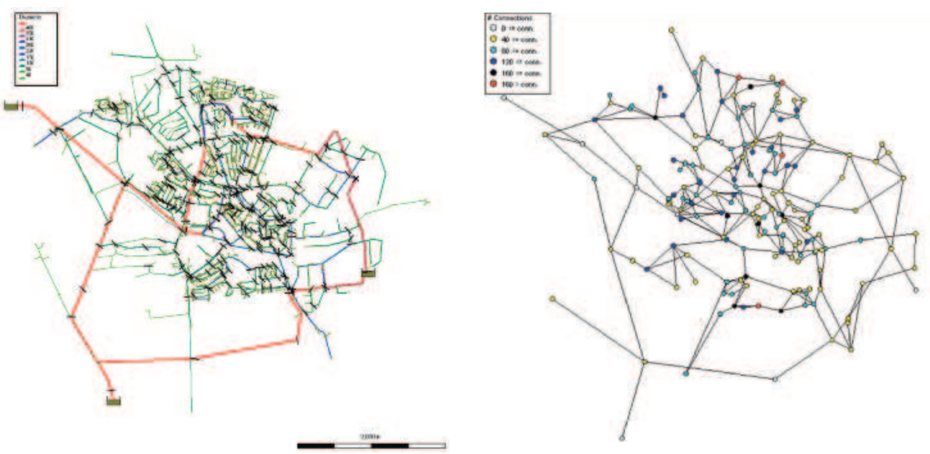

Figure 1 Winschoten configuration a) network layout, colours denote pipe diameters, the black lines are valves; b) section diagram. Circles are sections, lines are valves, and colours denote number of connections per section.

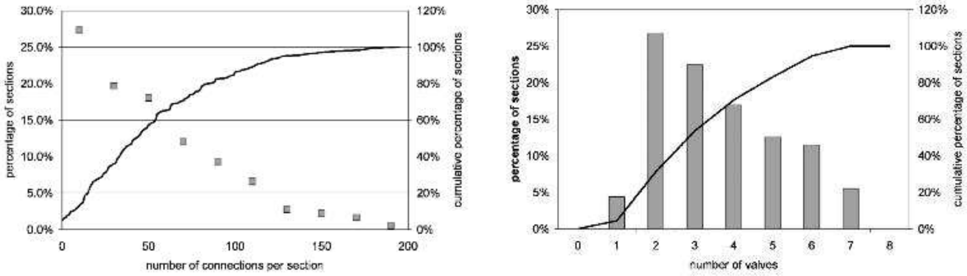

Figure 2 Configuration characteristics a) number of connections per section; b) number of valves per section.

section is also affected. Of the eight isolation sections with one valve (Figure 2b), three are feeding sections and five are dependent sections (Table 2). Some dependent sections may be present when sections would otherwise be too long. The maximum number of customers in a section is 195 (Figure 2a), the average is 52.5. The length per section varies from 43m to 3.3km, with an average length of ca. 830m.

The valve criticality analysis with CAVLAR was done with the parameters of Table 1. The valve reliability was set to a range of values. The failure rate of 0.04/km.year and the duration of interruption of 180 minutes are average values for the entire network of the water company. Water Company Groningen does not have an extensive maintenance programme it was estimated that the average valve reliability in the network is ca. 85 to 90%. With an intensified maintenance programme a reliability of 95% is achievable (van Thienen et al. 2011). With CAVLAR the most critical valves were identified.

Table 2: Network characteristics of the case study distribution networks.

Network characteristic	Winschoten	part of EPAL network
Total length (km)	151	65
< 100 mm	14%	11%
100 – 150 mm	52%	37%
150 – 200 mm	18%	19%
200 mm	4%	19%
≥250 mm	12%	14%
Number of customer connections	9602	12925
Number of valves	333	373
Number of isolation sections	183	250
Number of feeding sections	3	3
Number of dependent isolation sections	5	n.a.

Case study Lisbon

EPAL prepared an EPANET file that was imported into CAVLAR. The number of connections per section was determined by converting the base demand per node with 30 customers per m³/h. This means that large volume customers are given an extra weight in assessing the CML. Other sensitive customers such as hospitals, haemodialysis centres or schools can be given an extra weight, but there were none in the case study area. Table 2 shows some of the network characteristics.

A failure rate of 0.17 per km per year was used for the EPAL pipes. This is based on actual average failure rates of EPAL. Furthermore, the CAVLAR specific parameters (Table 1) were similar to the values of Water Company Groningen.

EPAL has systematically inspected its valves since June 2009. Until August 2011, 66% of the total number of 7036 was inspected. The valves were inspected on several aspects, and this was recorded. The valve inspection was usually done only if the maintenance people had some time left. The valves that were inspected were thus selected on their proximity to other work, not according to their importance. Table 3 shows that the valve reliability in Lisbon is 94% and the most prevailing failure mechanisms are identification and accessibility. The main question for EPAL was to determine which valves to focus on during the limited time that they have for valve inspection and maintenance.

Case study results

Winschoten

With the given probability of pipe failure, the duration of interruption and network configuration, the minimum CML (found with a maximum valve reliability of 100%) is eight minutes (Figure 3). With a valve reliability of 90% the CML is equal to 12 minutes.

With an intensified maintenance programme a reliability of 95% is achievable (van Thienen et al. 2011). Increasing the reliability of all valves from 90% to 95% will decrease the CML by 19% to 9:40 minutes. When only some of the valves are subjected to an intensified maintenance programme these valves will have an assumed reliability of 95%, while the rest of the valves still have a 90% reliability.

In case 20% of the valves with increased reliability are randomly selected this will reduce the CML with 3.9% (Figure 4) to 11.5 minutes. In case these valves are selected based on their criticality a CML reduction of 8.1% can be achieved (Figure 4). This means a reduction in CML from 12 to 11 minutes. A targeted valve maintenance programme will lead to a 100% higher benefit with the same investment. Moreover, this 8.1% is 42% of the maximum gain in CML (which is 19%) with only 20% of valves that need to be maintained.

Lisbon

To meet EPAL's question, which valves to focus on during the limited time that they have for valve inspection and maintenance, CAVLAR was used to prioritise the valves. The top 10% of most important valves according to CAVLAR was compared to the top 10% list of EPAL, based on practical experience. Some valves are the same, but there are also differences (Figure 5). The EPAL identified valves are mainly located at the trunk mains and tanks and pumps. CAVLAR helps to identify which valves in the distribution network, close to the customers, are the most important ones with respect to effect on customers.

For the case study of Lisbon, targeted valve maintenance was investigated as well. The case study of Lisbon leads to similar results as the Winschoten case of Figure 4, i.e. maintaining the 20% most important valves would lead to a 75% of maximum gain in CML.

General

Optimising valve maintenance of critical valves results in a good performance at a lower cost. Changing the valve configuration may have a larger impact on performance of the distribution network than valve maintenance. Generally, networks are

Figure 3 CML as a function of valve reliability for all valves in the network

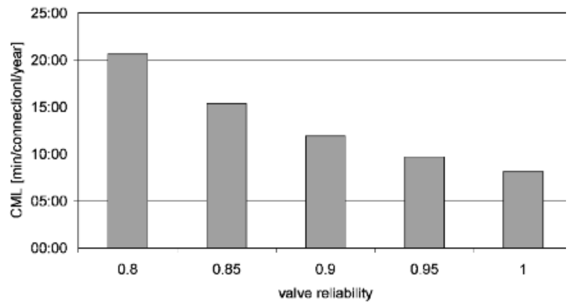

Table 3: Valve inspection results of EPAL

		Year of inspection		
		2009 (June –Dec)	2010	2011 (Jan – August)
Number of valves checked		1143	1449	2055
Number of anomalies	valve cannot be located	0	0	15
	valve cannot be identified	31	36	72
	valve cannot be accessed	20	29	48
	valve cannot be turned	15	9	14
	valve cannot be closed	1	0	1
Valve reliability		94.1%	94.9%	92.7%

characterized by an excess of valves. CAVLAR can also be used to evaluate different valve configurations (Trietsch and Mesman 2006). To find the optimal valve configuration, CAVLAR could be used in combination with optimisation methods (Giustolisi and Savic 2008; Jun 2005; Ozger and Mays 2005).

CAVLAR determines the effect of closed sections on the availability of supply to customers without doing a hydraulic analysis, i.e. without considering the pressure. There is no limit to the size of a network that CAVLAR can calculate. However, because of the pressure constraints in actual networks it is recommended to calculate parts of the network that can be supplied from all the available sources in the hydraulic model. Because The Netherlands is a flat country the pressure differences are small, and large networks can be analysed by CAVLAR. The Lisbon network has much larger differences in elevation than the Dutch networks do. The pressure differences may mean that some pumps or reservoirs are not able to supply a part of the network in case of a failure of another part. This should be considered when defining sub models for CAVLAR analysis.

The Lisbon network is configured with DMAs (district metered areas). This means that there are also some valves that are closed during normal operation. If such a valve cannot be opened, this should also be considered as a failure. This currently is not included in the valve inspection protocol, or included in CAVLAR, so is a feature that could be included in the next version.

Conclusion

Valves are an important component of drinking water distribution systems. However, valves are not 100% reliable and thus can influence the availability of the water distribution system as a whole. Valve maintenance increases the valve reliability. CAVLAR helps water companies to analyse complex networks and identify the most important valves. This means a targeted maintenance programme on valves can be determined. An optimised valve maintenance scheme reduces the costs of valve maintenance, while guaranteeing a good performance. A Dutch and Portuguese case study illustrate that, depending on the network configuration, with a targeted maintenance scheme on only 20% of the valves the affect on customers can be reduced by 42% to 75%. ●

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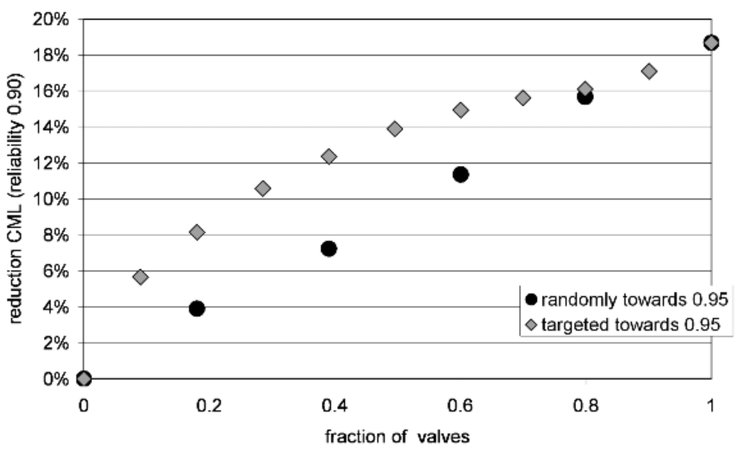

Figure 4
Reduction of CML in Winschoten case study when valve reliability is gradually increased from 0.9 towards 0.95 in a random order or targeted, i.e. based on valve criticality.

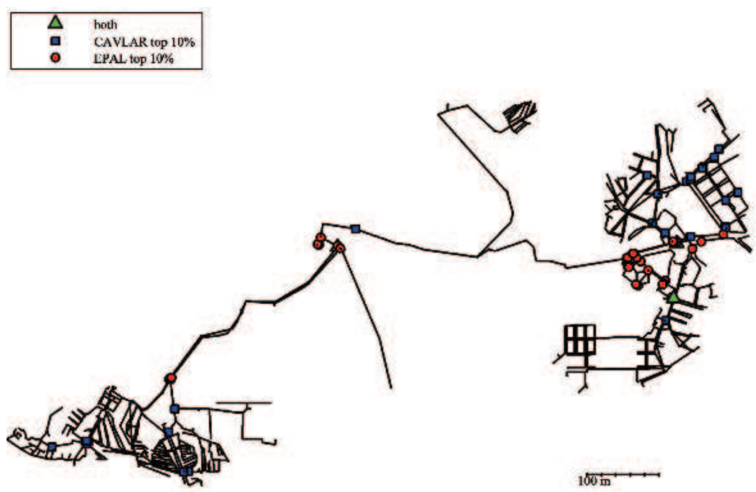

Figure 5
Top 10% important valves according to EPAL ranking and CAVLAR CML ranking

Measuring the effectiveness of condition assessment

Assessing maintenance effectiveness is critical for asset managers in order to evaluate the contribution of maintenance towards business goals and to plan preventive maintenance activities. In this paper, Delly Dlamini, Shaomin Wu and Simon Pollard propose a method for evaluating asset maintenance effectiveness when data are especially sparse.

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Maintenance is the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function (BS 3811, 1993). It provides critical support for heavy and capital-intensive industries by keeping machinery, equipment and infrastructure in a reliable operating condition. It is generally accepted that maintenance is a key function in sustaining long-term profitability of capital-intensive organisations (PAS 55-1, 2008). Maintenance costs must be contained and minimised to maximise profits. Such costs include capital expenditure and operating costs. In order to manage these costs, asset managers have to plan maintenance programmes in advance. This requires organisations to assess the effects of each maintenance action on the reliability or condition of the asset, which is referred to as 'maintenance effectiveness' (ME) assessment. Neely et al (1997) define maintenance effectiveness as the process of quantifying the efficiency and effectiveness of a maintenance action. Assessing maintenance effectiveness is important because it allows asset managers to determine the quality of their maintenance programmes for possible improvement.

Water utilities are particularly asset-intensive and allocate a large proportion of their capital to assets and operating expenditure to maintenance activities. Government regulation of the water industry means that water utilities cannot easily pass on maintenance costs to customers. Therefore, they are pressured to put in place and maintain effective maintenance strategies in order to minimise maintenance costs and maximise profits. Water utilities also maintain assets in order to preventatively manage risks to public health and the environment. To achieve optimal operation levels, utility operations managers have to ensure equipment in daily operations is in good order and kept at expected operational levels. This contributes to the monitoring of maintenance effectiveness. Such assessments of maintenance effectiveness are part of an effective maintenance strategy and can also contribute to, and be useful in: planning future investment; scheduling maintenance regimes; selecting maintenance companies; and evaluating the residual value of maintained systems. An effective maintenance strategy, therefore, is one that supports the organisation's main asset management processes, such as breakdown risk assessments, planned and reactive maintenance, predictive maintenance, reliability-centred maintenance programmes and total production maintenance (AWWA, 2006; UK Water Industry Research (UKWIR), 2002; British Standards, 2003). An effective maintenance strategy relies on some asset condition assessment.

Defined as the process of measuring the structural capacity of an item or asset given its deterioration levels, condition assessment is important in assessing maintenance effectiveness (Marlow and Burn, 2008). Maintenance and financial plans are usually developed from asset condition assessment information. Since it involves asset identification, inspection, data storage and contextualising the condition of assets, condition assessment can be complex. Maintenance and operations engineers are at the forefront of condition assessment. Data are typically gathered from daily operations and maintenance of water infrastructure equipment and used for strategic decision-making. Operations and maintenance engineers assess the conditions of water distribution equipment occasionally and the operations data are kept in log books or database systems. Maintenance managers therefore make key decisions on what asset condition data are important, and ensure that such data is logged by engineers daily.

Without the efficiency of the daily frontline operations, condition assessment is rendered ineffective or impossible, as it is dependent on such data to be effective (Chu and Durango-Cohen, 2008). Operational and maintenance managers should ensure, therefore, that systems are in place for frontline engineers to collect operational data as part of the organisation's value chain and effective asset management strategy. Different condition assessment models are developed based on computer-generated conditional probabilities and assuming full data availability (Kleiner, 2001 and WERF, 2007). Where there is no data, experts' opinions are usually sought for condition assessment in a water utility and fixed full values used without considering error margins (Werey et al, 2008).

Referred to as soliciting subjective opinions from experts, the use of expert elicitation in practical applications of reliability and risk analysis has increased over the years (Singpurwalla and Song, 1988; Hokstad, 1998; O'Hagan et al 2006; Boring, 2007). There are many opportunities for reliability analysts to develop procedures for using experts' opinions in asset management. Here we are concerned with expert elicitation in assessing the condition of an asset as a prerequisite for assessing the quality of its maintenance effectiveness. Few studies that use expert elicitation to assess system reliability have developed methods to assess maintenance effectiveness (Sandri et al, 1995 and Bedford et al, 2006). These studies do not focus on specific asset groups and tend to assess asset condition without linking it to maintenance effectiveness (Wang and Zhang, 2008 and UKWIR, 2002).

Method development

Here are outlined the steps used to assess asset condition and offer an approach to assessing maintenance effectiveness. Condition assessment can be conducted through subjective assessment, distress-based evaluation, or non-destructive testing. Subjective condition assessment is performed on the basis of visual inspection, in-situ measurements, or subjective expert opinion. This paper is concerned with assessing subjective expert's opinions. A typical protocol of the subjective condition assessment, widely used in many industries, includes the following steps.

- Step 1 – preparation. At this stage, a condition assessment protocol is developed. The main steps are:
  - Step A: identification of variables influencing the condition of an asset, and selecting those that are more important.
  - Step B: defining the grades of each variable that impact asset condition.
  - Step C: weighting the variables to assign an importance / weight score to each.
  - Step D: combination of the assessments to aggregate the condition grades from Step A and their corresponding weights defined in Step B to produce a condition assessment.
- Step 2 – training experts on the condition definitions and probability assessments.
- Step 3 – walk-through inspection: the experts will then score each variable defined in Step A above. This can also be performed by trained experts based on viewing CCTV tapes or digital movies, in conjunction with site inspections.
- Step 4 – aggregation: the scores of the variables assessed in Step C will then be aggregated with the method defined in Step D.

Steps 3 and 4 need to be done twice, before and after a maintenance action, which yields the maintenance effectiveness value.

Step A: identification of variables

The set of variables to be considered for each group of assets in assessing their condition and assessing maintenance effectiveness can be large. It is critical to determine the set of variables that provide a relevant representation of the phenomenon under study.

Suppose that there are M^i variables, where M^i represents a number of variables selected by an expert initially, that might impact the condition of an asset. The value M^i might, however, be too large, so we then select only variables with a significant impact on asset condition. We invite N^e, the total number of experts, for their opinions on the most important variables.

Within the M^i variables, experts are required to select a proportion (M^m). The experts also rate the importance of the variables they have already selected. They rate their M^m variables to be R_{ij}, where $i=1,\ldots,N^e$, and $j=1,\ldots,M^m$. C_{ij} means the importance of the j-th variable assessed by the i-th expert. Some R_{ij} might be zero, indicating that the variable does not contribute much to the asset condition.

After ranking $\sum_{i=1}^{N^e} R_{ij}$ in descending order, where $j=1,\ldots,M^m$, the most important (M^f) variables that have the largest importance $\sum_{i=1}^{N^e} R_{ij}$ are selected.

It should be noted that there are two widely used approaches to reaching a consensus of experts' opinions. These include behavioural approaches and mathematical approaches.

- Behavioural aggregation: group consensus opinion is treated as a single 'expert'.
- Mathematical aggregation: applies an algorithm to combine experts' separate distributions.

Step B: defining the grades of each variable

The grades of each variable that might impact asset condition are defined. For example, for the pump mentioned in Step A, the grades of the wear status might be defined as 'as-new', 'minor wear / tear', and 'significant signs of wear / tear'.

Step C: weighting the variables

The experts are asked to assign an importance / weight to each variable selected from Step A and to assess the condition of the item based on the final (M^f) variables they selected above. N^e experts assess the impact of each variable (M^f in total) on asset condition. Assume that the expert i assesses the importance of variable j to be S_{ij}, where $i=1,\ldots,N^e$, $j=1,\ldots,M^f$. The experts need to agree on their final decision. This will result in M^f different grades, say G_j, with $j=1,\ldots,M^f$.

Experts are then asked to carry out walk through inspection. Assume that expert i rates the j-th variable to be C_{ij}. For example, for a given pump, an expert might assess its wear status to be 'minor wear / tear'.

Step D: combination of the assessment

The asset condition is then estimated to be, for example, if a mathematical approach is applied:

$$\sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij} \qquad (1)$$

where G_j represents the condition rating of the relationship between the asset condition and each of the M^f variables. C_{ij} represents the rating of the importance of the j-th variable as assessed by the i-th expert.

Step E: assessment of maintenance effectiveness

In assessing maintenance effectiveness, first the experts determine the asset condition and give their condition rating before and after a maintenance activity, in line with equation (1). In qualitative terms, the asset could be 'as before', 'better than before', or 'worse than before' the maintenance action was carried out. The maintenance effectiveness is, therefore, given by:

$$\mathrm{ME} = \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}^{a} - \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}^{b} \qquad (2)$$

where C_{ij}^{a} represents the condition grade after a maintenance action and C_{ij}^{b} represents the condition value before the maintenance action (Figure 1). The asset condition value given by experts for after and before could be the same, indicating an ineffective maintenance (as before). Where the maintenance effectiveness value (ME) is positive, the asset could be classed as 'better than before'. A negative maintenance effectiveness value would be classed as 'worse than before'.

Case study analysis and discussion

In order to illustrate these approaches, an asset condition assessment case study from an artificially generated water utility is used below. A hypothetical water pump is initially assessed by external experts to determine its condition where there is no historical performance data to assess it.

Variable selection

Many performance indicators or variables impact on the pump's performance, so it is determined that only a few of the pump's performance variables can be used to assess its condition. The water utility management decides to invite five (N^e) experts to select the most important pump performance variables to use in assessing its condition. The total number of (M^t) variables that are associated with the pump condition have been identified and the experts are invited to first select (M^m) variables to use in determining the pump condition. The importance scores of each variable are also elicited (Table 1) and the final M^f variables are the ones with the highest importance scores.

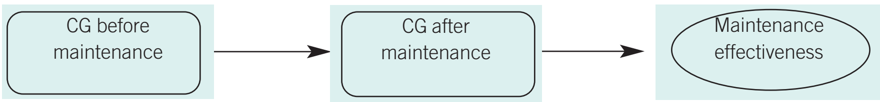
Experts are then asked to rate the importance of each of the M^m variables they have selected in the initial shortlist. The importance of each variable is ranked from 1 to 5 – with one being the least important and five the most important rank (Figure 2).

presented in Table 3.

Experts then rate the three variables they have selected for pump performance to assess the pump condition grade (Table 3). After rating each of the three performance variables for the pump, the experts then agree on an overall pump condition grade. In this case experts agree the pump condition grade is 1.5, which is between 'as new' and 'fair'.

The condition assessment method takes into account performance variables that are specific to the asset (a pump in this case). Internal operational and maintenance engineers assess the three major performance indicators established by the external experts and

Figure 1 **Maintenance effectiveness assessment process**



We assume that experts rate their M^m variables to be C_{ij}, where $i=1,\ldots,N^e$, $j=1,\ldots,M^m$, and C_{ij} means the importance of the j-th variable assessed by the i-th expert. Some of R_{ij} might be zeros. A variable can be selected several times by different experts and the importance total on the same variable is assessed. With all of the variables with difference importance weights, the most important final (M^f) variables are then selected. Table 2 show standard water pump performance indicators (M^t), from which experts select a few (M^m) for assessing the pump condition.

The performance variables finally selected to use in assessing the pump condition are wear status, vibration / sound and oil leakage. In order to assess the pump condition on a frequent basis, operational and maintenance engineers are oriented to the condition assessment criteria, including the basic variables selected by the experts and the variables used by the engineers to assess the pumps condition on a monthly basis. This is to ensure the condition assessment is mainstreamed as part of the organisation's value chain. The historical performance of components must be available for assessment over time. External experts are invited once the condition assessment system is established and operational managers implement it. This is done to condition assessment costs, as external experts are generally expensive to employ (Urquhart, 2006).

Pump condition assessment

Condition grades are defined and used by the experts to rate the condition of the pump. For the three most important variables that the experts chose, the condition grades are defined as

rate the pumps' condition on a regular basis, with intervals determined according to asset type and organisational data needs.

The method can be further developed to include other aspects that can measure asset condition, such as health and safety, statutory compliance and others. For example, the building condition assessment protocol developed for the housing sector includes these (HESA, 2009). This would enhance the strategic management value of asset condition assessment as it would provide a much wider overview of the asset demands on resources and further support strategic decision-making.

Although it is outside the scope of this paper, the results from the condition assessment can be used in establishing the probability of failure. In such a case, the output from a condition assessment would be a measurement of failure probability, which corresponds directly to the level of asset deterioration. In combination with assessment of failure consequence, condition assessment would allow the utility to estimate risk. Given an understanding of risk, utilities are able to determine appropriate operational, capital maintenance, and other asset management strategies. This said, a single condition assessment may not be enough to estimate probability of failure (Ansell et al, 2003). It is better to identify if a given asset is above a specified condition threshold where interventions must occur. In other cases, the data from condition assessment programmes can be used to develop asset remaining life curves for assessing the probability of asset failure, which can then be used in

developing effective asset management strategies (Wang and Zhang, 2008).

Maintenance effectiveness case

Maintenance effectiveness is assessed by inviting experts to determine a water pump's condition before a maintenance action. The experts are asked to estimate the asset condition after the maintenance action. The difference between the condition before and after the maintenance action is the maintenance effectiveness value (equation 2). Internal organisational engineers take over the role of experts as preventative maintenance activities are carried out on a frequent basis with fixed intervals. Maintenance effectiveness assessments are hence mainstreamed as part of the preventative maintenance activities within the organisation.

The condition rating for the pump (with the importance of the performance variables taken into account) after a planned maintenance is 1. The experts rated the pump at condition grade 1.5 before the maintenance action.

Therefore, maintenance effectiveness is: $1.5 - 1 = 0.5$

The maintenance action has reduced the condition grade from condition grade 1.5 to condition grade 1, which is a better condition. The maintenance effectiveness could be higher or lower and it is for asset managers to decide on if it is significant or not. In this case, the managers may decide that the 0.5 maintenance effect is significant and reduce the intervals between planned maintenance periods. They may consider that the asset would have deteriorated significantly for the effect of maintenance to be large. Maintenance engineers can measure maintenance effectiveness when carrying out planned maintenance, condition-based or reactive maintenance. On the other hand, they can assess the asset condition anytime – without carrying out any maintenance. An interviewed water utility stated that they carry out planned maintenance on their reservoir-to-distribution pumps once a year. This could also be scheduled as their main condition and maintenance effectiveness assessment for the asset group.

Werey et al (2008) used an expert elicitation approach for assessing

Table 1: Variable selection and importance scores

Variable (M^m)	Importance	Importance score
V i1	$S_{ij}1$	5
V i2	$S_{ij}2$	4
V i3	$S_{ij}3$	2
V i4	$S_{ij}4$	1

wastewater pipe condition. They used predetermined dysfunction or performance indicators, which indicate fixed condition grades of the pipes. The advantage of their approach is that experts relate each asset performance variable to the asset condition. This allows for the contribution of each variable to the asset condition to be assessed separately and thereby, recognising each variable's contribution. Wang and Zhang's (2008) approach presents a similar limitation in that it does not recognise individual performance variables' contribution to the asset condition. Similar limitations are observed in other sectors' expert-based condition assessments, such as in bridge management (e.g. Wang and Elhag, 2008) and flood defence management (Flikweert and Simm, 2009).

The activities of frontline engineers are not only critical in condition assessment, but the data they collect is essential in decision making regarding others aspects of asset management, such as: infrastructure risk; criticality of the asset; reliability-centred maintenance; failure mode-effects-remedies; and preventive / predictive or reactive maintenance.

It is therefore a major part of an effective asset management strategy. The risk of failure and criticality level of an asset can be determined from the routine condition assessment data. The reliability of the asset can also be determined and the necessary maintenance carried out on the component in the case of reliability-centred maintenance (NASA, 2008). As the risk and criticality level is determined, the mode and effect of the source of the possible failure can be determined and remedied as a predictive and preventative maintenance measure. As indicated by Davis et al (2008), such risk assessments and preventative maintenance measure can minimise large-scale network outages and high asset replacement costs, hence they contribute to the implementation of an effective maintenance strategy.

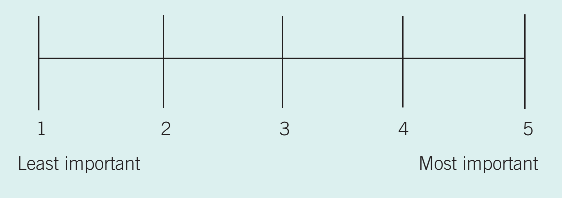


Figure 2
Variable importance rating scale

There are several other factors that may contribute to maintenance strategy decision making other than condition assessment and maintenance effectiveness. Decision makers could use maintenance effectiveness with other criteria, such as the risk posed by the asset to the whole network, how critical the asset is to the delivery of customer service, how easy or difficult it is to carry out maintenance work on the asset after assessing its failure modes and effects, how the asset affects the reliability of the whole network, and the design life of the asset. The design life may be used to determine required preventative maintenance (PM) as some assets may not require PM due to their low service life and capital value. Condition assessment and maintenance effectiveness are therefore aspects, amongst others, that can support decision-making in creating an effective maintenance strategy (Bertling et al, 2005).

Apart from supporting daily asset maintenance management, condition assessment contributes to maintenance policy management. The organisation's maintenance policy is then evaluated based on the maintenance effectiveness values obtained for each asset group. For example, preventative maintenance intervals may be extended where the maintenance effectiveness is observed to be very low or negligible for a group of assets, and vice versa. This adds value to maintenance operations as condition assessments helps in supporting management reviews and shaping overall maintenance strategy, making it specific to the needs of the infrastructure network and organisational resource capability.

Employing multiple experts helps minimise the error and subjectivity of the experts' opinions. Knowledge of the asset performance history also contributes to better results as the engineers who carry out the maintenance are the experts who assess the condition. This also helps minimise the elicitation costs as in-house experts' opinions are sought.

Other criteria for strengthening the experts' opinions can be developed. For example, evidence from the little maintenance data an organization has collected can be brought in to support and possibly strengthen the quality of the experts' opinions. The sparse performance history data of the asset or component can be presented to the experts before or after they give their opinions on the assets condition. This could be its failure history, alarm triggers register, or risk levels previously recorded. Such evidence-based aspects can strengthen the quality of the assessments (Bedford et al, 1999). Such models have been used in maintenance optimization and asset life assessments (Van Noortwijk et al, 1992).

Conclusions

Water utilities are under pressure to produce and deliver more at lower costs by regulatory requirements and other stakeholders. Hence, the proposed maintenance effectiveness measurement method provides maintenance managers with a framework for improving maintenance operations, whilst providing a decision-making support tool that prioritises the allocation of maintenance resources in the general drive to minimise maintenance costs. It shows how structured expert judgement might be a useful tool in reliability analysis – contributing positively to rational agreement where there is no data and uncertainty exists in maintenance decision-making. Experts give coherent judgements on important performance variables, condition classifications, and maintenance effectiveness related to various asset groups in line with their performance indicators.

Table 2: Adapted from ISO 13380, shows some variables that are relevant to pump condition

Fault	Fluid leakage	Length / dimension	Power	Head, pressure	Flow	Speed	Vibration	Temper -ature	Wear status	Appearance	Oil leak
Damaged impeller		✔	✔	✔	✔	✔	✔	✔	✔		
Damaged external seal	✔	✔		✔		✔	✔				
Eroded casing		✔									
Worn sealing rings			✔	✔	✔						
Eccentric impeller			✔	✔		✔	✔	✔	✔		
Bearing damage		✔	✔			✔	✔	✔	✔	✔	✔
Bearing wear		✔					✔	✔	✔	✔	
Mounting fault							✔	✔			
Unbalance								✔			
Misalignment		✔						✔			

Table 3: Pump performance variables used in condition assessment

Wear status	Sound / vibration	Oil leakage	Grade
As new	Very little	As new	1 (good)
Minor wear / tear	Quietly	Starting to show signs leakage	2 (fair)
Signs of wear / tear	Signs of vibration	Signs of leakage obvious	3 (adequate)
Advanced wear / tear	Obvious vibration	Advanced leakage	4 (poor)
Significant wear	Possibly excessive vibration	Significant signs of leakage	5 (awful)

Since the goal of applying structured expert judgement is to enhance rational agreement, the proposed method supports justifiable decision-making in asset management. The tool can yield results that can be used in deciding:

- Where to invest more maintenance human resources in order to remedy identified failure modes
- Which maintenance need is prioritised for those assets most at risk
- How to prioritise the allocation of maintenance resources at the budgeting stage
- How to modify or develop a maintenance policy in line with reliability centred maintenance in order to ensure effective maintenance.

A key feature of the asset condition assessment and maintenance effectiveness model is the involvement of frontline maintenance and operations personnel and its incorporation into mainstream maintenance activities. ●

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