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Senegal River Basin gets $228 million World Bank funding

Harnessing of the potential of West Africa's Senegal River Basin moved up a notch recently when the World Bank approved $228.5 million to finance the use of water for domestic, irrigation and power generation purposes.

The 300,000 square kilometre basin is shared among the four riparian states of Senegal, Guinea, Mali and Mauritania, covering a total population of 35 million people. 12 million live within the Senegal River Basin, which is thought to hold huge potential to help improve water and food security in the region in addition to generating cheap renewable energy.

The bank's Director for Strategy, Operations and Regional Integration in Africa, Colin Bruce, said the project will help communities in the Senegal River Basin 'meet people's energy and food needs and prevent and treat malaria and other borderless water-related diseases that routinely affect their health and ability to work.'

He said the multi-purpose water project will benefit 4.5 million people directly in the four countries which are ranked among the world's poorest 'with 42-53% of the population, mostly subsistence or smallholder farmers, living below the poverty line.'

'Reducing the withering impact of drought will dramatically improve the livelihoods of millions of farmers, herders, and communities across The Sahel, and help to boost peace and development across their region,' says Makhtar Diop, World Bank Vice President for Africa.

'If you want to help the people of The Sahel become more resilient to climate change, you have to fight drought first and foremost.'

A release by the bank said the project 'aims to improve water availability for agriculture and food production, support aquaculture and fisheries management, promote hydropower through feasibility studies, reduce malaria and other neglected tropical diseases that sicken millions of people, and pilot innovative approaches to adapt to climate change.'

'That is why this project is also tackling key deficits in health, water, power, food, and fisheries, through strengthened regional cooperation and coordination.'

The funding approval, the bank said, included $16 million grant from the Global Environment Facility and the Least Developed Countries Fund to strengthen the capacity of the Organisation for the Development of the Senegal River, which helps to reduce the vulnerability of people's livelihoods in the basin through coordinated water resource and energy development.

'This Senegal River project will demonstrate the power of regional integration and collaboration for a strategic group of countries which face rising energy and food shortages, and growing demand which increasingly hamper their economic performance,' says Shelley McMillan, the bank's Senior Water Resources Specialist and Team Leader for the Senegal River Basin Project.

The project is part of the World Bank-funded Senegal River Basin Multi-Purpose Water Resources Development Project.● **Shem Oirere**

Asset plan promises completion of Zambezi water project

The Zimbabwe government has set out an ambitious list of infrastructure projects in its latest economic blueprint, including the much-delayed National Matabeleland Zambezi water project, the aim of which is to end the city of Bulawayo's water shortage.

The $900 million ZimAsset project was first suggested for the country's second city nearly a century ago, as a way of resolving ongoing water problems in the Matabeleland region that have hampered its industrial growth. Bulawayo residents have gone without tap water for up to 72 hours a week as part of the city's strict restrictions on water use – restrictions have currently been relaxed to two days a week.

Dumisani Nkomo, CEO of the Habakkuk Trust and spokesperson for the Matabeleland Civil Society Forum, claimed it was 'highly unlikely' that the government would complete the project by 2018 as predicted.

The project would involve constructing a major dam on the Zambezi river and a 450km pipeline to Bulawayo, built in two phases. The proposal has faced stiff resistance from Zambia, which claims that the majority of the Zambezi river basins fall within its territory.

Mr Nkomo noted: 'They will continue talking, but there is never any delivery or transparency in their activities. They should come clean about the deal they signed with the Chinese, which was announced by Samuel Sipepa-Nkomo [the former water resources minister].'

A deal was announced two years ago, with the government claiming that a Chinese company had been awarded the contract to construct the Gwayi-Shangani dam. However, construction has failed to materialise, amid reports that heavy rainfall and flooding swept away the first stages of the dam wall early last year.

The ZimAsset plan also calls for water treatment plants and boreholes to be constructed and refurbished in every province and city, and among the projects are a number of other dams. ●

water asset management INTERNATIONAL

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Report warns that inadequate water and sewage systems risk disease

Human rights group Human Rights Watch has launched a report on the water situation in Zimbabwe's capital, Harare, which warns that residents have extremely limited access to clean potable water and sanitation, and often resort to drinking water from shallow, unprotected wells contaminated with sewage.

The US-based group argue that the conditions violate people's right to water, sanitation and health. Its 60-page report is based on research undertaken in the city in 2012 and 2013, including interviews with residents who spoke of queuing for up to five hours a day to obtain water from boreholes, and revealed that violence was common when queues were long.

Many residents complained of raw sewage flowing into homes and streets from burst pipes, and a lack of functioning indoor toilets or outdoor latrines was reported to have left locals with little choice but to defecate in the open.

The report, 'Troubled water: burst pipes, contaminated wells, and open defecation in Zimbabwe's capital', warns of an increase in the threat of cholera, dysentery and typhoid unless the city's sanitation system is repaired.

Tiseke Kasambala, Human Rights Watch's Southern Africa director, said at the report's launch: 'The water and sanitation in Harare is very, very serious. As you might recall, in 2008 there was a serious cholera crisis that killed thousands of people. And we are concerned; we recently heard of a typhoid outbreak in Harare. We are concerned that these outbreaks of diseases are coming about as a result of poor water system throughout Harare, in particular in high density suburbs of the city.'

Simbarashe Moyo from the Combined Harare Residents Association added: 'From the report we are witnessing [the] ruralisation of urban areas. When you have unprotected wells… in Harare, Epworth, Chitungwiza and so forth, surely that is an indication that we are now in rural areas, you are no longer in town.'

Precious Shumba, the Director of the Harare Residents Trust, supported the report's claim that corruption and mismanagement at local and national government levels made the situation worse. He alleged serious problems of bloated management structures, communications failures and a failure to ring-fence funding intended for water and sanitation.

Human Rights Watch called for investment in low-cost sanitation and water strategies, including community toilets and pit latrines, and boring and maintenance of boreholes so that residents do not need to use contaminated sources. The group also called for sliding-scale fees to provide affordable water, and said that no-one should be disconnected from the city supply for non-payment. ●

Lyonnaise des Eaux wins drinking water contract for French town

The town of Olivet in central France has awarded the management of its public drinking water production and distribution to Lyonnaise des Eaux, a subsidiary of Suez Environnement.

This contract, which will run for nine years, will take effect in February 2015 and will generate around €10 million ($13.6 million) in total evenue, Suez said in a statement.

The contract will commit to protecting groundwater by optimising farming practices and monitoring emerging and phytosanitary pollutants in the groundwater and the Loiret river, as well as rolling out 6000 smart meters to save water resources. ●

Kahramaa announces strategic storage project

Qatar's electricity and water corporation, Kahramaa, is to undertake a $3 billion project that will provide seven days of strategic water storage within the country's water network.

The water security mega reservoirs project will be one of the largest in the world and will increase the country's water storage capacity tenfold, according to Kahramaa technical director Ahmed al-Naser, who estimated the storage capacity at about 3500 million gallons (13,250 ML).

Kahramaa is also planning an independent water and power plant with a 130MGD (492MLD) desalination capacity. The plant, known only as Facility D, will be sited in the Qatar Economic Zone near Doha.

The plant will partly use RO, the first time the technology has been deployed on a large scale in the country. ●

EC launches Horizon 2020 calls for projects

The European Commission has launched the first calls for projects under Horizon 2020, which will be the EU's largest research and innovation programme so far, with a budget of nearly €80 billion ($109.8 billion) for the period 2014 to 2020.

The funding will encompass 12 focus areas, including one titled 'Water innovation: boosting its value for Europe'. The budget for water-dedicated calls is €67 million ($92 million) for 2014 and is estimated to be €96 million ($131.8 million) for 2015.

There are also opportunities for water-related research and innovation in other parts of the calls, according to the WssTP. ●

Good practices and tools in asset management implemented by Japanese water supply utilities

From the 1950s to 1970s, many water supply facilities were constructed in Japan as the use of water services rapidly increased. Now, the country is entering an era when much of this infrastructure must be renewed, although many utilities do not have sufficient funds for the work. Takayuki Sawai highlights examples of asset management that can be used in other countries, and outlines simple asset management tools.

Takayuki Sawai
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Japan's water supply infrastructure grew rapidly during the country's period of rapid economic growth from the 1950s to the 1970s – most of its water supply facilities were constructed during this period. As a result, water supply coverage rose from 26.2% in 1950 to 80.7% by 1970. Water supply coverage in March 2013 was 97.6%, indicating that this infrastructure now covers the whole of Japan. In addition, thanks to a thorough management system, one of the features of the country's water supply services is that safe drinking water comes out of all taps throughout the country; an asset that the Japanese people can be proud of.

Need for implementing asset management and asset management guidelines

The number of old facilities has been increasing over recent years, but the percentage of renewed infrastructure is not high enough, despite the fact that water supply utilities need to steadily renew their infrastructure. Revenue from water charges cannot be expected to increase as demand for water drops and the population declines, so many water supply utilities are delaying increases in charges for water that are needed to continue in business. In reality, not many water supply utilities are strategically securing corporate funds.

Because of this, the Ministry of Health, Labour and Welfare (MHLW) established the 'Asset management guidelines for water supply utilities' in 2009 as a part of its responsibility to supervise the water supply administration of Japan and encourage water supply utilities to implement asset management (AM). One of the features of the guidelines is that they encourage water supply utilities to start implementing AM for those aspects that they can manage.

A characteristic of water supply utilities in Japan is that many mid- to small-scale water supply utilities do not have basic data on human resources and the infrastructure. Recognising this issue, the guidelines allow water supply utilities to start using AM through simplified methods, accepting some deficiencies in precision where there are insufficient available data, diagnoses, and assessments of the infrastructure.

The implementation of AM increased by around 4% over the two years between the announcement of the guidelines and 2011. Water supply utilities have also been increasing their individual AM-related practices.

MHLW's simplified AM support tool

Table 1 shows the status of AM practices undertaken by water supply utilities under the management of MHLW. This table shows that the reason for the low AM implementation percentage in the overall score is the extremely low implementation rate among small-scale water supply utilities, of which there are many.

In order to encourage small-scale water supply utilities to adopt AM and improve operation of all water services, MHLW provided a simplified support tool for asset management in June 2013. This tool consists of Excel spreadsheets with formulas and descriptions, and can be downloaded from the MHLW website www.mhlw.go.jp/topics/bukyoku/kenkou/suido/vision/am/130605-1.html (Japanese version only).

The key feature of this tool is that users can implement AM with a minimum of processes. Examinations

Table 1 Implementation percentage of asset management (2010 / 2012)

(Unit: No. of Utilities)

Supply Population		less than 50,000	50,000 - 100,000	100,000 - 250,000	250,000 -500,000	more than 500,000	Bulk Water Supply	Total
2010	Ratio	8.2%	41.7%	59.6%	67.2%	79.3%	62.4%	25.7%
2012	Target Utilities	963	211	145	61	25	91	1,496
	Implemented	120	98	96	44	21	61	440
	Ratio	12.5%	46.4%	66.2%	72.1%	84.0%	67.0%	29.4%
Increasing Ratio 2010 - 2012		4.3%	4.7%	6.6%	4.9%	4.7%	4.6%	3.7%

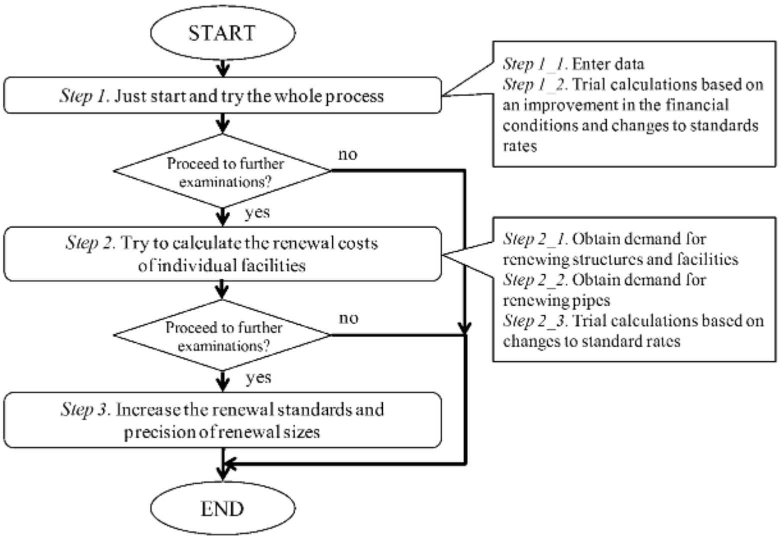

Figure 1
Three steps of the support tool method

using this tool consist of three steps, for which Figure 1 presents an overview.

Step 1

This tool is designed to forecast future values based on data provided by a user about construction improvement costs over the years and financial balances from the latest fiscal year. This tool automatically produces a forecast of renewal demand and financial balances. For example, if a water service began in 1973, simply entering around 65 data sets, including construction improvement costs over 40 years and some 25 categories of settlement prices from the latest fiscal year, into the system produces the information and diagrams necessary for an AM examination. With this information, anyone can understand the concept of AM as a first step.

Initial values are set for individual accounts, based on various hypotheses in the financial balances during this step. In the next step, the future values of accounts are improved to reflect the actual status of individual water supply utilities within a possible set of ranges. For example, entering data that allows forecasts of future redemption schedules of principle interest on past debts and fee payment schedules allows users to obtain results that are closer to reality. Then, as a way to secure sources of funding, the system calculates the level of water charges that will prevent a water supply utility from running a financial deficit.

In Step 1, users get a rough estimate of the funds they need to renew their infrastructure and how to change their charges to secure the necessary funds in the mid- to long-term.

Step 2

The system needs to know what (specific infrastructures), when (timing of renewal), and how much (renewal cost) to improve the precision of the examination, so it creates a list of currently available infrastructure and when it needs to be renewed, and calculates the approximate renewal costs based on the size and capacity of the asset.

For water pipes, the system produces the demand for renewal (length of pipe to be renewed) by setting an annual length of installed pipes through a process of automatic allocation based on pipe length information from water supply utilities. The system automatically calculates the renewal cost based on set values of unit prices. As described above, the precision of the simulation can be improved by calculating renewal demand for individual infrastructure, as the system calculates the renewal cost based on information such as infrastructure capacity.

Given that the precision of renewal demand has improved, users may change the setting of future values of their various accounts for a balanced financial outlook. The system also examines the levels of water charges as a means of securing a source of funds, if the result of the financial balance is unfavourable.

Step 3

In this step, users change the renewal standards (the number of years between one renewal and the next) for the infrastructure set in Step 2, for each piece of infrastructure, to reflect the integration, cancellation of infrastructure and down-sizing within water supply utilities. For example, users can add information, such as that distribution reservoir A is to be renewed in 40 years, the legally specified service life, but the renewal standard for distribution reservoir B may be set at 80 years based on the result of an earthquake resistance diagnosis.

Examining the outlook of financial balances and water charges is undertaken in the same way as in Step 2. In Step 3, the system allows users to set renewal standards for individual infrastructure, which allows more detailed investigations and greater precision within the renewal standard to explore the standardisation of renewal demand. In this way, users can produce a renewal plan with sources of funds based on mid to long-term perspectives.

Expected effects

The New Water Service Vision, the MHLW's general policy for water services set in March 2013, states that one of the current goals is for all water supply utilities to adopt the AM and clarify future renewal plans and financial balances. In this sense, this tool provides a starting point for water supply utilities to recognise their situations and look at ways to conduct business in future. One of the most important issues for Japan in building sustainable water services throughout the country is that all water supply utilities become aware of problems with their current business operations.

Developing an inventory management system

When implementing asset management, water supply utilities must keep track of the status and the soundness of assets – that is, the water service infrastructure they own. For example, the Ube City Gas and Waterworks Bureau in Yamaguchi Prefecture was managing water pipes using a mapping system. Meanwhile, it was managing the information for other water service infrastructure provided by experienced engineers on paper. This meant that establishing infrastructure renewal plans was not an easy task. Therefore, the utility established a team to build an infrastructure management system, working under the city bureau's water service infrastructure renewal plan establishment committee. The aim was to build a process for their system development that on-site workers could easily operate and use to store daily infrastructure management information.

System development

A unique aspect of developing the water service infrastructure chart system was that all employees were involved in its development, and entered basic information using free software. Therefore, the development costs were simply the cost of the work of city employees and of building a server. In addition, there were no operational costs because the city employees manage the system.

Nevertheless, the project required more work than expected, and it took several years to establish rules for

	Pipe types	External anti-corrosion	Internal anti-corrosion (Lining)		Year of installation	Accident hazard level		Hydraulic functions		Earthquake resistance strength 3)		Water quality maintenance functions		General physical assessment score for individual pipes (Si) 4)
		Poly-ethylene sleeve	Straight pipes	Non-straight pipes		Co efficient	Point (S_F)	Co efficient	Point (S_H)	Co efficient	Point (S_S)	Co efficient	Point (S_Q)	
1	NS, SII (DIP)	Y	Y	Y	1982 - Present	0.00	100.0	1.0	100.0	0.0	100.0	1.0	100.0	**100.0**
	A, K, T (DIP)	Y	Y	Y	1983 - Present	0.02				0.3	69.3			**91.2**
		N	Y	Y	1974 - 1982	0.05	77.1							**85.5**
	A, T (DIP)	N	Y	N	Est. - 1973	0.05	77.1	0.7	48.6	0.3	69.3	0.5	29.3	**52.5**
2	Socket-and-spigot joint, A (CIP)	N	Y	N	Est. - 1965	0.20	21.0	0.7	48.6	1.0	22.4	0.5	29.3	**28.6**
3	HIVP	—	—	—	1981 - Present	0.10	50.0	1.0	100.0	0.7	19.4	0.9	85.2	**53.6**
	VP	—	—	—	Est. - 1980	0.15	32.4			1.0	7.8			**38.3**
4	SUS, SP 1)	—	—	—	1987 - Present	0.02	100.0	1.0	100.0	0.3	69.3	1.0	100.0	**91.2**
	SP	N	Y	Y	1978 - 1999	0.05	77.1							**85.5**
	SP 2)	N	N	N	Est. - 1977			0.1	9.2			0.1	10.1	**26.5**
	VLP	N	Y	N	Est. - 1989			0.7	48.6		44.7	0.5	29.3	**47.1**
5	Hose lining pipes	N	—	—	—	0.05	77.1	1.0	100.0	0.3	69.3	1.0	100.0	**85.5**

Note 1) SP (NCP) of ones installed since 2000
2) Including water supply SP (1953 to 1970)
3) For 100 to 150mm in diameter (ϕ50mm for HVP, VP, and VLP only)
4) A score obtained by adopting 1.0 (lapsed year=0) as an aging coefficient (CY)

Table 2
General physical assessment scores of individual pipes. DIP: ductile iron pipes; CIP: cast iron pipes; HIVP: high impact vinyl pipe; VP: vinyl pipe; SUS: stainless used steel; SP: steel pipe; and VLP: vinyl lined steel pipe. NS, SII, A, K and T are joint types used in ductile iron pipes.

categorising, organising, and digitising the data for entry into the system. Because of this, the city of Ube adjusted the system specifications to suit employees involved in daily management of the infrastructure, and built the system by processing the data as infrastructure management units.

Features of this system

This system allows users to manage information on the infrastructure, such as timeline (date of acquisition, legally designated service life, and so on), and maintenance and management. Users can easily share information because they can enter and view data on the internet via the City Hall LAN client. Registered information can be output in .CSV format and analysed using Excel, and registered information on the chart can be output as PDF files, which can be used as a reference for briefings.

Effects of system development

City employees saved as much money as possible by developing the system themselves. In addition, a noteworthy aspect of this project was that it improved workforce motivation, because the employees involved in system development transferred information and technologies among themselves, and communication between office and technical employees increased.

At this point, this system is effectively being used for micromanagement as set out in the MHLW Guidelines. This means that the organisation is managing costs based on accurate information on its infrastructure and sharing the information among employees, and thus analysing the infrastructure status and establishing renewal and improvement plans to properly implement proposed measures. The system is also effective in reflecting the opinions of site-based technicians in actions taken, by collecting daily maintenance and management information on the infrastructure. The city is planning to expand use of the system to establish effective renewal plans for its entire infrastructure.

Use of general physical assessment scores for pipes in AM

The city of Toyonaka in Osaka Prefecture needs to renew its aging infrastructure, but an increase in revenues from water services cannot be expected as the water supply peaked in 1990. Among its 800km of pipes, 20% have been in service for over 40 years, the legally designated service life, and that percentage is increasing.

The city began using an assessment method that scores each pipeline as a way of objectively and quantitatively assessing the infrastructure. The aim is to efficiently renew and improve the earthquake resistance of aging infrastructure by establishing a basic plan for water distribution infrastructure development in the city. This sets out the efforts to optimise infrastructure development.

Method and standard of assessment

Using the legally designated service life as the renewal standard is not practical, considering the improvements in pipe functionality in recent years. Because of this, water supply utilities are exploring ways to assess infrastructure soundness that reflect the actual conditions, and using that information to prioritise renewals.

The city of Toyonaka is objectively assessing the soundness of its pipes using a method that includes categories unique to the city: an assessment of individual pipes and the presence of external covering and internal anticorrosion are added to the general physical assessment categories for pipe installation, based on the water service infrastructure renewal guidelines issued by the Japan Water Works Association (Table 2).

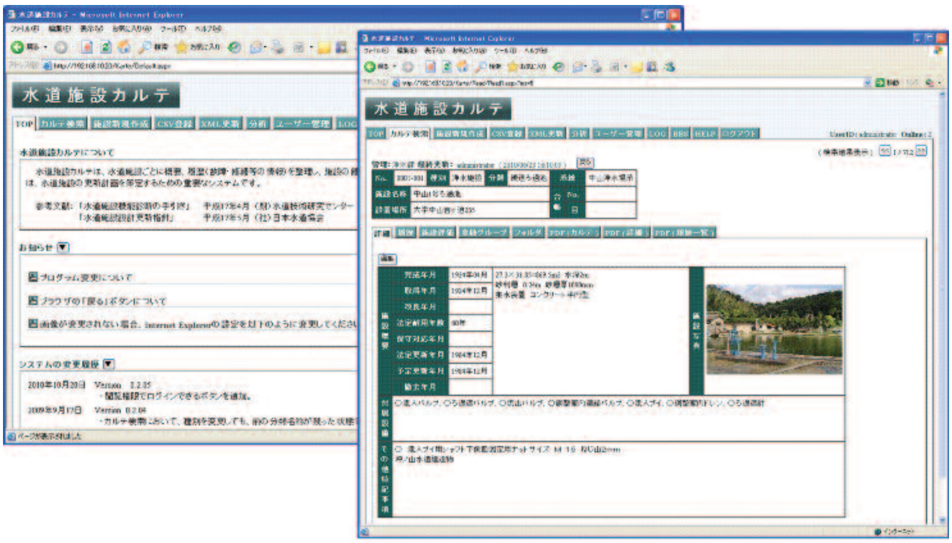

Figure 2
Example of the information displayed in the water service infrastructure chart

General physical assessment score for individual pipes (Si)	General assessment of individual pipes
75 points ≦ Si	In good condition
50 points ≦ Si < 75 points	Permissible, but weaknesses need to be improved and reinforced
25 points ≦ Si < 50 points	Not in good condition; strategic renewal is necessary
Si < 25 points	Extremely bad; immediate renewal needed

Table 3
General assessment for individual pipes

Specifically, pipes whose general physical assessment scores are below 25 points are labeled extremely bad, and in need of immediate renewal. The city is determining renewal priorities by considering the financial balance and strategically renewing infrastructure in light of its overall operations, so the score will not dip below 25 points (Table 3). The city is also implementing self-assessment of pipe renewal status using the Performance Indicator (PI) issued by the JWWA.

Future goals
The city of Toyonaka is entering an era of renewing water service infrastructure built during the rapid growth period from around 1955 to 1965. The city cannot renew all its ageing pipes over a short period for financial reasons, and because water services cannot be interrupted. For these reasons, the city implemented AM using unique assessment indexes, and worked with renewal plans. For the future, the city set a goal based on infrastructure development plans such that the general physical assessment scores for all pipes in the city will be 75 points on average in fiscal year 2020. In addition, the city intends to develop effective and efficient infrastructure development after downsizing the water service systems based on the presumption of an era of a declining population.

Establishing distribution pipe renewal plans

The city of Fukuoka had around 3900km of distribution pipes in 2011, around 1200km of which do not have the polyethylene sleeves that were installed in the 1960s. The legally designated service life for all these pipes is expiring, so the city needs to strategically and efficiently renew them by balancing the operational load and financial aspects.

Renewal plan establishment process
Renewal prioritisation zones are created for distribution pipes of 350mm diameter or less based on investigations into pipe condition, soil and history of leakage. The city is renewing the pipes in order of priority. For distribution pipes of 400mm diameter or greater, renewal plans have been established based on the unique flow process described below, to effectively and strategically renew old pipes and reduce the financial burden. The city plans to renew its pipes in a set order of priority.

Examination of the pipe networks
Based on the goal that water services would not be interrupted during normal operations and in case of accidents, such as a shutdown of water distribution facilities, repeated pipe network calculations were performed by changing the block injection points and downsizing pipe routes to find pipes that could be removed or reduced in size to optimise pipe networks. These calculations found about 29km of pipes that could be removed or reduced in size.

Investigation of corrosion on pipes and soil investigations
The city investigated corrosion of pipes, nuts, and bolts in around 100 locations and then sampled the soil and groundwater around the buried pipes to analyse the factors that may affect the pipe condition.

Producing a corrosion forecasting formula
Based on the outcome of the two analyses above and references such as terrain maps, the city categorised its buried pipes into four groups and produced a pipe corrosion forecast formula.

Assessment of aging
Using the corrosion formula above, the city ranked the ages of all pipes in the water distribution system, from level I to V. Pipes ranked levels I and II were the oldest, and these were earmarked for renewal.

Examination of renewal priorities
Using the calculated ages as a basis, the city gave scores to each assessment category (Table 4), such as remaining service life, the importance of a given pipe, and the amount of damage that would be suffered during an earthquake. The city determined its priorities by adding weights to these factors.

Examination of annual operation load
The city found a point at which the sum of the annual renewal cost and the cost of the risk of damage caused by earthquakes and water leaks were balanced, to determine the justifiable amount of investment. Next, the city made sure that the number of old pipes to be renewed (levels I and II) would not increase, by extending renewals based on justifiable investment.

The city of Fukuoka will continue investigating pipe conditions and soils to check and verify the current corrosion forecasting formula and its renewal priorities.

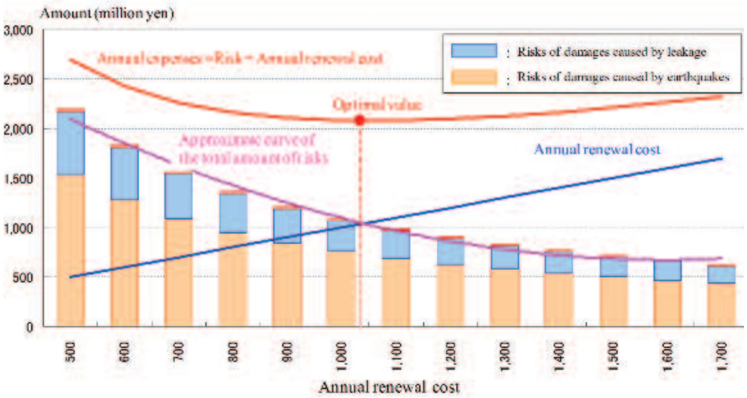

Figure 3
Investigation of the justifiable amount of investment

Leakage prevention efforts

The Tokyo Metropolitan Waterworks Bureau is a massive water utility that supplies an average of 4,200,000m³ of water to around 13 million people each day. Yet, thanks to strategic and detailed leak prevention measures, leakage from the pipes managed by this bureau is extremely low. Leakage was less than 3% in 2010 and 2.8% in 2011. Pipe renewal and repair prioritisation by detecting leakage points is considered one of the most important operations in terms of AM, because it results in pipes being renewed at the correct time based on the belief that loss of water produced by water supply

Assessment category	Factors of scores
Remaining service life	Remaining service life, history of water leakage
Importance	Roles of pipes (trunk water pipes, sub-trunk water pipes, etc.)
Earthquake resistance	Rate of damage suffered during expected earthquakes (the Kego fault, M7.2)
Hydraulic quality	Flow rates before and after changing diameters of pipes

Table 4
Assessment categories

utilities should be reduced as much as possible. Specific operations are described below.

Round inspections
This inspection is conducted by zone. This type of inspection includes individual household inspections to check leakage by placing a leak sound detection bar on water meters at individual households as well as acoustic inspections, which identify the location of leaks using a digital leak detector on the road surface at night when there is little traffic. Inspection zones are chosen based on past inspections, leakage that occurred the previous year, and the location of the remaining lead water pipes. Since 2003, the bureau has been undertaking individual household inspections using a time integral type leakage detector in place of a leak sound detection bar in some areas.

Leak measurement
Measurements are undertaken to estimate the amount of leakage for the entire metropolitan area and to keep track of any trends. To identify the optimum amount of leakage in a metropolitan area where activities continue 24 hours a day, the bureau limits the measurement target to about 400 taps, which is the upper limit for a period of no water use, and measures the minimum amount of water used (the amount of water leakage) at night. Measuring the amount of leakage in a specific number of sections enables the bureau to estimate the amount of water leaks across the entire area. These data are used to determine measures to prevent future leakage, and for the leakage measurements and inspections described in the next section.

Leak measurement and inspection
Leak measurements and inspections are based on simulations undertaken to secure water supply routes in case of a disaster – for example, to reduce water supply shutdowns in the event of an earthquake and to enable the infrastructure to recover quickly. First, the bureau checks the functions of the outlet valves on distribution mains, and then inspects the functions of the control valves that secure water supply routes, assessing the number of routes with excess leakage by taking measurements. The bureau then gradually expands the water supply areas, inspecting each based on the level of leakage and repairing leaks once they are found.

Need for leak prevention
The Tokyo metropolitan government is working to prevent and reduce leaks in its vast water supply network through these strategic operations. The safety of the dams that supply its water has been reduced because of the precipitation trends in recent years. In addition, the secondary effects of leakage in the metropolitan areas, such as insufficient water flows, road and building flooding, would be massive. For this reason, the Tokyo Metropolitan Waterworks has actively positioned leakage prevention as one of its most important measures.

Conclusion

The people of Japan take it for granted that they enjoy an extremely high quality of water services, drinking tasty water at any time from any tap. The water service management technologies are some of the best in the world.

However, the population and demand for water are declining, and the overwhelming majority of water supply utilities are small to mid-size companies. For water supply utilities to sustainably pass on the advanced water service systems that have been developed to future generations, they need to tackle new challenges: renewal and reconstruction of water service infrastructure.

When it comes to AM, Japan is falling behind the advanced countries of the world. Britain's PAS 55, the AM specification of the British Standards Institution (BSI) defines AM as 'systematic and coordinated activities and practices through which an organisation optimally manages its assets, and their performance, risks and expenditures over their lifecycle for the purpose of achieving its organisational strategic plan.'

Today, it seems that many companies in Japan understand AM as being almost identical to establishing mid to long-term infrastructure renewal plans. To reach the level where AM is a continuous activity throughout an organisation, they must be reformed based on this principle, which is probably a major obstacle for public entities in Japan.

Meanwhile, the development of unique methods, based on the MHLW's AM Guidelines and using them to establish plans for infrastructure renewals, is advancing. Water supply utilities are expected to share information about useful tools that could be used by companies outside Japan. ●

This paper was presented at LESAM 2013 – the IWA Leading-Edge Strategic Asset Management conference, held 10-12 September 2013 in Sydney, Australia.

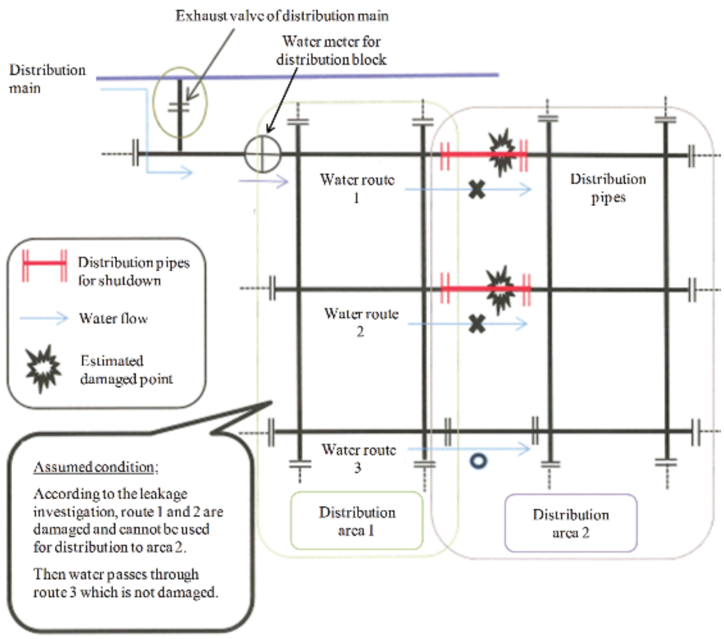

Figure 4
Leakage measurement and inspections

Asset management at the Yokohama Waterworks Bureau

Most of Yokohama city's water assets need to be renewed in the near future, and earthquake resistance has to be urgently improved following the Great East Japan earthquake of 2011. Yoko Tsujino, Yoshinobu Ono and Toshiyuki Ushikubo explain the asset management method being used to improve assets effectively and efficiently, despite decreasing income.

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The Yokohama Waterworks Bureau (YWWB) was established in 1887, and has constructed assets since then as Yokohama, Japan's second largest city, has evolved. The majority of assets – pipes in particular – were installed as the population increased during the period of high economic growth from the mid 1960s onwards (see Figure 1).

The Bureau has had to accelerate its programme to improve the earthquake resistance of water assets following the Hanshin-Awaji earthquake of 1995 and the Great East Japan Earthquake of 2011. However, in recent years, there has been a decline in water rate revenues caused by a reduction in water demand, despite the fact that the population supplied is increasing (Figure 2). As a result, the Bureau has been trying to renew its water assets efficiently and effectively, with limited financial resources, to achieve a sustainable water supply operation.

Figure 1 Pipe length installed by year

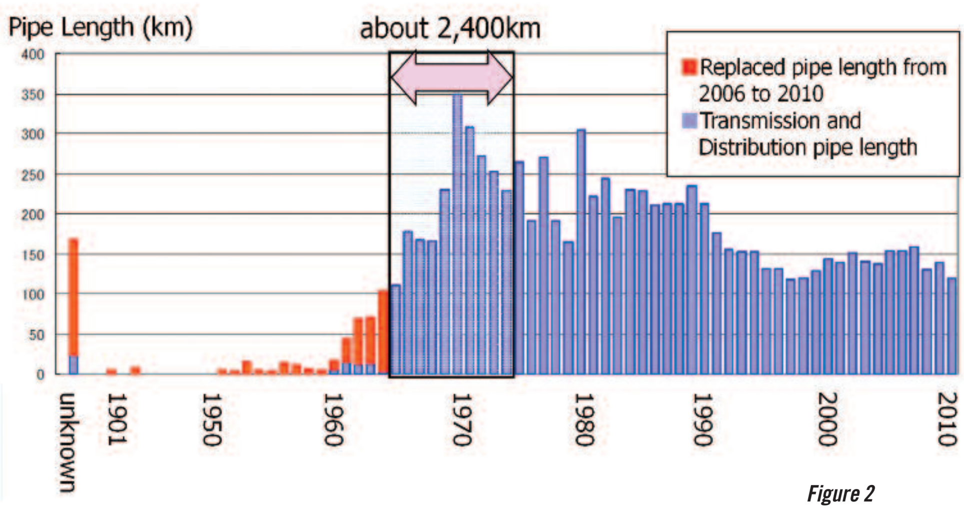
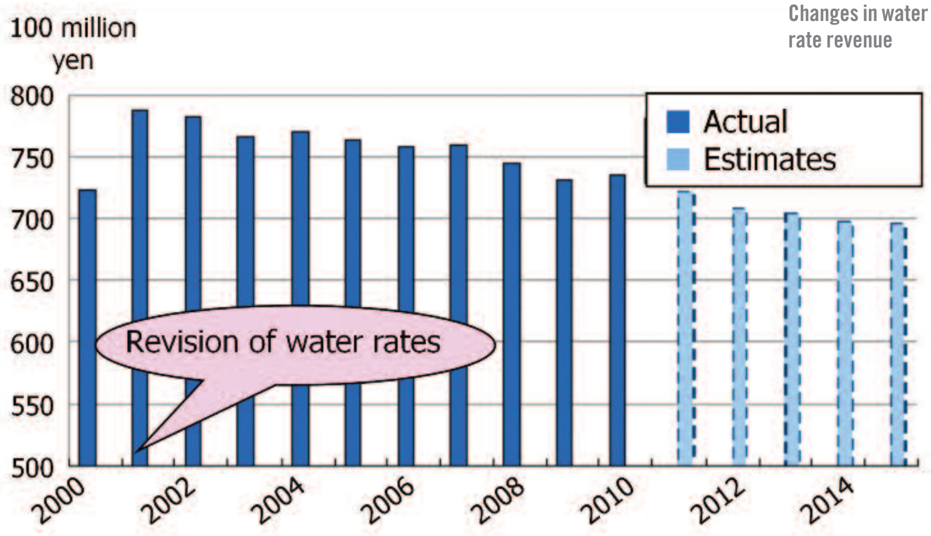


Figure 2 Changes in water rate revenue



Basic concepts of renewal and improvement

The Bureau categorises its water assets into pipelines, civil engineering structures and equipment, and classifies its basic renewal concepts depending on the asset characteristics. Table 1 shows the waterworks asset categorisation and specific assets.

Pipeline renewal periods and priorities are determined by building a database that attaches attributes such as material type, diameter and year to the pipe diagrams (a mapping system) and recording daily maintenance, accident history and so on. Pipelines are, in principle, renewed according to their expected useful life, which the Bureau has established, but important lines and those at high risk are given high priority for renewal. Renewal and earthquake resistance reinforcement are integrated by ensuring that pipelines are replaced by pipes with earthquake resistant joints.

Civil engineering structures are managed separately in asset units, building up data such as year of construction, history of reinforcement and repairs. The target useful life is set with the renewal period as the yardstick. Taking life cycle costs into consideration, judgements are made about whether to extend each structure's useful life through earthquake resistance reinforcement or large-scale repairs, or whether to reconstruct the structure, thus reducing the overall work costs.

Just like civil engineering structures, equipment is managed in asset units and is renewed according to its useful life, which is set based on its past maintenance history. When the time comes for renewal, introducing energy-saving measures and reusing parts are looked at as possible ways to minimise life cycle costs.

Keeping a balance between renewal demand and financial planning

The Bureau harmonises renewal demand and financial planning, as shown in Figure 3.

To predict renewal demand, the Bureau has developed an aged pipe renewal (earthquake-resistance) plan for distribution pipes, an asset improvement plan for water conveyance, treatment, water transmission and water distribution assets, and an equipment renewal plan for equipment. Renewal plans are prepared depending on the characteristics of the assets and renewal priority is set for each plan to smooth out the quantity of work and work costs. Details of each renewal plan are presented below.

The aged pipe renewal (earthquake-resistance) plan controls distribution pipe improvement projects and the asset improvement plan and equipment renewal plan control the main asset improvement projects. The costs of both projects are combined and allocated as construction and improvement expenses. Quantities of work and work costs that cannot be fully set at the planning stage are adjusted between work projects.

To predict its finances, the Bureau has studied changes in water rate revenue, where it is predicted that the present water rate system will continue. It also studied changes in revenue income and expenditures, capital revenue and expenditures, fund balance and outstanding revenue bond debt to confirm that the calculated renewal demand does not cause financial problems.

Asset management and progress management in practice

In 2006, the Bureau developed a long-term vision, enshrining as its basic philosophy the operation of a sustainable water service that responds to the need for a safe, good-tasting water supply. This is the image of the future set for the mid 2020s, when the city's population is predicted to peak. The long-term vision has six basic pillars – to produce top-level safe and good-tasting water; to deliver a constant supply of fresh water to taps; to construct lifelines that can be relied on to resist disasters; to provide water supply services that satisfy customers; to display a corporate spirit characterised by the energy to create and face challenges; and to build water supply systems that are kind to the environment. This vision advocates not only maintaining waterworks simply by renewing facilities, but also by striving to improve services.

Categorization	Specific facilities
Pipelines	Conveyance, transmission and distribution pipes
Civil engineering structures	Intake facilities, purification facilities (sedimentation basin, filter basin), distribution reservoirs
Equipment	Pumps, motors, power receiving / distribution equipment

Table 1
The categorisation of water works assets

At the same time as the Bureau was developing its long-term vision, it also developed a ten-year plan to realise the philosophy of the long-term vision, consistent with its future financial revenues and expenditures. The Bureau's target facility earthquake resistance compliance rate and length of deteriorated pipeline to be renewed have been set, and their progress is being managed.

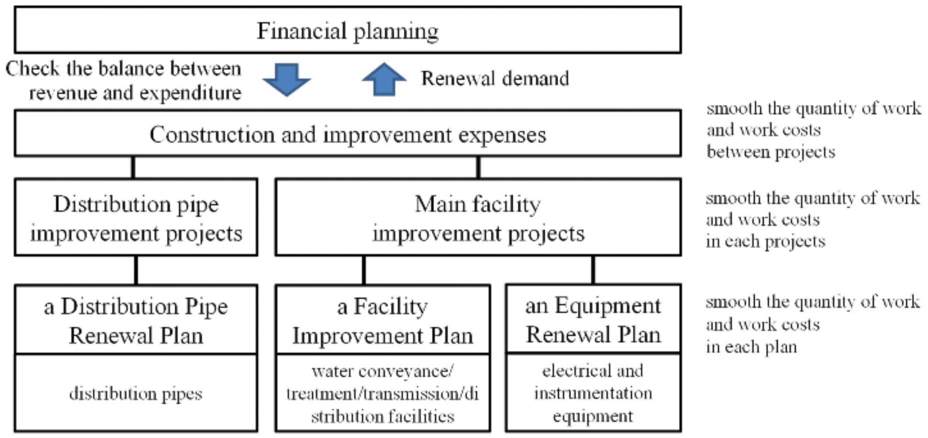


Figure 3
How to balance renewal demand and financial planning

As a means of implementing the ten-year plan, a three to four year medium-term management plan has been developed, and work is being undertaken to reflect this in the annual operational guideline or budget. Work is executed more efficiently by dividing the long-term targets into medium and short-term targets, as efforts are made to realise the long-term vision (see Figure 4). Work progress is announced annually using the target values or work indices set under the operating plan.

Problems in asset management

In recent years in the city of Yokohama, a decline in water demand, the spread of water-saving equipment and changes in people's lifestyles have accelerated a downward trend in water rate revenues. Table 2 compares predicted water rate revenues under the ten-year plan developed in 2006 and the medium-term management plan developed in 2012.

In 2006, for example, it was predicted water rate revenue would tend to decline, but by 2012 it was projected that revenues would be around five billion yen lower than was thought in 2006. As prospects for water rate revenues get worse, the Bureau is working to reduce expenditure in a number of ways: through more efficient management; by cutting work costs; and ensuring revenue by using assets effectively to strengthen the foundations of management, thus balancing its fiscal revenues and expenditures. Plans for future work must take a long-term perspective, but as the economic environment changes, the Bureau also has to continually revise plans for the medium and short-term.

Figure 4
Conceptual diagram of management plans in the Bureau in 2006 and 2010

Construction work is often affected by water supply control and management requirements, so in order to ensure a stable day-to-day water supply it is often necessary to revise initial plans for long-term works. In the following case the construction period was revised as a result of the power supply instability following the Great East Japan earthquake.

During the Great East Japan earthquake and accompanying tsunami of March 2011, an electric power plant on the Pacific coast was severely damaged,

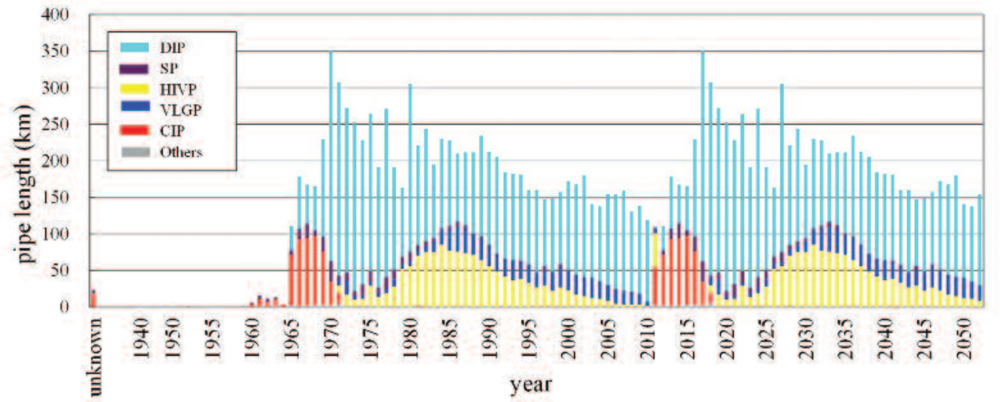


Figure 5
Renewal demand where pipes are renewed at the legally required useful life (40 years)

reducing its capacity to supply power. It was predicted that during the summer and winter, when power demand is high, the power supply would be restricted and planned rolling blackouts would be introduced.

As a result, the Bureau revised the schedule for reinforcement work on a water conveyance channel and treatment plant, which relied on backup from a pump system and treatment plant whose power supply would probably be limited by the restrictions. This meant avoiding, as far as possible, undertaking these works in the summer and winter.

In addition, the Bureau had made plans to undertake earthquake resistance reinforcement for two distribution reservoirs at a particular treatment plant, starting in 2011, but because the storage volume would need to be reduced during the reinforcement work, improvements to one of the reservoirs were delayed in order to ensure sufficient storage volume during a planned rolling blackout.

Renewal plans

The aged pipe renewal (earthquake-resistance) plan

The city of Yokohama has a total of around 9000km of water transmission and distribution pipelines. The pipe length was extended by between 250 and 300km each year in the 1970s and 1980s, reducing to between 100 and 150km a year from the mid 1990s onward. Because of the unavoidable rapid increase in renewal demand in future, it will be necessary to undertake renewal and earthquake resistance reinforcement systematically.

Past efforts

Work to improve the Bureau's deteriorated pipelines began in 1969 and by 2011 a total of 4000km had been renewed. As a result, the 30,000 annual pipe bursts that occurred during the 1960s and 1970s have been reduced to around 2000 per year. In response to the Hanshin-Awaji earthquake disaster of 1995, earthquake resistant pipelines were adopted at diameters of 400mm or greater, for pipelines in areas with a seismic intensity of 7 (on the Japanese scale of 0-7) and in areas where liquefaction will occur. Since 2006, in principle earthquake resistant pipelines have been adopted in all regions and at all diameters, and the Bureau has undertaken a programme of earthquake resistance reinforcement for pipelines.

Developing the aged pipe renewal (earthquake-resistance) plan

Starting in 2011, the Bureau began to develop a new deteriorated pipeline renewal and earthquake resistance reinforcement plan, in anticipation of the rising demand for pipe renewal. The plan relies on accurate prediction of renewal demand, setting priorities for renewal based on objective data, and smoothing out work costs.

Renewal is undertaken by integrating deteriorated pipeline renewal and earthquake resistance reinforcement, replacing the failing pipelines and joints with pipelines that have highly earthquake resistant joints.

Setting the expected useful life

In Japan, the legally required useful life for distribution pipes has been set at 40 years, but renewal at this age does not keep up with demand (Figure 5). The fact that there are differences in performance depending on material type and burial conditions has been made clear by the results of past performance and surveys. To perform renewals on an appropriate cycle, an expected useful lifetime was set (see Table 3).

Table 2
Predicted water rate revenues (billion yen)

	2004	2010	2015
Ten-Year Plan (developed in 2006)	77.1 (actual)	75.3 (predicted)	74.5 (predicted)
Medium-term Management Plan (developed in 2012)	77.1 (actual)	73.6 (actual)	69.7 (predicted)

Setting renewal demand

Figure 6 shows renewal demand in the case of simple renewals based on expected useful life. The amount of work will peak after the 2040s, making it difficult to manage renewals. The amount of work has been adjusted based on the expected useful life of ductile cast-iron pipe (with polyethylene sleeves, and earthquake resistant pipelines) laid during renewal, assuming that 9000km of water transmission and distribution pipe renewed on an 80 year cycle would be renewed at a rate of 110km per year.

For cast iron pipe, hard polyvinyl chloride lined steel pipe, and hard impact resistant polyvinyl chloride pipe in particular, which are scheduled for renewal beginning in 2015, completion years will be determined with a view to setting the amount of work. For instance, for ductile cast iron pipes without polyethylene sleeves whose renewal peak will be in the 2040s, the renewal of pipes buried in corrosive soil (which causes rapid deterioration) will be accelerated, and renewal of those judged to be sound based on diagnostic work will be postponed. Adoption of earthquake resistant pipe for renewal was planned to ensure earthquake resistance reinforcement would accompany renewal of deteriorated pipelines.

Figure 7 shows future renewal demand after adjustment. It was possible to set work costs and to develop sustainable works plans by undertaking well-balanced renewal based on material type and pipe diameter. The period from 2011 to 2020 is set as the first phase for implementing the plan.

Efficient earthquake resistance reinforcement efforts

The 2011 pipeline earthquake resistance compliance rate was low, at about 17%, and because pipelines are renewed on an 80-year cycle, it will take a long time to reach 100%. Renewal is therefore undertaken efficiently by prioritising important lines for earthquake resistance reinforcement.

From 2006 to 2012, earthquake resistance reinforcement of pipelines to disaster medical treatment base hospitals and emergency notification medical treatment bodies (emergency hospitals designated by prefectural governors), which are important facilities where medical treatment is provided during a disaster, were undertaken.

Starting in 2013, prioritised earthquake resistance reinforcement

Pipe material	Expected useful life (years)
Polyvinyl chloride lining galvanized steel pipe (VLGP)	40
Hard impact resistant polyvinyl chloride pipe (HIVP)	40
Cast iron pipe (CIP)	50
Steel pipe (SP)	60
Ductile cast iron pipe (without polyethylene sleeves)	70
Ductile cast iron pipe (with polyethylene sleeves)	80
Ductile cast iron pipe (with polyethylene sleeves and earthquake resistant joints)	80

Table 3
Expected useful life by material type of pipe

of pipelines to ward offices, civil engineering offices, hospitals, other facilities that serve as important bases for restoration after earthquake disasters, and at regional disaster prevention bases in regions where a seismic intensity of 7 would cause liquefaction is being carried out. Over a period of five years, the earthquake resistance of pipelines to bases at 50 locations will be reinforced.

Future challenges
When implementing a plan, pipelines are renewed more efficiently by determining the state of existing pipelines through diagnosis and appropriate maintenance, and by considering down-sizing to prepare for a decline in the quantity of water supplied. The aggressive adoption of the newest technologies such as GX pipes, which are said to have a 100-year lifetime, and the trial adoption of 50mm diameter ductile cast-iron earthquake resistant pipes will contribute to prolonging the renewal cycle and accelerating earthquake resistance.

The facility improvement plan

In its facility improvement plan, the Bureau has tried to improve earthquake resistance and the backup function of civil engineering structures such as water conveyance lines, treatment plants and distribution reservoirs, because when those types of facilities are damaged the impact is considerable. To create water supply systems that are effective and kind to the environment, the Bureau prioritises improvements to gravity flow systems over pump-boosted systems.

Earthquake resistance and extending asset life
To undertake earthquake resistance reinforcement effectively, priorities are determined and the work is undertaken, while adjusting work costs in line with the importance of each asset and its role in the water supply system, the impact on citizens if it fails during a disaster, and the danger of a secondary disaster.

Table 4 shows target earthquake resistance compliance rate under the medium-term management plan developed in 2012. For water conveyance lines, the aim is to prioritise improvements to the energy efficient gravity flow lines and to build a system capable of providing raw water, even during disasters. For treatment plants, an earthquake resistance reinforcement plan was created that focused on future demand. Distribution reservoirs have water storage functions in the event of earthquakes and other disasters, so their earthquake resistance reinforcement is undertaken more aggressively than that of other facilities.

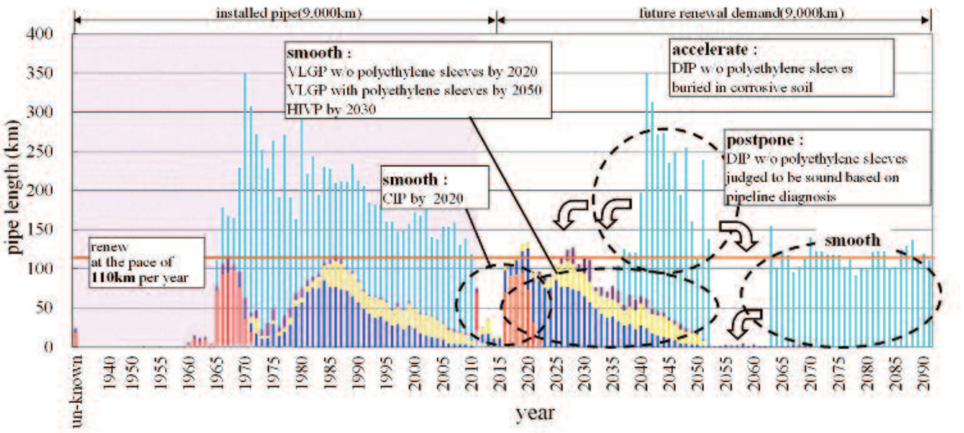


Figure 6
Future renewal demand where pipes are renewed at the end of their expected useful life

Loop line network improvements
The Bureau is currently improving the Loop line network, which links treatment plants and water distribution blocks to provide backup during emergencies, even when a large earthquake, water resource accident, or blackout has shut down a treatment plant or water transmission functions.

The present improvement rate is 96% and the completion of the tentatively-named Shin-isogo line, which is now being constructed, and of the network shown in Figure 8, are scheduled for 2014.

Building an efficient water supply system
Figure 9 shows the altitude of water resources and treatment plants owned by the Bureau. There are two gravity flow lines: the Doshi River line and the Sagami Reservoir line, and one pump-boosted line, the Banyu River line. Raw water from those lines is treated at the Kawai treatment plant, Nisiya plant and Kosuzume plant respectively. Treating raw water from each source at each treatment plant results in efficient treatment.

The bureau plans to prioritise improvements to the Kawai plant and Nisiya plant, to utilise the energy-efficient gravity flow lines to their maximum.

The Kawai plant, where treatment is currently based on rapid sand filtration, is being redeveloped into a membrane filtration facility that will treat 172,000m³/day, the maximum amount of water that the Bureau is permitted to take from the Doshi river. Introducing

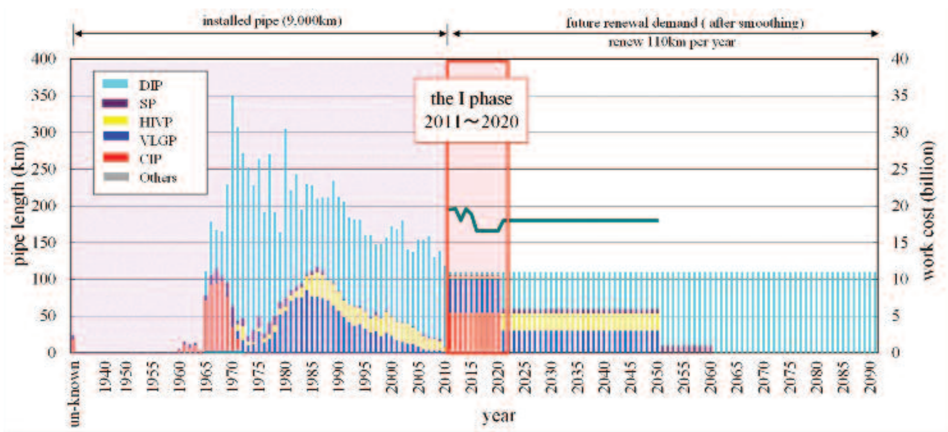


Figure 7
Future renewal demand after adjustment

the membrane filtration facility will bring better water quality, more effective use of water pressure, and save space.

Future challenges for civil structure improvements

The Bureau promoted facility improvements as water demand increased, however it is now necessary to improve the stable water supply system given the decline in demand. The Bureau therefore tries to predict future demand, and is looking at downsizing and revising water distribution blocks.

The equipment renewal plan

Renewal of equipment is performed systematically depending on a useful lifetime that is based on past maintenance performance. By making repairs and revising the useful lifetime, the equipment life is maximised while its condition is clarified, and rational renewals and improvements are carried out.

Revising the useful lifetime

The useful lifetime of industrial instruments was considered to be 18 years, but the results of investigations into 18 cases where industrial instruments exceeded their useful lifetime showed that they exceeded their predicted life span by an average of 3.6 years, so this criteria has been increased by two years to 20 years. Even if the present useful lifespan is exceeded, there is no increase in repair and inspection costs and no increase in the frequency of accidents, confirming that the extension will not cause problems. Water quality instruments have similarly been extended by two years from 13 to 15 years.

Cost reduction at pump renewal

At renewal time, introducing energy saving pumps is considered as a possible way to minimise life cycle costs. Specifically, speed control systems for distribution pumps, for which power consumption differs depending on the time slot, are being changed to the variable voltage variable frequency system from the liquid resistor system. Pumps are analysed at their renewal date, and if parts such as casings are judged to not need replacing, they are reused.

Future challenges for equipment improvement

The Bureau will continually revise its equipment renewal plan by revising the useful life span, based on the number of years equipment exceeds the existing useful life span and the frequency of accidents. In addition, it is necessary to examine how equipment inspection is undertaken and determine equipment condition through regular inspections and repairs.

Figure 8
Route of the Loop line network

Conclusion

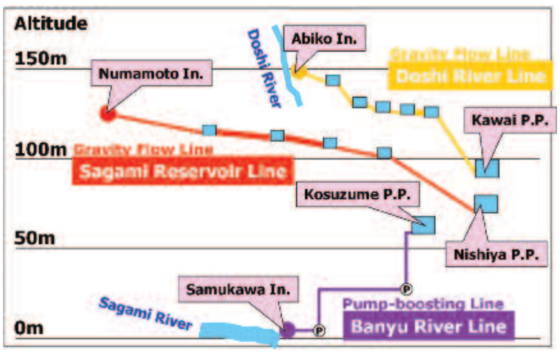
Improving infrastructure is costly, but water utilities need to achieve a sustainable water supply operation even while their water rate revenue is decreasing. To do this, it is important to develop a renewal plan that is harmonised with the medium and long-term financial plan and to revise it continually according to changes in water demand and advances in new technologies. In addition, public relations should be utilised to share management information with citizens, which enables smoother operation. ●

	2010	2015
Conveyance line (gravity flow)	75%	80%
Purification facility	0%	43%
Distribution reservoir	59%	93%

Table 4
Target earthquake resistance compliance rate under the medium-term management plan developed in 2012

This paper was presented at LESAM 2013 – the IWA Leading-Edge Strategic Asset Management conference, held 10-12 September 2013 in Sydney, Australia.

Figure 9
Altitude of water resources and purification plants



AM DIARY

A listing of upcoming asset management-related events and conferences. Send event details to WAMI for inclusion.

The Future of Utilities
25-27 March 2014, London, UK
Web: http://marketforce.eu.com/events/utilities-energy/the-future-of-utilities

Water Loss 2014
30 March - 2 April 2014, Vienna, Austria
Web: www.iwa-waterloss.org/2014

SMi presents the 3rd annual conference on: Smart Water Systems
28-29 April 2014, Marriott Regents Park Hotel, London, UK
Web: www.smi-online.co.uk/goto/2014smartwater26.asp

IWA European Utility Conference
14-17 May 2014, Oslo, Norway
Web: www.IWA-EUC2014.org

Water, Energy and Climate Conference 2014 'Solutions for Future Water Security'
21-23 May 2014, Mexico City, Mexico
Web: www.wecmexico2014.org

6th Singapore International Water Week + Water Convention 2014
1-5 June 2014, Singapore
Web: www.siww.com.sg

ECWATECH 2014 – Including NO-DIG Moscow: Trenchless Technologies in Russia, CIS and Baltic States
3-6 June 2014, Moscow, Russia
Web: www.ecwatech.com

13th International Conference on Urban Drainage 2014
7-11 September 2014, Sarawak, Malaysia
Web: http://www.13icud2014.com/index.php

IWA World Water Congress & Exhibition 2014
21-26 September 2014, Lisbon, Portugal
Web: www.iwa2014lisbon.org

LESAM 2015
17-19 November 2015, Yokohama, Japan

For a full list of water sector events taking place in 2014, visit: www.iwapublishing.com

Long-term corrosion of buried cast iron water mains: field data collection and model calibration

External corrosion of buried cast iron water mains is a major problem for the Australian water industry. To improve maintenance and replacement strategies, a method to estimate remaining service lives, predict long-term corrosion losses, pit depths and the extent of pitting is required. Robert Petersen, Matthew Dafter and Robert Melchers explain a conceptual model that has been developed and field observations from Hunter Water Corporation sites.

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The external corrosion and failure of cement-lined cast iron water mains is a significant problem for the Australian water industry. In 2011 a joint industry research project began, aimed at improving methods to predict pipe remaining service life. A number of industry partners and three universities are involved in the project (see acknowledgements). The role of the University of Newcastle in the project is to develop models to describe and predict the long-term corrosion losses and maximum pit depths of cast iron and steel buried in soil.

The processes controlling the long-term corrosion of cast iron buried in a soil and the external soil conditions influencing long-term corrosion were reviewed in Petersen and Melchers (2012). Corrosion of cast iron (and other ferrous metals) in a soil appears to be 'wet' corrosion and was shown to follow a bi-modal trend with time (Figure 1), generally similar to that which has also been observed for steels. The stages of bi-modal behaviour are described in Petersen and Melchers, 2012.

For future life prediction of cast iron pipes, in practice both the magnitude of the long-term corrosion loss and rate of future corrosion are of most interest. This includes average corrosion and maximum pit depth and pit area. A simple, practical model for predicting long-term corrosion (either maximum or average corrosion loss, and also pit depth) as a function of time can be obtained by bounding the bi-modal model as shown in Figure 1 (Petersen and Melchers, 2012). The model parameters c_s and r_s are expected to be functions of the soil environment surrounding the pipe, including soil moisture.

To calibrate the long-term corrosion model, field data from actual pipes under long-term service conditions is required. A field work programme has begun to collect data for model development and calibration. The field work procedure, data collected at each site, and the results from recent field work is presented below. Details of an initial model calibration, using the data collected from recent fieldwork are also given.

Field work method

The University of Newcastle was invited to visit a number of recent pipeline condition assessment sites within Hunter Water Corporation's network to collect data for model development. These works were conducted by Hunter Water Australia, and involved the exhumation and subsequent abrasive blasting of selected pipe sections to assess their condition. To date, data for model development has been collected from 11 water main sites and seven sewer main sites. Results from the water main sites are presented below. An outline of the data collection strategy is also provided here.

At each site, information on the pipe details was recorded, including manufacture type, nominal diameter and pipe wall thickness, exposure time and environment, such as ground cover, bedding and backfill conditions, burial depth and presence of groundwater (see Table 1). Additional information on pipe section length, joint type, internal lining information and any external coating was also recorded.

Soil samples were collected at each site and sent to an external laboratory for testing to characterise the soil environment surrounding the pipe. A 5kg sample of soil was taken from the exposed face of the excavated pit next to the exposed pipe (Figure 2a). The soil sample was excavated with a pickaxe and placed into a sealed plastic bag, which was then put into a cool insulated container for transport to the laboratory. These samples were analysed at SESL laboratories in Sydney for the following properties: texture class, permeability class, moisture content, pH, resistivity, chloride, sulphate, nitrate, and phosphate content, and total organic carbon (TOC).

In addition to the samples taken for analysis at SESL, the second author also collected samples for his own

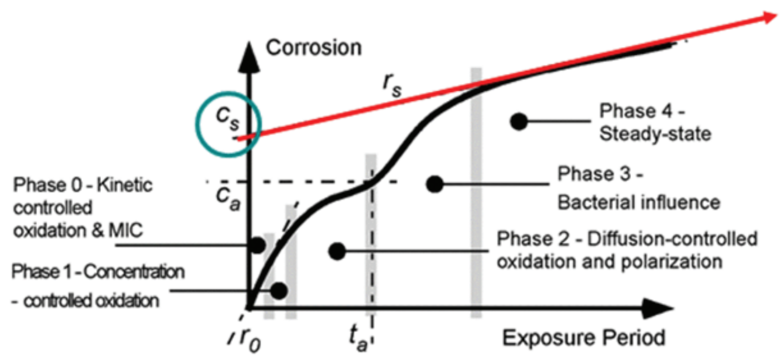

Figure 1 Bi-modal corrosion behaviour and long-term corrosion loss model

Figure 2 Photographs of pipe in excavated trench showing soil sample collection location and surface scanning in progress (after abrasive blasting). a) Soil sampling location; b) external surface of pipe WS5 being scanned.

independent studies. As a part of these, he determined the moisture content of the soil in-situ and at field capacity, and these values were used as additional data for this project. A cylindrical core sample of soil was also taken by the first author next to the pipe using a thin walled metal tube, in the location shown in Figure 2a. From this sample the bulk density (mass of soil/volume of soil), moisture content (mass water/mass soil), and porosity (volume voids/volume soil) were determined.

The degree of saturation of the soil (volume water/volume voids) was then determined using the calculated porosity and an average of the three moisture contents determined by the independent testers (SESL, the first author and the second author). Methods to determine the bulk density, moisture content, porosity and degree of saturation are well-known and are described in detail in many soil mechanics or soil sampling and testing text book, such as Tan (2005).

Following abrasive blasting at each site the external corrosion losses were quantified. Where possible, a selected portion of each pipe (typically a metre in length) was scanned using a hand-held Creaform laser scanner to accurately map (in 3D) the external surface of the pipe. The general procedure involved randomly placing adhesive positioning targets onto the pipe surface (approximately 50mm to 100mm apart), calibrating the scanner and then performing the scanning operation. The scanning operation involved pointing the handheld device at the pipe surface and sweeping across the area to be scanned (Figure 2b). The time taken to apply targets and scan each pipe was approximately one hour. A scanning resolution of 2mm was chosen for this work.

In addition to the laser scanning, each pipe was inspected visually and the deepest pits were measured using a pit depth gauge. Due to the constraints of the laser scanner and workplace health and safety (WHS) issues at certain sites (for example, where the water table prevented exhumation of the entire pipe) it was not always possible to obtain a laser scan of each pipe or indeed the whole pipe. In these cases manual techniques, including use of a pit depth gauge, were used to supplement or replace the laser scanning results.

The 3D surface scans were later post-processed to determine maximum and average corrosion losses. The software programme supplied with the laser scanner was used to determine and map relative corrosion depths over the surface of the pipe. Corrosion depth versus axial and circumferential position were exported into tables of 2mm x 2mm grid spacing, and imported into Microsoft Excel for analysis. The maximum penetration and average corrosion loss were determined from the tabulated data. Note that additional corrosion parameters can be determined from the data produced by the scans, such as the statistical variation of maximum losses, volume of corrosion losses, and area of pits and pit clusters.

Field work results

A summary of the data collected from field sites is presented in Table 1. The pipes inspected covered the complete range of cast iron pipe types used in Australian pipe-laying practice over a period of 36 to 129 years. The pipes are differentiated by manufacture process and include: vertically sand cast; deLavaud; Super deLavaud; and Yennora spun. Information on Australian pipe-laying practice is summarised in Nicholas and Moore (2009).

All of the pipelines inspected were buried under grass easements, and all sites were backfilled with native soil (as was the common practice before 1960, see Nicholas and Moore, 2009). A select sand backfill may have been used at sites RT1 and RT2; however the backfill material was indistinguishable from the surrounding native sandy soil. Soil groundwater conditions ranged from no observed water table to pipes being half-submerged.

The majority of soils were inorganic clays, with inorganic sandy soils encountered at only a few sites. The levels of pH, chloride content and sulphate content, measured at all sites, are considered non-aggressive to steel that is in contact with disturbed soil according to AS2159:2009 (Standards Australia, 2009). The levels at which they are considered to become mildly aggressive are pH < 5, chloride content > 5000 mg/kg, and sulphate content > 1000 mg/kg. Therefore it is unlikely that these are significant factors affecting the corrosion of these pipes. The moisture content presented in Table 1 is an average of the three values determined by SESL, and the first two author's independent tests.

At most sites the soil in contact with the pipe was relatively uniform, and the soil sampled next to the pipe was considered representative of the soil surrounding and touching the pipe. At two sites, however, the soil surrounding (touching) the pipe varied greatly. At site MC3 the soil surrounding the pipe was made up predominantly of a sandy soil, but also included clay lumps (of varying sizes) interspersed throughout. The worst identified location of corrosion on this pipe was found underneath a clay lump stuck to the surface of the pipe. Only this clay soil was sampled for analysis. At site MC5 the soil changed from clay at one end of the excavated pit, to sand at the other end of the excavated pit (pit length was approximately 3m). Both the sand and clay soils were sampled, as was a soil sample under the water table at the site.

The location, depth of maximum corrosion penetration and corrosion form was recorded for all pipes. In some cases only a portion of the pipe

Figure 3 Photographs of pipes MC4 and WS4 after abrasive blasting, and 3D scans of corroded external surface. In the 3D scans the position of the white arrow indicates the top of the pipe and the contour plots represent pipe wall thickness loss (as a percentage of the original thickness). (a) MC4 pipe in trench; (b) WS4 pipe in trench; (c) MC4 3D pipe scan results; and (d) WS4 3D pipe scan results.

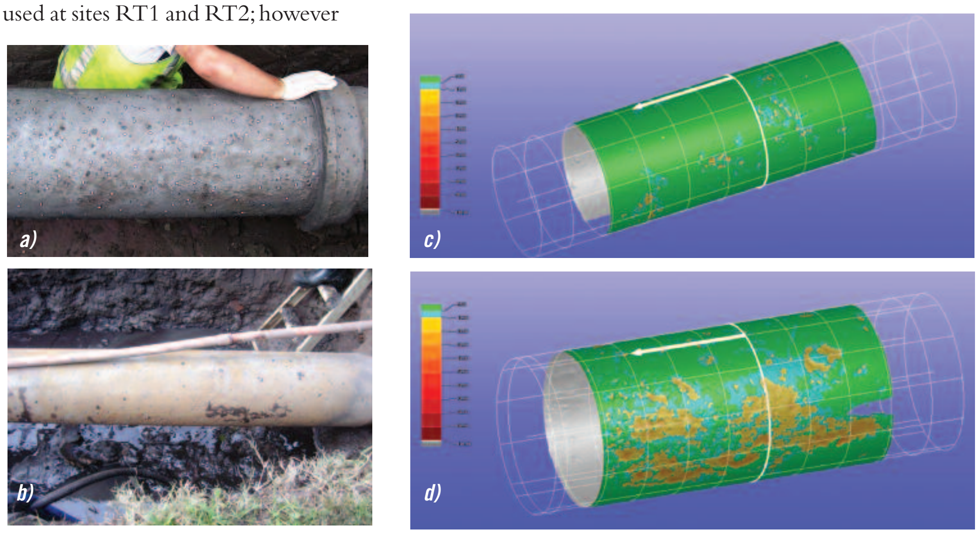

Table 1 Data collected at field sites.

Site	Pipe details				Environment				Soil properties															Corrosion		
	Type	Nominal Diameter (mm)	Thickness (mm)	Exposure time (yr)	Ground cover	Bedding	Backfill	Burial depth (mm)	Groundwater	Texture class	Permeability class	Bulk density (kg/m^3)	Porosity	MC in-situ (g/g moist soil)	MC field capacity (g/g moist soil)	Degree of saturation	pH	Resistivity (Ohm.m)	Chloride (mg/kg)	Sulphate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)	TOC (% g/g soil)	Maximum penetration (mm)	Location of max (degrees. 0 at top)	Corrosion form
RT1	YS	500	14	36	G	N[b]	N[b]	500	M	LS	High	-	0.36[a]	17.8	9	1.03	5.4	425	10	30	0.6	2.9	2.10	1.7	180	I
RT2	YS	500	14	36	G	N[b]	N[b]	600	-300	S	High	-	0.36[a]	14.8	7.7	0.83	5.3	168	50	30	<0.3	0.9	0.20	3.8	180	I
RT3	SD	250	13.2	58	G	N	N	400	no	SC	Low	-	0.50[a]	19.8	19.1	0.66	7.3	21	230	30	0.2	1.7	2.10	7.6	180	G
MC1	VC	450	16-18	90	G	N	N	850	no	SC	Low	1586	0.50	17.4	21.9	0.57	6.4	11	600	190	0.0	0.19	0.12	8.5	335	G
MC3[c]	SD	500	17	54	G	N	N	1400	M	SC[c]	Low	1649	0.55	25.7	27.6	0.76	7.9	22	80	60	0.6	0.06	1.30	6.4	0[c]	U
MC4	YS	300	11	46	G	N	N	600	B	SCL	Low	1152	0.69	24.9	19.2	0.39	8.3	16	60	50	0.0	0.43	1.24	6.5	180	I
MC5[d]	D	500	16-17	74	G	[d]	N	900	B	SdC[d]	Low	2062	0.38	19.8	16.8	1.07	6.3	25	190	130	0.8	0.05	0.35	5.7	110[d]	G
WS1	VC	375	17-20	129	G	N	N	500	no	SC	Low	1824	0.46	20.2	24.3	0.78	5.1	10	200	410	0.0	0.04	0.48	6.5	90	G
WS2[e]	VC	375	17-20	129	G	N	N	1500	-200	LC	Low	1504	0.54	17.2	19.9	0.47	6.3	10	650	190	0.6	0.48	0.32	12.0	320[e]	G
WS4	VC	375	17-20	129	G	N	N	500	no	SdC	Low	1233	0.49	15.3	15	0.49	7.9	38	180	40	1.2	0.07	2.02	6.1	260	G
WS5	VC	600	22.2	83	G	N	N	650	no	SC	Low	1875	0.41	17.7	21	0.76	5.6	58	70	160	0.0	0.16	0.14	10.6	180	G

Pipe type VC=Vertically sand cast, D=deLavaud (AIS), SD=Super deLavaud (AIS), YS = Yennora spun CI; **Ground cover** G=grass; **Bedding/Backfill** N=native; **Burial depth** measured from ground surface to top of exposed pipe; **Groundwater** M=middle of pipe, B=touching bottom of pipe, -300 = 300 mm below bottom of pipe, no = not observed; **Texture class**: S = sand, LS =loamy sand, SC = silty clay, SCL = silty clay loam, SdC = sandy clay, LC = light clay; **Corrosion form** (subjective interpretation) I=isolated pits, G = general/interacting pit clusters, U = unknown.

[a] assumed
[b] bedding/backfill could not be distinguished from native sandy soil
[c] MC3 site: highly variable soil; sandy soil plus clay lumps. Corrosion damage was found under adhered clay lump. Clay soil was analysed. Only top half of pipe inspected. Not abrasive blasted.
[d] MC5 site: variable soil; clay at one end of pit (max corrosion observed) and sand at opposite end. Three soil samples collected: clay, sand, & clay below wt. Properties of clay soil (at measured corrosion site) presented in table. Bottom of pipe not inspected. A hardwood and stone platform was observed underneath the pipe, indicative of wet ground conditions at construction
[e] WS2 site: Pipe buried at another location for first 65 years of exposure. The pipe orientation was likely different at original site.

was inspected due to restrictions on site (such as a high water table). These cases are identified in Table 1. External surface scans of five pipes were conducted (MC1, MC4, WS2, WS4, WS5), from which the maximum corrosion penetration and average loss were determined. Only the maximum penetration is presented and discussed in this paper. Figure 3 shows photos of pipes MC4 and WS4 after external blasting and 3D scans of these pipes.

The deepest corrosion was observed at the base of many pipes (180 degrees rotation from the top of the pipe), which is common experience (Romanoff, 1957). However, this was not observed for all pipes. Some pipes were not inspected at the base due to site restrictions (MC3 and MC5), and the location (around the circumference) of maximum corrosion on pipe WS2 was not known (see Table 1 footnotes).

Two forms of corrosion loss were identified: isolated pits and general patches of corrosion or interacting pit clusters. An example of corrosion identified as isolated pitting is shown in Figure 3c on a 46 year old Yennora spun CI pipe. An example of general / interacting pit cluster corrosion is shown in Figure 3d on a 130 year old vertically cast CI pipe. In general isolated pits were observed on younger pipes (Yennora spun) and the general / interacting pit cluster corrosion was observed on the older pipes of the other manufacture types. It is possible that manufacturing type may affect corrosion form, but it seems more reasonable that corrosion form is more greatly affected by length of exposure. It is suspected that initially individual pits form, but over time these join together to create clusters. Environmental conditions are also likely to influence corrosion form. The factors influencing corrosion form require further investigation.

A remaining external bitumen coating was observed on pipes RT1, RT2 and MC3, identified by their shiny black appearance. No remaining coating was observed on the other pipes (or it was not clear). This does not mean that a coating was not originally applied, however. It is likely that the vertically sand cast pipes (pre 1929) had a thick bitumen coating applied by hot dipping after casting. Pipes manufactured after 1929 (or less than 84 years old) were specified to have a painted bitumen coating (considered to offer little protection, Nicholas and Moore, 2009), but whether or not this was applied to a particular pipe was difficult to determine.

It is expected that the most significant factor influencing long-term corrosion rate and extent is the degree and time of wetness of a soil. To define the degree of wetness of a soil the degree of saturation is likely to be the most useful quantitative measure (more useful than soil moisture content alone – see Gupta and Gupta, 1979). The degree of saturation is equal to the volume of water divided by the volume of voids in a soil.

To study the effect of soil moisture on long-term pipeline corrosion it was assumed that the soil moisture content measured in the field was equal to the long-term average moisture content. This assumption was considered reasonable for the pipes buried in clay soil sites, as the variation (in time) of soil moisture content at depths below approximately 800mm in clay soils is typically low (less than 5% to 10%) (Rajeev et al, 2010). This is not the case for sandy soils, so the sites in sandy soils were left out of the following analysis.

Most soils were collected at depths of at least 800mm. At the clay sites the measured in-situ moisture content was close to the experimentally determined field capacity. The field capacity is typically assumed to represent the long-term average in-situ moisture content in a soil above the water table. This provides additional confidence that the in-situ moisture content is a good approximation of the long-term moisture content. Note that the in-situ moisture content was used (with the bulk density calculations) to determine the degree of saturation of the soil.

Figure 4 shows a plot of maximum penetration versus exposure time for the inspected pipes. Each data point is labelled with the site name and degree of saturation (Sw). Note that the sandy soil sites (RT1 and RT2) and the non-typical sites (those with site specific factors – MC3, MC5, and WS2) were not considered in this analysis. Point KK3 is an additional data point from ongoing site investigations on sewer rising mains, and has been included for additional information. The degree of saturation of MC4 was revised to reflect the fact that the deepest pits were observed on the bottom of the pipe, which was in contact with the

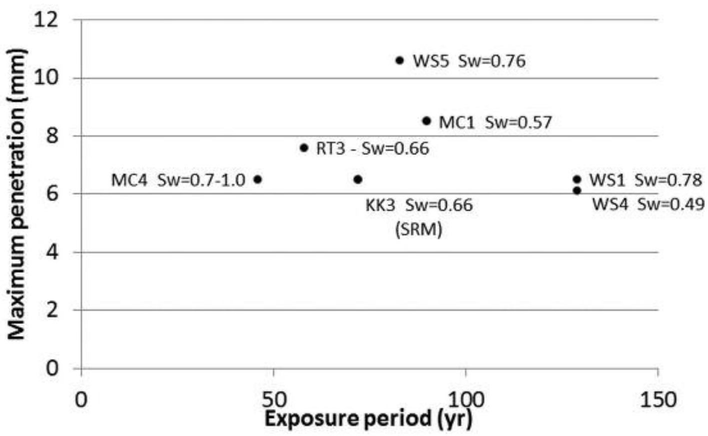

Figure 4
Maximum penetration versus exposure period for inspected pipes. Sw = degree of saturation of soil adjacent to the pipe.

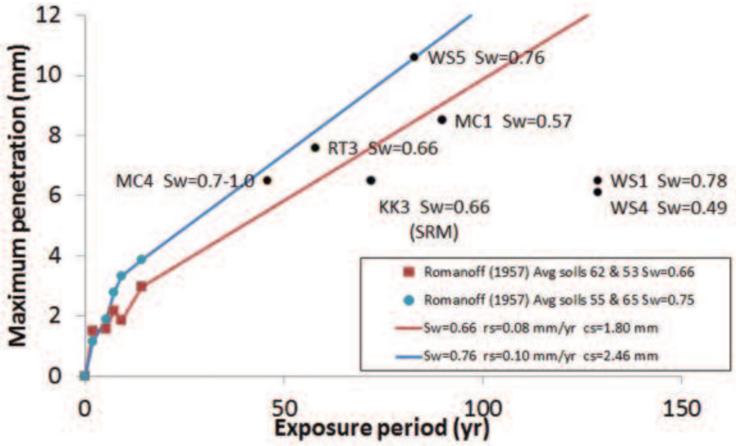

Figure 5
Maximum penetration versus exposure period for inspected pipes. Plot includes: long-term results from the current study, short-term results from Romanoff (1957), and model fit.

water table. The general data trend shown in Figure 4 suggests that the corrosion rate increases with increasing wetness, with the exception of the data point from WS1. The reason why the data point WS1 does not support this trend is unclear.

Relating collected long-term data with historical short-term data and initial model calibration

To calibrate the corrosion model, the collected long-term data needs to be related to short-term data under similar environmental conditions. Finding datasets under the same exact conditions is unrealistic. Instead, the approach taken here is to relate sites together based on the parameters that are considered to be most significant to long-term corrosion. These are, in decreasing order of expected influence: moisture, nutrients, pH, and compaction.

In this article sites are related by the first parameter, moisture, which is defined by the degree of saturation of the soil. The other parameters are not considered yet, and at this stage are just considered to add some noise to the results.

The (relatively) short-term data presented in Romanoff (1957) was used for this analysis. In this report corrosion versus time data is presented for cast iron pipes buried in 14 different soils for 14 years. Data for both average mass loss and maximum penetration is presented.

Romanoff collected a comprehensive set of soil data at each site, though this analysis did not report moisture content. Instead a subjective, qualitative measure of the site drainage conditions was given (good, fair, poor, or very poor). Romanoff did, however, report the apparent specific gravity and percentage air pore space of each soil, from which both the moisture content and degree of saturation can be estimated. For these calculations a soil particle density of 2670 kg/m^3 was assumed. As before, it was assumed that the estimated moisture content and degree of saturation values were a good approximation of the long-term values. Results for soils with degree of saturation values of 0.66 and 0.76 were used to relate to the long-term data. Selected soil properties and details for these sites are provided in Table 2.

The maximum penetration data (average values) of these soils are shown with the collected long-term data in Figure 5. Lines were drawn to connect the short and long-term data: soils 53 and 62 (Sw = 0.66) were related to site RT3 and KK3 (Sw = 0.66); and soils 55 and 65 (Sw = 0.76) were related to site WS5 (Sw = 0.76). The results from short-term study appear to be consistent with the results from this longer term study. Also, the trend observed, that corrosion increases with increasing moisture, is also consistent between the datasets. This consistency adds confidence to the proposed approach for constructing the long-term corrosion (maximum penetration) versus time behaviour.

The model outlined in Section 1 was fitted to the data in Figure 5. The model fit results are shown in the figure and are as follows: for Sw =0.66, rs = 0.08 mm/yr and cs = 1.80 mm; for Sw = 0.76, rs = 0.10 mm/yr and cs = 2.46 mm.

Summary and Conclusions

This paper has presented preliminary results of a field study on the corrosion of cast iron pipes buried in soils. The following conclusions may be drawn from the study to date:

- Long-term maximum corrosion penetration increases with increasing soil wetness (measured using degree of saturation) for the sites investigated
- Using long-term and short-term data from different data sets and using only the most significant parameters influencing corrosion appears to produce rational and consistent results based on degree of saturation to represent the moisture available for corrosion.
- The initial calibration for model parameters is for cast iron pipes buried at standard depths in

Table 2: Selected soil properties at Romanoff (1957) test sites

Number	Soil type	Drainage	pH	Air pore space (%)	Apparent specific gravity	Degree of saturation
53	Cecil clay loam	Good	4.8	18.2	1.60	0.66
62	Susquehanna clay	Fair	4.5	14.9	1.79	0.66
55	Hagerstown loam	Good	5.8	15.5	1.49	0.75
65	Chino silt loam	Good	8	15.8	1.41	0.76

relatively homogeneous, low-permeability, soils with degrees of saturation equal to 0.66 and 0.76
- Further work is required for model calibration, including the collection of data from additional field sites and from historical studies and the analysis of non-typical cases that were removed from the present analysis. ●

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Evaluation of machine learning for predicting critical main failure

Machine learning is a new approach for critical water main failure prediction. Vicky S Whiffin, Craig Crawley, Yang Wang, Zhidong Li and Fang Chen report on a test of its performance that used machine learning techniques to predict failures based on ten years of data from two areas of Sydney.

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Critical water mains are large pipes (generally >300mm diameter) that have significant impacts on the water supply and the community when they fail. They are defined as critical based on the network location (for example, a single trunk line connecting distribution areas or under a major road) or size, which infers impact potential. The impacts of breaks in these mains have greater financial and community consequences so a proactive management approach is taken.

From a utilities perspective there are two goals for critical mains asset management:
- Minimise unexpected critical main failure by prioritising timely renewals
- Avoid replacing a pipe too early before the end of its economic life

Traditionally, a significant number of network repairs have been performed on an unscheduled basis, generally in response to pipe or other component failures in the area (Dehghan, 2009). Although this approach fixes the issues as they arise, it generally results in higher costs compared to preventative work and burdens the community with unplanned service disruptions. Further, it raises significant challenges for forward planning of renewal budgets and tends towards leaving a maintenance legacy as assets age.

Size of the challenge

Over the past ten years, Australian utility Sydney Water has spent around $3.5 million each year on reactive critical water main repairs. If high-risk pipes can be identified before a failure occurs, it is likely that repairs can be completed with minimal service interruption, water loss and negative reputational and community impacts. Identification of an accurate predictor measure that indicates imminent failure will allow Sydney Water to take actions to mitigate the failure for a lower cost than repairing a full-scale failure. This will contribute to extending the service life of pipes that are still in good condition and allow the utility to run the mains to an acceptable defined risk limit.

Currently Sydney Water's critical main network consists of 4700km of pipes, with an average pipe age of 50 years over a geographical area of 12,700km^2. As the average age of the network increases, it will become more important to accurately predict the risks of pipe failure and provide the right level of pipe maintenance and renewal at the right time, according to risks associated with each pipe.

Pipe failure prediction

The failure mechanisms of pipes have been studied over many years and have resulted in many attempts to improve prediction (Goulter & Kazemi, 1986; Kleiner & Rajani, 2000; Rogers & Grigg, 2009). Although the engineering material properties of pipes are reasonably well understood, in-situ failure is a complex process that is influenced by a wide range of internal and external factors. These factors can be driven by physical, operational and environmental processes that can change significantly over a pipe's service life. Consequently, even within a specific pipe cohort, there is a wide range of failure rates and therefore accurate failure prediction is very

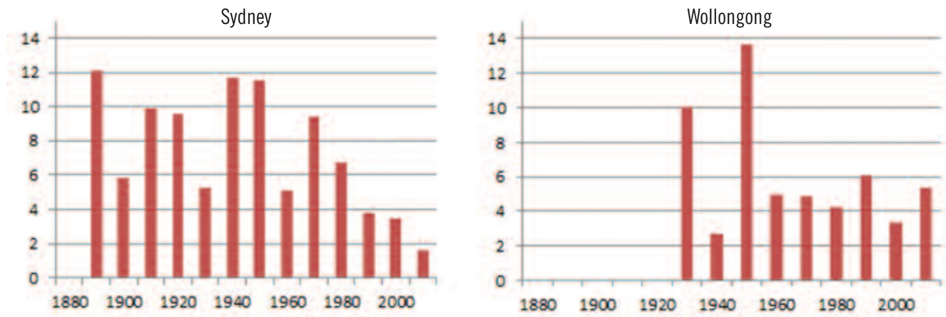


Figure 1
Distribution of failure rate versus laid year for critical water mains (failure rate over ten years per 100km pipe)

difficult to achieve.

Sydney Water has an industry-recognised risk-based framework for critical water main renewal decisions that includes failure likelihood, failure consequence (economic), engineering judgement and condition assessment information. Mains that are allocated a high failure risk are condition assessed prior to renewal. The decision of where to direct condition assessment is determined by an economic model. The model requires input of set parameters that are then processed using a Weibull algorithm (Weibull, 1951). The utility's experience with this method indicates a low level of accuracy and often does not identify pipes that are in poor condition, meaning that condition assessment activity can be misdirected to the wrong areas.

Data quality issues

Any pipe failure model needs to be able to cope with the data that is available for input. The available data is not continuous over the pipe's life and has a number of issues that need to be considered:

- The current data set shows no obvious consistent patterns of pipe failure. This means that failures are probably due to the impact of multiple factors rather than individual factors, some of which may not be documented at all (e.g. manufacturing conditions).
- Incident data is very sparse compared to non-incident data. In Sydney, less than 1% of critical mains break each year. Pipe records for laid date, material and location have been kept since 1888 but good records that document failures are only available from around 2000.
- The current predictive quality of the collected data is unknown. Sydney Water does not know if it is currently collecting the best parameters for prediction or if the collected frequency is at the optimum resolution.

Machine learning

Machine learning is particularly suited to complex data sets like pipe condition and failure as it avoids assumptions on the model structure. This approach aims to develop a model that performs accurately on new, unseen examples after having first trained on a real historical data set. Machine learning has been successfully used to improve prediction accuracy on complex data sets in other industries, such as predicting the prognosis for cancer patients (Cruz & Wishart, 2006), weather forecasting (Krasnopolsky & Fox-Rabinovitz, 2006) and economic market price predictions (Yan & Chowdhury, 2013).

This type of modelling is a relatively new approach for predicting critical water main failures. It relies on 'learning' representation rules from existing real data sets and using these to form generalisations that can be applied to predict future outcomes. It is non-parametric in nature, meaning that it is not necessary to define the relationship of specific parameters (such as age, material, size) with a known failure impact using an assumed model function. Rather, the model is presented with multiple sources of data from which it can derive the most valuable parameters for predicting failure outcomes. It is well recognised that many factors which influence failure prediction are not well defined (such as early manufacturing variations, manufacturing inconsistency, traffic and weather impacts) and this poor definition usually results in exclusion from traditional modelling approaches. A significant advantage of the Bayesian non-parametric-based machine learning approach is the ability to include this data in the data set that is available for predictions.

To test the machine learning approach for predicting critical water main failure, 12 years of data (1999-2010) was provided for a comparative analysis. Two urban areas in Sydney were characterised – the Sydney Central Business District and Wollongong (17,000 and 14,000 pipe segments, respectively). Information was provided on asset identification number, age, length, material, diameter, location, coating and soil type. The data was split into a learning data set (1999-2007), which was used to train the machine learning model and a testing data set (2008-2010), which was used to compare the models prediction to the actual failures that occurred.

To assess the accuracy of prediction, the same data set was analysed by the machine learning approach as well as two other traditional parametric models (Cox and Weibull models).

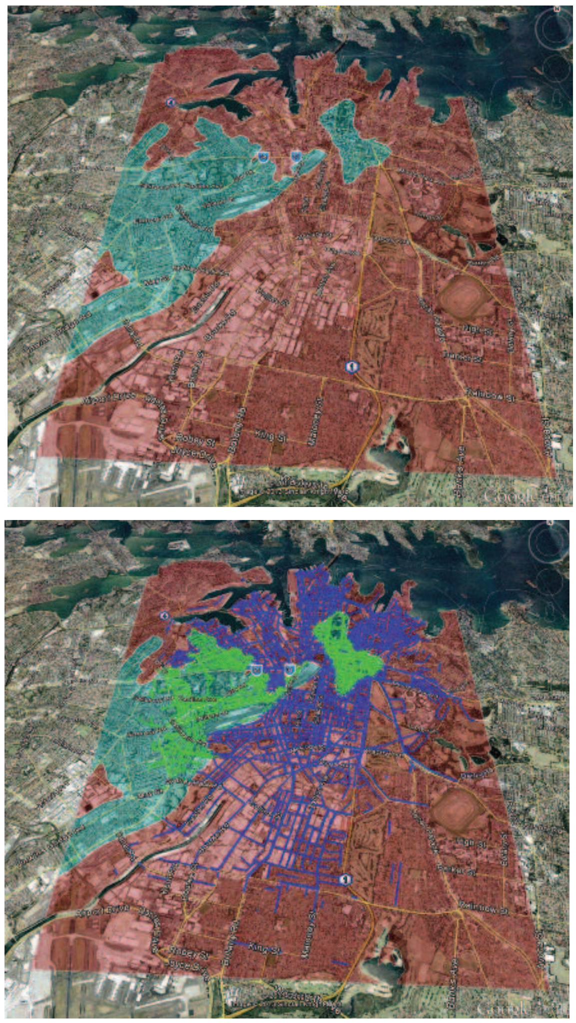
Factor analysis

The impact of individual factors on water pipe failure was investigated and compared with failure rates to determine if there were obvious correlations in the data set. An example of this analysis is shown in Figure 1, representing the distribution of laid year and ten-year failure rate for critical water mains in Sydney and Wollongong. It can be seen that the failure rate of water pipes does not always increase with age. In some instances, older pipes have a lower failure rate than those laid in later years.

Similar analyses were done to compare failure rates with pipe diameter, pipe material and coatings in both regions. Overall, these indicated no strong patterns that could be matched to pipe failure.

Further analysis was done on the geographical locations of the pipes. Figure 2 shows the distribution of soil aggressiveness in Sydney, where non-aggressive soil and aggressive soil are represented using different colours. For each water pipe, the pipe failure history was matched to the aggressiveness map based on its location. A similar analysis

Figure 2
Distribution of soil aggressiveness in Sydney. Non-aggressive regions are in blue and aggressive regions in brown. Line segments on the right represent water mains.



was also done for the Wollongong area (not shown).

Again no obvious correlations could be seen between the pipe failure history and the soil mapping.

Influence of individual factors

To assess the influence of individual factors, the information gain for each was calculated. Information gain is a widely used and simple machine learning technique that provides an estimate of the correlation between individual factors and pipe failures. Given a factor x (such as year laid or material), the information gain IG on pipe failure z ($z = 1$ for a failed pipe, otherwise $z = 0$) can be determined by:

$IG(x;z) = H(x) - H(x \mid z)$

where $H(\cdot)$ and $H(\cdot|\cdot)$ represents entropy and conditional entropy respectively.

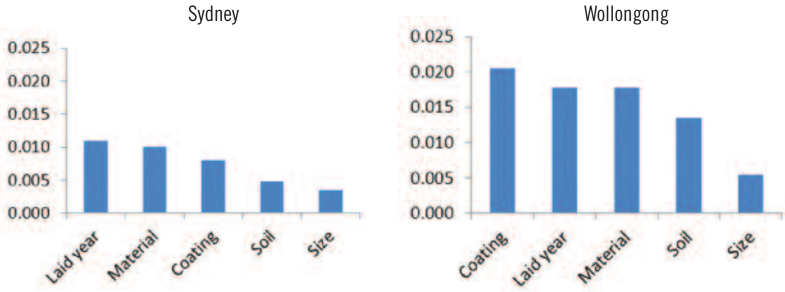
The importance of each factor for failure prediction was different for the two assessed areas. For example, the year the pipe was laid was the most important factor for failure in Sydney, but it was the second most important factor for pipe failure in Wollongong (Figure 3). Further, the magnitude of influence for each of the parameters was greater in Wollongong than in Sydney. These results indicate that the patterns of water pipe failure are not consistent between different regions, even though they are only 85km apart.

Failure prediction

To test the machine learning approach, Bayesian non-parametric learning was applied to predict the probability of critical main failure, based on the available historical records. These methods have become well accepted in practice because they offer a more general modelling strategy with fewer assumptions about the model structure. Compared to existing statistical prediction methods, they offer a more flexible model structure to accommodate the volume and diversity of historical data and are less sensitive to the effects of various noisy factors. It is also possible to incorporate spatial relationships among neighbouring pipes to better predict infrequent failures.

A hierarchical beta process (HBP) (Thibaux & Jordan, 2007) has been used to model the data. For a water-distribution system that consists of multiple groups of pipes, $\pi_{k,i}$ is denoted as the probability of failure for a pipe in the k-th group. Considering hierarchical construction for pipe condition assessment,

Figure 3
Influence of factors for predicting pipe failure



$q_k \sim Beta\,(c_o q_o, c_o(1-q_o))$, where $k=1.2\ldots K$

$\pi_{k,j} \sim Beta\,(c_k q_k, c_k(1-q_k))$, where $i=1.2\ldots n_k$

$z_{k,i,j} \sim Ber\,(\pi_{k,i})$, where $j=1.2\ldots m_{j,k}$

where q_k and c_k are the mean and concentration parameters for the k-th group, q_o and c_o are hyper parameters for the hierarchical beta process, $z_{k,j} = \{z_{k,i,j} \mid j=1.2\ldots m_{j,k}\}$ is the history of pipe failure, $z_{k,i,j} = 1$ means the pipe failed in j-th year, otherwise $z_{k,i,j} = 0$.

An inference algorithm was developed to estimate both mean and concentration parameters for the hierarchical beta process (Li et al, 2013). For critical main failure data, the available ten-year observation period is relatively short compared to the life cycle of the pipes, such that most (about 99%) pipes do not fail or fail only once during the observation period. The sparseness of the data could be used for approximation of the inference process to further reduce the computational complexity.

The HBP method was tested and compared with two other survival analysis methods, the Cox (Cox, 1972) and Weibull models. Figure 4 shows the comparison results of predicting pipe failures in the two regions. The pipe failures for a given year were predicted using all failure records available before that year as training data. The model ranks pipes so that the highest failure risk pipes are ranked first (that is, first pipe inspected) and lowest failure risk pipes are ranked last (that is, last pipe inspected). If the model has perfectly ranked all pipes then 100% of network failures will be found in the first 1% of pipes inspected (assuming 1% of pipes fail in any given year). If the model is poor then 1% inspection will find 1% of network failures simply by chance.

The results for each model are shown in Figure 4 with the x-axis representing the percentage of condition assessed water pipes starting at the top of the list, and the y-axis representing the percentage of actual failures detected from those inspections.

The HBP (machine learning) model achieves better performance in most cases (Figure 4). Compared to the Cox and Weibull traditional models, machine learning modelling is not limited by a fixed model structure, so it is able to adjust the model complexity adaptively to the accumulation of failure data. This flexibility enables the HBP method to provide a robust performance of pipe failure prediction in different regions.

For the purposes of targeting condition assessment to the correct areas, it is only economically viable to condition assess a limited proportion of the whole network (for example up to 5%). Given this, it is most useful to consider the models results between 0 and 5% of pipe length inspected (x-axis). In Figure 4, the HBP model provides a significant improvement over other the other models. For example in Sydney assessing 3% of the critical mains network based on the HBP predictions would provide 25% of the following years failures, compared to 5% using the Cox's model and 10% using the Weibull model.

The estimated failure probability provided by this method allows all pipes in a system to be directly ranked based on their probability of failure. From this information and geographical location it is then possible to create risk maps based on failure probabilities, as in Figure 5, which can be used to identify pipe sets requiring attention.

Conclusions

In this evaluation, the machine learning model outperformed the other traditional modelling approaches by predicting future failures with improved precision. The approach generated whole-of-system risk maps that allowed an overview of clustering in the spatial pipe networks and incorporation of some predictive characteristics like soil type that are usually not able to be incorporated in traditional models.

It was shown that individual factors impacted failure in different geographical areas in an inconsistent way. This type of modelling allows individual factors to be represented differently in different areas rather than impose a one-size-fits-all approach to pipe cohorts.

The findings presented here were part of a preliminary investigation of this approach and further research is underway to develop the model further and assess its full potential for critical mains failure prediction. This work has also expanded to include data

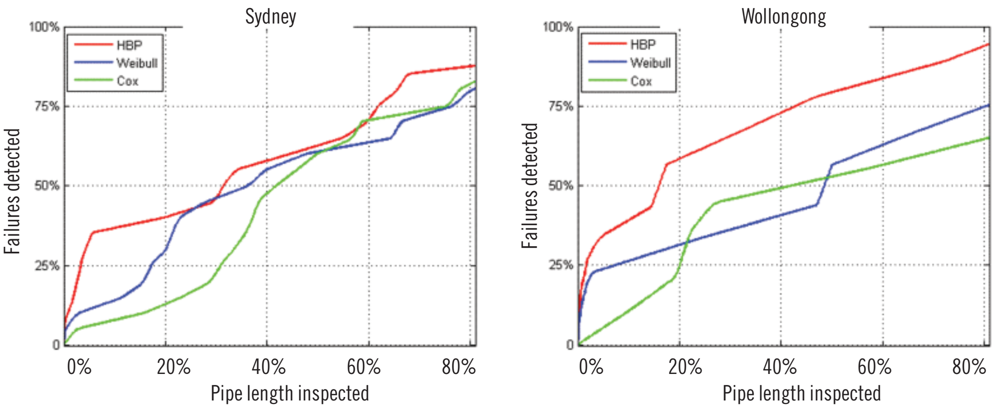


Figure 4
Results of pipe failure prediction using different models

contributed by other collaborating utilities.

It is hoped that applying machine learning techniques to the water industry will provide:

- Improved understanding of how parameters predict critical main failure
- Identification of the most useful indicators that can be monitored and reported regarding critical water mains
- Improved accuracy for identification of high risk mains

These outcomes will lead to better management of critical water mains and optimal renewal investment decisions. ●

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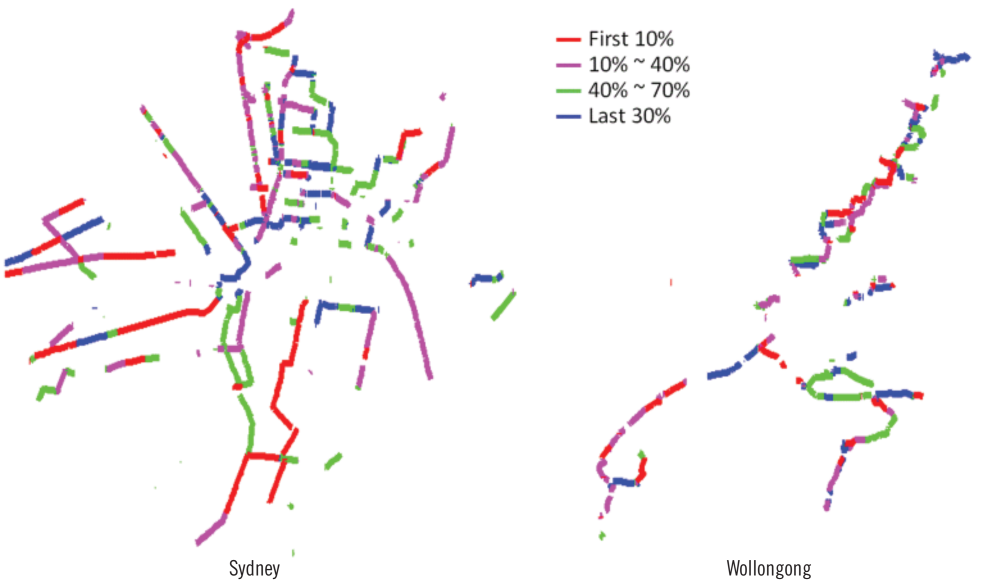
Figure 5
Ranking of pipe failure probabilities. Red indicates the highest failure risk (top 10%) followed by pink (10% to 40%), green (40% to 70%) and blue (lowest failure risk 70% to 100%)



PUBLICATIONS

Flood Grouting for Infiltration Reduction on Private Side Sewers

INFR5R11

Author: Martha Burke

The sewers in Seattle's Broadview neighborhood, built in the 1950s, experience significant inflow and infiltration. Flood grouting was used to treat an entire section of the sewer system between two maintenance holes, including the side sewers. To determine the success of the project, flow meters were installed in the system to document before and after conditions for modelling analysis. The effectiveness of this approach at reducing infiltration compared to the cost, the challenges associated with working on private property, and lessons learned are documented in this paper.

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A Practitioner's Guide to Economic Decision Making in Asset Management - Part 1: Background Document and Part 2: Guidance Document

SAM1R06b1 and SAM1R06b2

Author: David Marlow

For many water service providers (WSPs), meeting the financial demands of maintaining, extending and upgrading infrastructure systems is increasingly challenging. These challenges mean that there is an increasing need for asset managers to embrace new approaches to decision support. With this in mind, work has been undertaken to develop a 'Practitioner's Guidelines for Economic Decision Making'.

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National investigation of failure rates from Australian water supply pipes

Water supply pipe failures are unfortunately common. Scott Gould, David Beale, Paul Davis, David Marlow and Jaimie Hicks present descriptive and cohort analyses using an asset and failure dataset that incorporates 13 water utilities across Australia, and is believed to be the most extensive ever created.

Scott Gould, David Beale, Paul Davis and David Marlow, CSIRO Land & Water, Highett, Victoria, Australia.

Jaimie Hicks Water Services Association of Australia, Docklands, Victoria, Australia.

The failure of water supply pipes is an unfortunately common occurrence, and understanding the failure behaviour of pipes is an important aspect of asset management (Burn et al, 2009). Understanding failure behaviour can enable asset managers to make the most effective use of their assets. An integral part of that process is collecting and maintaining pipe asset and failure data. These records can be used for a number of purposes, including regulatory reporting, identifying problematic pipe cohorts and developing statistical models to predict future performance.

The Water Services Association of Australia (WSAA) recently ran a project, which was completed in 2013, which gathered pipe and failure information from its member utilities across Australia. The final dataset collated for analysis was used to create a multi-utility database. Developing multi-utility databases such as this has been found to provide valuable information (Vloerbergh and Blokker, 2010), which can be used to improve understanding of pipe performance.

Analysis of the data can provide utilities with valuable insight into the performance of their own networks and how their networks compare to others around Australia. For example, a comparison of pipe cohort performance between utilities may identify why one utility experiences higher failure rates than a second, comparable utility.

This paper presents descriptive and cohort analyses using an extensive asset and failure dataset incorporating 13 water utilities across Australia. This dataset is believed to be the most extensive of this type created and covers major urban and rural areas providing water to over 14 million people, or around 64% of the Australian population.

Data summary

The size of the 13 utilities varies between around 54,000 and 1,800,000 connected properties (National Water Commission, 2012). Summaries of the pipe and failure data used in this investigation, following integrity checking, are given in Table 1 and Table 2 respectively.

Integrity checking was undertaken to identify and remove unreliable asset and failure records from the supplied data before analysis. To account for the removal of otherwise reliable failures that could not be reliably associated, or 'matched', asset matching rates were calculated. Matching rates (m_r) are calculated as the proportion of the number of failures retained for analysis following all data integrity checks (f_f) over the number of failures relevant to the analysis (f_l) (see Equation 1). Matching rates prevent the artificial reduction of calculated failure rates as the result of removing failure records from the data. However, they also result in a smearing of the 'unmatched' across all pipes.

$$(m_r) = \frac{f_f}{f_l} \qquad \text{Equation 1}$$

Method

Two types of analyses were undertaken: a descriptive analysis and a cohort analysis. The descriptive analysis explores trends in pipe failure using asset and failure characteristics, specifically asset material, asset diameter and failure month.

The cohort analysis defines cohorts in terms of pipe material, diameter and installation decade, for example CI ≤ 300mm 1950 to1959 (cast iron pipes of 300mm diameter or less installed in the 1950s). Each cohort was then classified as good, average or poor by undertaking a quantile analysis on cohort failure rates. Average cohorts were classified as those with failure rates within the interquartile range (IQR), good and poor cohorts had failure rates below and above the IQR respectively. Cohort classification was undertaken within each utility and using merged data at the national level. The results of cohort classification are then used to investigate potential causes of variations observed in the classifications.

Cohort variations are investigated at four levels of granularity:

- Asset characteristics
- Operating environment
- Broader environment
- Asset management paradigm

Results

Descriptive analysis

Failure rates are presented from the combined data disaggregated by utility, pipe material and pipe diameter. Figure 1 shows the failure rate for each utility and the failure rate for all the combined networks of all utilities. A clear variation in these failure rates can be seen. The differences in failure rates are related to a large number of potential factors, which are investigated in the discussion.

Trends in pipe failure rate relating to pipe material have been reported by a number of authors (Pelletier et al, 2003; Vloerbergh and Blokker, 2007; Gould, 2011). The reported trends contained different numbers of materials and varying material rankings, but in general, based on the reported values, pipe failure rates are expected to decrease in the following derived order: CI, AC, GWI, RC, DI, PE, PVC, and S (cast iron, asbestos

Table 1: Summary of pipe data following integrity checking

Number of utilities	13			
	Total	**Maximum**	**Median**	**Minimum**
Asset length (km)	120,587.4	30,597.1	4935.8	582.4
Number of assets	1,702,466	343,735	144,796	4156
Exposed length† (km.years)	1,487,848	514,911.2	64,574.8	1449.4
Pipe installation period	1840-2009	1937-2009	1884-2009	1840-2009

† Exposed length is the length of assets within that group multiplied by the number of years for which that pipe was in service during the observation period††.
†† The observation period is the years over which failure data is available for analysis.

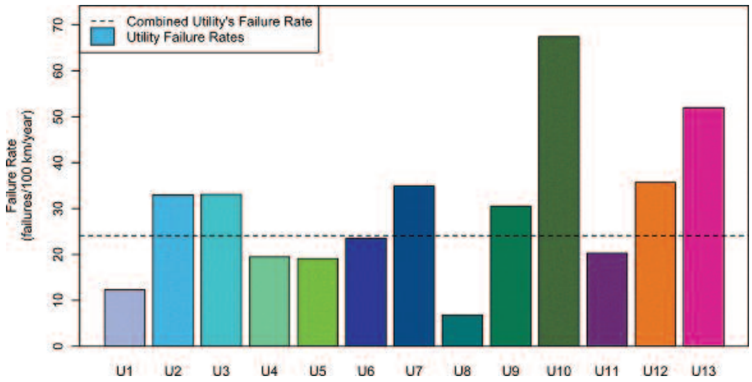


Figure 1
Failure rate by utility

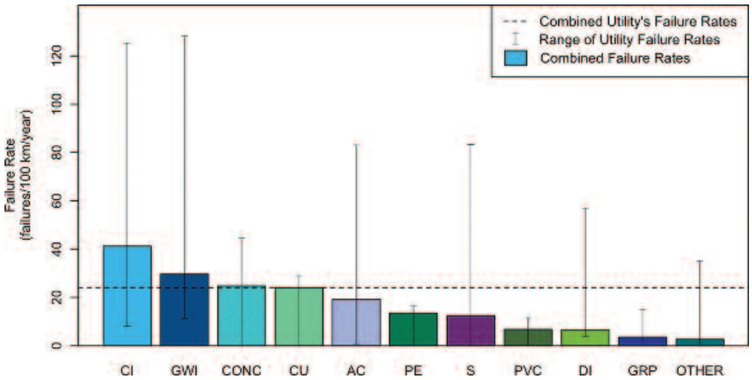


Figure 2
Failure rate by pipe material

cement, galvanised wrought iron, reinforced concrete, ductile iron, polyethylene, polyvinyl chloride and steel).

It can be seen in Figure 2 that this derived order is not followed faithfully, which was not unexpected as the derived order shown was developed based on disparate data. Additionally, it can be seen from the range bars in Figure 2 that the failure rates for each material vary between utilities. The largest range was seen for AC followed closely by CI, with failure rate ranges of 117.2 and 116.9 failures per100km per year respectively.

Trends in pipe failure rate with reference to pipe diameter have been reported by numerous authors (Newport, 1981; Kettler and Goulter, 1985; Rajani and Zhan, 1996; Hudak et al., 1998; Pelletier et al., 2003; Boxall et al., 2007; Hu and Hubble, 2007; Gorji-Bandpy and Shateri, 2008; Gould, 2011; Vloerbergh and Blokker, 2007). All authors reported that pipe failure rates were observed to decrease as pipe diameter increased, for pipes with nominal diameters of 100mm (4in) or greater.

Below this diameter Gorji-Bandpy and Shateri (2008), Gould (2011) and Vloerbergh and Blokker (2007) reported that the failure rate was observed to decrease. It can be seen that the trend shown in Figure 3 supports the trends reported in the literature. Above 100mm, the failure rate is seen to decrease as diameter increases, though there is a minor departure from this trend at 250mm. Within each diameter group there is strong variability in failure rates between utilities, generally decreasing with increasing diameter.

Cohort classification

The cohort analysis identified the poor and good cohorts and can be applied at multiple levels, for example within a utility, with a group of similar utilities and across all utilities. At the national level cohorts can be compared between utilities and to the combined cohort classification. This enables utilities to identify poor and good cohorts at a broader scale, enabling each utility to benchmark the performance of each of their cohorts at the national level.

This provided a valuable insight into network performance and highlighted those cohorts requiring particular attention. This insight could be used as a basis for targeting future rehabilitation strategies.

Analysis of cohort variations

Following the cohort classification presented above, a framework was developed that can be used to investigate observed variations in the classifications between cohorts and between the same cohorts in different networks. This framework identifies four levels of possible causes of variations in cohort failure rate:

- Asset characteristics
- Operating environment
- Broader environment
- Asset management paradigm

This framework facilitates the understanding of the performance of cohorts within water networks. Application of this framework is demonstrated by using it to identify the likely cause of an extreme variation in the failure rate of a polyethylene cohort (PE ≤ 300 1980 to 1989) from one utility compared to the performance of this cohort across all utilities.

Investigation framework

The potential causes of cohort failure rate variation between utilities can be separated into four distinct levels of factors that affect pipe failure. A summary of these levels is shown in Figure 4 and expanded upon below. Due to the larger number of potential factors, not all, for example water table, are shown in Figure 4 and expanded upon below. For further details on all factors refer to Gould, et al (2013).

Variations in asset characteristics can cause noticeable variations in observed failure rates, as the characteristics of the asset determine how it will respond to its environment.

Material

This determines corrosion behaviour, mechanical strength, response to applied stresses and deterioration mechanisms (Al-Adeeb and Matti, 1984; Davis et al, 2007) (Makar and McDonald, 2007; Davis et al., 2008).

Diameter

Depending on the failure mechanism, diameter affects the failure rate for various reasons including changes in wall thickness and joint reliability, and change in moment of inertia (Kettler and Goulter, 1985; Hu and Hubble, 2007). However, regardless of this, the failure rate is expected to increase as diameter decreases.

Installation method / quality

The installation method and quality will influence the performance of assets. A lower quality installation may introduce damage to the pipe (Burn et al, 2005), its lining or coating, resulting in additional loadings that would not otherwise occur or exposing the pipe to sources of deterioration. Installation method and quality can also relate to fittings installed in the pipe. Poor installation of fittings can cause damage

Table 2: Summary of failure data following integrity checking

Number of utilities	13			
	Total	**Maximum**	**Median**	**Minimum**
Number of pipe failures	303,150	71,854	20,587	457
Observation period (years)	163	22	12	1

to the pipe, its lining or coating and introduce a source of additional corrosion due to dissimilar metals.

Variations in an asset's operating environment can cause noticeable variations in observed failure rates. The characteristics of the operating environment determine the stresses acting on the pipe and the rate of material deterioration. The operating environment includes both the external and internal environments. It should be noted that for the purposes of this paper the operating environment is the environment in close proximity, that is either in direct contact or within 2D of the pipe centroid where D is the pipe burial depth (if buried). It should be noted that the comments below may not be applicable to all pipe material types.

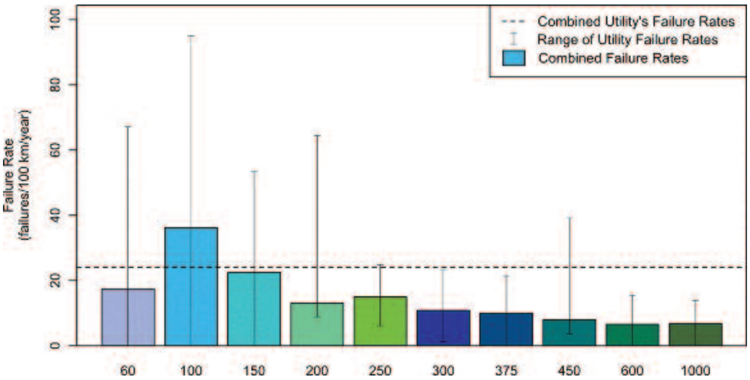
- Internal pressure: internal pressure including water hammer determines the loads applied to the pipe.
- Internal water quality: influences the rate of lining and/or material deterioration (Davis et al, 2008).
- Soil type: affects the loads acting on the pipe and the rate of coating and / or material deterioration.
- Soil reactivity: determines the stresses applied to a buried pipe as the result of soil movement due to soil moisture change (Hudak et al, 1998; Gould et al, 2011). Also known as soil expansiveness and shrink / swell potential.

The broader environment, that is, the environment more than 2D from the pipe centroid, acts upon the pipe's operating environment and so influences the pipe via its surrounding environment.

- Weather: influences pipe environment in the short-term, that is, over a period of less than three months, by altering the conditions of the pipe's surrounding environment. For example, rainfall, and lack thereof, influences the soil moisture which, along with soil type, can result in soil movement (Gould et al., 2011)
- Extreme events: droughts and floods are extreme examples of the effect of weather on a pipe's surrounding environment. Earthquakes are another example of an extreme event.
- Season: this influences the weather acting on a pipe's surrounding environment. This effect is evident in the intra-years variations in observed failure rates (Hu and Hubble, 2007; Gould et al, 2011).

The asset management paradigm applied within a utility can strongly influence the observed failure rate by determining the quality, and therefore

Figure 3
Failure rate by pipe diameter



reliability, of records. The paradigm will also determine the rehabilitation (replacement or renewal) schedule for pipes.

Asset data quality will dictate the assets to be included in the calculation of failure rates and the accuracy of the characteristics of that asset. For example, if a new asset has the same identifier as the asset it replaced it may be incorrectly allocated failures. Assets with the wrong diameter may increase or decrease the failure rate calculated for that cohort, depending on the number of observed failures on that asset.

Failure data quality will dictate the number of failures included in the calculation of failure rates, how these failures are allocated to assets and the reliability of the calculations. Without the direct linking of failures to assets it is possible that when asset links are made, they will be done incorrectly. Additionally, short observation periods (length of failure records) will influence the reliability of failure rates by increasing the associated error.

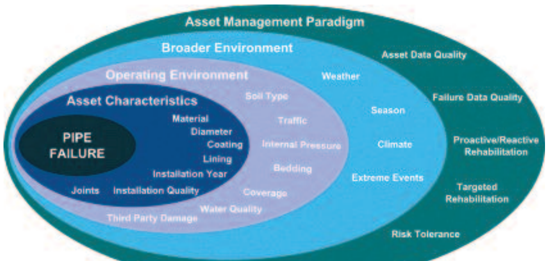
Proactive / reactive rehabilitation will dictate when an asset is rehabilitated. The more proactive a utility's rehabilitation works, the lower the expected failure rate for specific cohorts due to interventions to prevent the occurrence of failure.

Framework demonstration on cohort PE ≤ 300 1980-1989

The breakdown of utility specific failure rates for this PE cohort and the general failure rate across all utilities are shown in Figure 5. It can be seen in Figure 5 that not all utilities had this cohort in their networks.

The observed failure rates significantly differ from the generally low failure rate across another seven

Figure 4
Summary of factors affecting pipe failure (adapted and extended from Vloerbergh and Blokker (2010) and Boulaire, et al (2010)).



utilities. The most significant departure was observed for utility two, where the observed failure rate was around 455 failures per 100km per year compared to an average failure rate of around 13 failures per 100 km per year.

Referring back to Figure 4, failure rates in PE materials can theoretically be influenced by:

- Asset characteristics – poor material and installation quality
- Operating environment – internal pressure excursions (for example pressure surge and fatigue); third party damage; and coverage
- Broader environment – no factors at this level
- Asset management paradigm – asset data quality; and failure data quality

With regard to asset characteristics, material quality problems are no longer widely observed in existing Australian PE networks. While premature failures were observed in early generations of PE material (Davis et al, 2007), it is expected that the assets affected by these types of failures would have been replaced before the observation period. Again, while issues such as point loads and installation damage have occurred in the past it is generally perceived that installation standards for PE pipe are well adhered to.

Likewise for the operating environment, the availability of design guidelines accounting for dynamic pressures means that surge and fatigue are also unlikely explanatory factors. While third party damage cannot be prevented, the extreme departure from the average failure rates is not corroborated through actual records of third party damage in that particular utility. If the failures were related to surface type (coverage), structures or flora (trees) above the pipe, it would be reasonable to assume that actions to mitigate or eliminate the source of repeated failures would have been undertaken. Therefore, these factors are also unlikely to be the cause of the extreme departure observed.

At the broader environment level, climate-related events such as seasonal rainfall / temperature and more extreme events such as drought can lead to diametrical and axial bending of PE pipes. However, their relatively

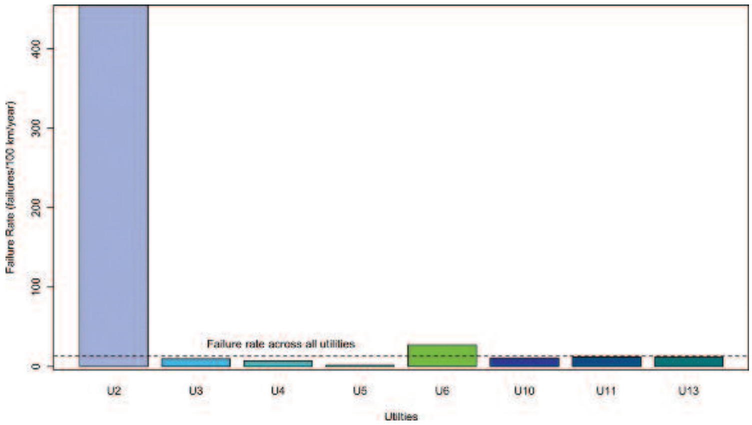


Figure 5
Breakdown of utility specific failure rates for cohort PE ≤ 300 1980 to 1989

high strength / stiffness ratio accommodates these events.

With other factor levels unlikely to be the cause of the variation seen, it is proposed that problems with asset data and failure data quality are the most likely explanations for the observed departure. Whilst the high failure rates are attributed to PE assets, the actual failure events are more likely to be occurring in another more vulnerable material. A second possible explanation is that the failures relate to an asset that has been replaced but has been erroneously associated with in-service assets. For example an existing pipe may have been pipe burst or slip lined, and the new asset allocated the same Pipe ID as the old asset, which means the new asset would be associated with the failures of the old asset.

Conclusion

Data from 13 utilities was collected and analysed to investigate failure rate trends across Australia. This dataset is believed to be the most extensive of this type created and covers major urban and rural areas providing water to over 14 million people, or around 64% of the Australian population.

A descriptive analysis of the data showed trends in failure rate relating to pipe material and pipe diameter that are supported by other datasets. The order of materials with an observed increasing failure rate, as presented in this article, varied from that found in the literature, which was not unexpected as the derived order shown was developed based on disparate data. The observed trend of decreasing failure rate with increasing diameter, from 100mm upwards, is in agreement with the literature, as is the increase in failure rate below 100mm diameter.

A cohort analysis investigated the failure rate of asset cohorts, defined on the basis of material, diameter and installation decade, both at utility-specific levels and across all utilities. The cohort analysis classifies each cohort as good, average, poor or very poor on the basis of a quantile analysis. This analysis identifies the classification of the combined utility data and the spread of classifications for each cohort at a utility level.

Following the cohort classification presented above, a framework was developed that can be used to investigate observed variations in the classifications between cohorts and between the same cohorts in different networks. This framework identifies four levels of possible causes of variations in cohort failure rate: asset characteristics, operating environment, broader environment and asset management paradigm. This framework aids understanding of the performance of cohorts within water networks. ●

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