Asset planning for water reticulation systems – the PARMS model

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Abstract Traditionally water reticulation systems have been operated so that pipeline repair/renewal occurs on a reactive basis, based upon the number of failures, the consequence of failure and the cost. Planning for future replacements and the costs associated with these has been based upon a best guess of pipe lifetimes, which have generally been very conservative, when compared to the actual pipe life obtained. Factors such as the required level of customer service, trade-offs between repair and renewal, or operating practices such as pressure reduction or shut-off block reduction have not been widely considered, except when they are required under the water authorities operating licence. To allow long-term strategies to be implemented for the repair/renewal of water pipelines, a Pipeline Asset and Risk Management System (PARMS) is being developed. This planning model has been designed to allow a range of “what if” scenarios to be analysed to determine their effects on water authorities’ long-term costs. This model is based upon whole of life costing and includes data on externality and customer impact costs. It analyses the failures of individual pipe assets, rather than the traditional practice of predicting failure of pipe cohorts, currently used by many authorities. This paper discusses the application of the PARMS planning model to allow selection of pipeline repair/renewal, and briefly analyses the influences that a range of customer service or operating decisions can have on a water authority’s capital and operational expenditure.

Keywords Planning models; pipe failure; pipe lifetimes; pipelines; whole life costing

Introduction Pipeline failures are a major factor in the maintenance and capital expenditure costs of water authorities and with increasing failure rates in older assets these costs are expected to rise. The cost of maintaining and replacing existing water infrastructure was in excess of A$250M, Australia-wide in 1998/99 (WSAA, 2000) and worldwide the total cost is estimated to be over 100 times this. Decisions on repair/renewal expenditure, replacement strategies and operating methodologies are critical if the overall cost implications to the world economy are to be minimised. Consequently planning models are needed that allow the cost of different customer preferences and operational practices to be assessed.

To allow long-term costs to be assessed for the repair/renewal of water pipelines under different strategies, planning models have been developed in Australia and elsewhere. Several planning models are currently available, e.g. KANEW, NESSE and UtilNets (Deb et al., 1998; Cromwell et al., 2001; Hadzilacos et al., 2000). Some of these models require analysis of the failure data for all pipe assets, to enable the development of lifetime distributions and survival functions and they generally rely on modelling the behaviour of large pipe cohorts. Although the development of survival functions for each asset and its subclasses is ideal, for many newer assets such as plastic pipes and ductile iron, the lack of failure data is such that valid failure and survival curves cannot be developed. In these cases statistical models need to be complemented by physical models of pipe failure. Additionally, the models do not allow (i) analysis of the risk (probability of failure vs.
consequence) associated with the operation of individual assets under different operating and installation conditions, because they rely on the analysis of pipe cohorts (Herz, 1996, 1998 and Deb et al., 1998), (ii) assessment of the cost implications under different repair/renewal strategies or (iii) assessment of the effects of customer preferences. For this reason, a Pipeline Asset and Risk Management System (PARMS) is being developed to allow analysis of the long term cost implications of a range of scenarios, such as different customer service requirements, different operational strategies or repair/renewal strategies.

Asset planning and prioritisation requires both cost and pipe lifetime data and input from operational practices, such as pressure reduction and valve insertion (shutdown block reduction) that can affect pipe lifetimes and operational costs. Although cost data include traditional cost items such as capital and operating costs, they should also include customer impact, externalities (such as traffic disruption) and environmental costs.

**Customer preferences**

One of the critical factors that defines the end of a pipeline’s useful life is the customer’s requirement. If customers are unwilling to accept any failures in their water supply then the useful life of the pipeline is much shorter than that for a pipeline whose customers are willing to accept failures and the subsequent repair of these failures. However, the additional cost of providing this higher level of service needs to be compared to a customer’s willingness to pay. At the moment customer service levels are set by legislation rather than on a willingness to pay basis. These customer requirements are defined in customer charters in most Australian states and, as shown in Table 1, they vary significantly across Australia, depending on whether planned or unplanned interruptions are being assessed. Planned interruption generally have at least 2 days written notice and work is carried out between 9.00 a.m. and 5.00 p.m.

In the regime of customer service legislation and the potential variation in costs of providing different levels of service, it is important to know the costs of providing this service when assessing different methods of renewal/replacement or different methods of operation of water reticulation systems. Because of the expected increase in failure rates in the future, customer’s expectations and their willingness to pay for a higher level of service will become a critical factor as the costs associated with maintaining our water infrastructure increase rapidly over the coming decades.

The Water Corporation of Western Australia (Market Equity Pty Ltd, 1997) conducted a study to examine community attitudes towards water supply reliability. In the study, most respondents regarded issues related to water supply continuity as the second highest priority of the Corporation in managing the State’s water resources, with quality of water supply

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**Table 1** Water Authority Policy for unplanned interruptions

<table>
<thead>
<tr>
<th>Water Authority</th>
<th>Unplanned interruptions</th>
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<tbody>
<tr>
<td>SouthEast Water</td>
<td>– No more than 5 per year&lt;br&gt; – 95% of unplanned interruptions will be restored within five hours&lt;br&gt; – Bursts fixed within 4 hours if serious, 24 hours in other cases</td>
</tr>
<tr>
<td>Hobart Water</td>
<td>– Local media will be notified of unplanned interruptions, 24 hour on call service</td>
</tr>
<tr>
<td>Sydney Water</td>
<td>– 95% of property interruptions will be restored within 6 hours&lt;br&gt; – 98% of customers will not experience pressure below 15 meters head</td>
</tr>
<tr>
<td>Water Corporation</td>
<td>– If disruption is seen to be longer than 6 hours, drinking water will be made available&lt;br&gt; – Respond to urgent water faults within 2 hours</td>
</tr>
<tr>
<td>SA Water</td>
<td>– Fixed as quickly as possible, some cases the media will be notified&lt;br&gt; – Serious bursts will be attended to within 1 hour and fixed within 5 hours&lt;br&gt; – All other interruptions will be repaired within 24 hours</td>
</tr>
</tbody>
</table>
seen as the most important priority. A more recent and detailed research into customers’ views on water continuity (Sydney Water, 2000) was conducted to provide information on its system performance standards and the major issues raised were similar to the Western Australian study. Generally the following views were reported.

- Respondents were fairly accepting that water shut-offs are inevitable, but more so for shut-offs due to maintenance work than shut-offs due to a system breakdown.
- Most respondents were very or quite satisfied with the way the water shut-off was handled.
- Most respondents were not willing to accept interruptions to supply of longer than 5 hours. The most frequently mentioned time was three to four hours that customers preferred to have their water shut off.
- The two most convenient times nominated by customers to have their water supply shut-off for maintenance were between 10.00 p.m. and 6.00 a.m. and between 9.00 a.m. and 4.00 p.m.
- Respondents felt less inconvenienced if they were given advance notice.
- Most respondents did not want to be compensated. They preferred water authorities to fix the problems.

Overseas, the values consumers place on water supply reliability is reasonably well researched. For example in the United States, Griffin and Mjelde (2001) used Contingent Valuation Methods (CVM) to examine the values people placed on the current and possible future water restrictions in terms of their strength and duration. Out of 2,032 respondents, only 21% indicated that they would be willing to pay a one-time fee to avoid a current interruption. Of those willing to pay, a low income household would be willing to pay a one-time fee of $17.19 to avoid a current water interruption whereas a high income household would be willing to pay $44.04. Respondents who had experienced water interruptions in the past five years were on average willing to pay less for increased reliability than those who had not experienced a restriction.

Recent work in Australia has indicated that the main customers that are impacted are those in strip shopping centres such as restaurants and that interruptions to these businesses can have a significant economic impact. Consequently provision for compensation for loss of service is being built into the PARMS model as well as cost calculations associated with the provision of different levels of service.

**Whole-of-life costing and life-cycle analysis**

Cost details are one of the critical components needed to allow planning models to work effectively and allow comparison of the costs of customer preferences. Traditionally the water industry has only concerned itself with capital costs when undertaking long-term strategic planning, with maintenance and operating costs playing a peripheral role. Residual asset costs were generally ignored, as were costs such as customer disruption and externalities such as traffic disruption. Life-cycle costing (LCC) methodologies are starting to be considered in the water industry, but in many instances the consideration is still peripheral (Lamb, 1995; Hadzilacos et al., 2000). LCC is a technique that enables a comparative cost assessment to be made for various alternatives, over a specified period of time, taking into account all relevant economic factors, both in terms of initial capital costs and future (estimated) costs. It is critical that in addition to the direct costs associated with renewal, the estimation of cost should include expenditures for maintenance, retrofit and eventual replacement (Chang et al., 1997). This is particularly important for infrastructure expected to be functional for a long period of time, such as water reticulation pipes. The design and optimal management of water reticulation systems should aim to minimise the Life Cycle Costs (Lamb, 1995). King (1995), for example, discusses a decision analysis model, which
estimates the minimum life cycle cost for a given set of options and associated uncertainties (risks) for a water resources strategy. The model allows the analysis of many permutations of alternative options, calculates the expected cost of each, and determines the cheapest option. Muir and Glasgow (1993) discuss issues relating to implementing asset management systems for water and sewerage assets. The aim is to optimise the operation and maintenance activities of the water utilities to maximise the life of existing assets at a level of service acceptable to their customers. They present a systematic approach aimed at minimising the problems associated with the implementation of such a system.

What is assumed but never explicitly stated is that the costs are those costs for which the decision-maker utilising LCC is responsible, i.e. any external costs borne by others are omitted. In the case of water authorities operating as businesses, the costs are only those for which they have to pay directly. Externalities are usually identified but not costed in LCC modelling. Whole-of-life costing (WLC) is a newer concept, which has several different definitions. For the development of our models we consider WLC to cover all of those costs included in LCC, plus those costs associated with customer disruption as well as externalities such as the cost of traffic disruption. WLC should include environmental costs, but because of the difficulties of putting a cost structure on these values, a points-based system called life cycle analysis (LCA) has been developed to allow the environmental costs to be assessed (Bartlett and Edwards, 2001). Eventually as the systems become more sophisticated it is expected that LCA will merge with WLC.

The application of WLC methodologies requires the development of cost functions for establishment, operation and maintenance of the infrastructure, where the cost functions are defined as mathematical functions of one or more variables relating to the physical size, nature, throughput, capacity or type of infrastructure item. The cost functions so far developed are as simple and generic as practically possible for the various items of the water reticulation system. For example, it would be very desirable to have one function for all pipes. However, in practice, there is a common form of formula but with different coefficients, depending on pipe type as detailed in Eq. (1).

\[
\text{Total renewal cost} = A \times \text{design cost} + B \times \text{trench cost} + C \times \text{laying costs} + D \times \text{reinstatement cost}
\]

where trench cost consists of excavation costs, backfill costs, shoring costs and dewatering costs (as required); laying costs consists of pipe cost, fitting cost, laying/jointing costs, bedding costs and reconnection of services, reinstatement consists of landscaping to original condition (grass verge), repair to footpaths (bitumen, concrete) and repair to roadways (bitumen, concrete). Significant effort has been put into developing the cost functions for customer impacts and externalities such as traffic disruption. However; although they have been determined for costs of various pipe type and installations, these cost functions have only been incorporated into the PARMS model at the aggregate level, and not further discussed here.

**Asset failure models**

The lifetime of a facility and its components is a critical factor in using planning models. For a detailed WLC or LCC analysis, the lifetimes of all the components need to be known so that expected future replacement costs can be estimated at the optimised replacement time. In the PARMS model, statistical models are used to predict future failures for individual assets across the whole range of installation and operating conditions. These need to be tailored for each water authority implementing the model. Predictions of number of failures is critical in any rational analysis because the expected long lifetimes of the assets can...
easily make a maintenance-only operational procedure the most attractive option, especially if high discount rates are used and externalities costs such as customer disruption are not included.

For many water authorities, asset failure prediction relies on failure rates among cohorts of pipes of a given age and material. Future failure rates are extrapolated from these. Although these techniques have been used successfully for cast iron and asbestos cement pipelines, problems can be encountered in practice, for the following grounds.

- Such cohort data is usually represented in terms of failures 100 per km per year. Consequently, only average failure rates can be extrapolated, the geographical spread of future failures cannot be determined and multiple failures cannot be predicted.
- In most cases, different failure modes are not distinguished. Consequently, external factors governing failures are not anticipated, e.g. inherent vs induced failures.
- New pipe materials with relatively short service histories provide only a limited amount of existing failure data for extrapolation.

Some methods proposed consider the estimation of survival time between successive failures versus age; for example, Mavin (1996). In most data sets encountered by the authors, detailed and reliable records of failures are only available in relatively recent times and there is no way of knowing how many failures a particular pipe has experienced.

A preferred approach, used in the PARMS model, is to obtain separate failure rates for each individual pipe in the network. This is done by modelling the number of failures in a pipe each year by a smooth curve over age, typically using a different power function for each material class, modified by factors which account for diameter, pressure, soil type and traffic conditions (Constantine et al., 1998; Jarrett et al., 2001). A more recent development includes a Bayesian prediction for each pipe, which combines the expected number of failures obtained by the above modelling with the known failure history of that pipe (Jarrett et al., 2002). This allows additional forward modification of the expected number of failures in each individual pipe in future years. If a strategy proposes the replacement of a particular pipe with a new material, the relevant failure curve allows similar prediction of the number of failures for the replacement pipe. By this means, alternative replacement strategies can be compared, both in terms of expected numbers of failures and the costs associated with them.

It is important in these models to distinguish different types of failure, since these often imply different costs (e.g. for repair), and to provide adequate models for those materials with a relatively short failure history, such as PVC or ductile iron. Physical models have proved very useful in complementing the lack of data in the latter case and the models existing for pipeline materials such as PVC and asbestos cement have been reported elsewhere (Davis and Burn, 2001; DeSilva et al., 2002).

The analysis of the data from several water authorities has highlighted the need for standardised data collection procedures to allow predictive failure models to be developed for all pipe types and especially for newer pipeline materials such as plastics. To cover pipeline systems adequately, this data is used by a combination of both statistical and physical models in the PARMS model, with the two methods providing a synergistic methodology.

The planning model – PARMS

PARMS incorporates WLC and failure predictions for individual pipes and allows assessment of the pipe and external costs associated with different scenarios for pipeline repair/renewal. This model is very flexible and in this analysis has been used to predict the capital and operating costs yearly for the next 30 years for a number of operational scenarios. Several factors were incorporated into this planning model to allow various scenarios to be explored, in relation to the way water authorities manage and cost their strategies for
customer service, pipeline operation and repair/renewal. These factors are flexible and allow different cost and lifetime structures to be built by the model.

Several scenarios were analysed using PARMS to demonstrate how WLC analysis could be used to optimise the timing of pipeline renewal. Scenarios were analysed for a hypothetical water distribution system with 6260 km of pipeline, as detailed in Table 2.

One significant and clearly understood option practiced by water authorities is to replace pipes once a specific number of failures (in this definition a failure is an unplanned interruption) occur in any year. The PARMS model is particularly suited for such investigations and the annual costs of using various replacement trigger levels from 1 to 5 calculated with this model are shown in Figure 1. It should be noted that the failures indicated here are for unplanned interruptions and do not include hydrant or third party failures (these failures can be included in the PARMS model). The initial annual costs are extremely high when the trigger level is a single failure, but the ongoing consequences should be that the pipe network would fail less often because of the renewed pipes. However, if we analyse future costs out to 2030, we see that this only occurs for a short period and that by 2030 the annual costs for replacing after a single failure is still the highest due to new groups of pipes starting to fail after a minimum had been achieved. If we compare the NPV cost of replacement we can see that replacement after one failure is $260m more expensive than the next cheapest option, as shown in Figure 2. Figure 2 also shows the effect that replacement at different failure options has on the NPV expenditure over the next 30 years. It can be seen that using a discount rate of 6% for most assets, renewing pipe after three failures (not including failures associated with hydrant and third party damage) is the cheapest option for operating a water reticulation scheme. However, Figure 2 does not show the costs of externalities and customer impacts, which are still being fully quantified.

Table 2 Pipe lengths (m) of each pipe type and size in analysed reticulation system

<table>
<thead>
<tr>
<th>Pipe type/pipe size</th>
<th>100–149</th>
<th>150–224</th>
<th>225–300</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asbestos cement</td>
<td>997,917</td>
<td>354,105</td>
<td>223,762</td>
<td>1,575,783</td>
</tr>
<tr>
<td>Cast iron, cement lined</td>
<td>1,054,725</td>
<td>523,632</td>
<td>100,045</td>
<td>1,678,402</td>
</tr>
<tr>
<td>Cast iron (grey cast iron)</td>
<td>466,495</td>
<td>70,259</td>
<td>32,998</td>
<td>569,751</td>
</tr>
<tr>
<td>Ductile iron, cement lined</td>
<td>322,072</td>
<td>290,821</td>
<td>103,667</td>
<td>716,560</td>
</tr>
<tr>
<td>Galvanized wrought iron, cement lined</td>
<td>42,472</td>
<td>111</td>
<td>0</td>
<td>42,583</td>
</tr>
<tr>
<td>Mild steel, cement lined</td>
<td>5,128</td>
<td>11,293</td>
<td>60,811</td>
<td>77,232</td>
</tr>
<tr>
<td>Medium density polyethylene</td>
<td>41</td>
<td>291</td>
<td>167</td>
<td>499</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>4,140</td>
<td>4,039</td>
<td>603</td>
<td>8,781</td>
</tr>
<tr>
<td>UPVC – Class 20</td>
<td>879,672</td>
<td>428,133</td>
<td>70,157</td>
<td>1,377,962</td>
</tr>
<tr>
<td>UPVC – Class 12</td>
<td>137,431</td>
<td>59,106</td>
<td>10,998</td>
<td>207,534</td>
</tr>
<tr>
<td>Total</td>
<td>3,912,437</td>
<td>1,744,573</td>
<td>603,642</td>
<td>6,260,652</td>
</tr>
</tbody>
</table>

Figure 1 Effect of replacement at different failure levels on future non-discounted costs
Conclusion

A long term planning model, the Pipeline Asset and Risk Management System (PARMS), has been developed to allow the modelling of a range of different operational and strategic scenarios used by water authorities, to take into account the cost of a range of customer preferences. Whole-of-life cost assessments and pipe failure models have been developed for implementation in PARMS to allow optimisation of strategies for renewal of pipelines. PARMS models the failure of individual assets and thus allows a great deal of flexibility in the range of “what if” scenarios that can be modelled. It incorporates strategies such as pressure reduction, shut-off block reduction, repair-only strategies and variable replacement strategies to allow various proportions of individual assets to be replaced or adjoining assets to be replaced. Replacement after different levels of failure is also modelled and importantly often-neglected costs such as customer compensation, customer disruption and externalities such as traffic disruption are considered.

References


