
IPART optimisation model – Water Continuity Standard for Sydney Water

Mike Smart

5 December 2018

We designed this spreadsheet optimisation model to find a least-cost asset management strategy for Sydney Water’s potable water network. Relevant costs are network costs incurred by Sydney Water and inconvenience costs suffered by Sydney Water customers when interruptions to their water service occur. We valued these inconvenience costs using the Phase 2 customer engagement work undertaken by Sydney Water and CIE, as reported in October 2018.

The network

Sydney Water provided a list of pipe diameters used in its water network and indicated the number of metres of pipe in each diameter class. While Sydney Water was unable to provide information about the number of properties potentially affected by a break in each type of pipe, we made an inference on the following basis. Assuming approximately equivalent pressure in all pipe types,¹ the amount of water that each pipe can deliver is proportional to its cross-sectional area, which is proportional to the square of the diameter. Thus, the number of properties likely to be affected by a break in each type of pipe is proportional to that pipe’s cross-sectional area. The number of properties is also proportional to the square of the diameter. We were able to estimate the constant coefficient of proportionality by normalising the modelled number of properties affected by a long unplanned interruption in the status quo to the actual 2018 result.

We understand that parts of the water network are designed in a “meshed” way that provides alternative supply paths in the event that one pipe becomes unavailable. We took account of this feature by drawing a distinction between breaks or leaks in water pipes and those breaks or leaks that lead to a supply interruption. For the part of the water network designated as the “reticulation water main” system, where there are generally no alternative supply paths available, the majority of breaks or leaks lead to an interruption. However, for the part of the water network designated as the “critical water main” system, where alternative supply paths are often available, a smaller fraction of breaks or leaks lead to an interruption.

Network management strategies available

Sydney Water adopts one of two network management strategies for each part of its water network:

- ▼ Avoid fail, or

¹ We asked Sydney Water for information about pressure classes for their water pipes, but for the great majority of the water network, they were unable to provide it.

▼ Run to fail.

It applies the Avoid fail strategy to the critical water main system and the Run to fail strategy to the reticulation water main system.

Under Avoid fail, critical water mains are subjected to condition monitoring (on a sampling basis, guided by asset age, performance history and sophisticated predictive modelling). As a result of these measures, Avoid fail water mains experience a significantly lower rate of breaks or leaks per kilometre of pipe per year.

In contrast, under Run to fail, reticulation water mains are not subjected to condition monitoring, and asset renewals are deferred until three failures have occurred. This policy leads to lower renewal costs per kilometre of pipe renewed, but a significantly higher rate of breaks or leaks per kilometre of pipe per year.

When a break or leak is reported, Sydney Water dispatches a work crew to assess it, rectify it and restore water service to affected properties as soon as practicable. We assume that the time taken to restore service follows a lognormal distribution. This assumption is consistent with data provided by Sydney Water on the mean, median and standard deviations of service interruptions.

Customer valuations of service continuity

Sydney Water provided interim results for its Phase 2 customer engagement program in mid-October 2018. This work produced valuations on both a Willingness to Pay (WTP) and Willingness to Accept (WTA) basis for defined improvement and worsening of current levels of water service interruption. Participants were asked how much they would be willing to pay to achieve an improvement in service levels or how much compensation they would be willing to accept to suffer a worsening in service levels. They were asked to nominate separate valuations for an unplanned water service outage lasting between 1 and 3 hours, and for an unplanned interruption lasting between 6 and 8 hours. We have used the results of that survey work in our model.

All interruptions do not have the same duration

Sydney Water provided us with information on the statistical distribution of interruption durations that affect the critical water main system and on the distribution of interruption durations on the reticulation water main system. They provided the mean duration, the median duration, and the standard deviation of durations for each of critical and reticulation systems. From this information, we were able to estimate the parameters for a lognormal distribution of interruption durations for each system, and confirm that the lognormal distribution was reasonably representative.²

² Unlike a normal distribution, the interruption durations are always positive numbers, the mean is greater than the median, and the distribution is skewed toward high duration values. The lognormal distribution type is one of several possible mathematical distributions that has these properties. Compared to some other commonly used distribution types, such as Weibull, the lognormal distribution allows simple calculation of the relevant parameters and characteristics.

Under the assumption that these distributions are approximately lognormal, it is possible to estimate the parameters for each distribution knowing only the mean, median and standard deviation, and then to use these parameters to estimate the fraction of interruptions that will last for five hours or more.

What we optimise and how we will use the results

Assuming current levels of efficiency of operation, we have assumed that there are two strategic choices Sydney Water can make that affect the network costs and the frequency and duration of service interruptions:

- ▼ Which parts of the network to subject to the Avoid fail management regime, and
- ▼ How many work crews to make available.

Currently, Sydney Water classifies water mains with diameter of 300mm or above as critical, and these are subject to the Avoid fail management regime, while water mains of lower diameter are classified as reticulation, and are subject to the Run to fail management regime.³


In searching for a least-cost strategy, we consider drawing the classification boundary between Avoid fail and Run to fail parts of the network at diameters other than (both smaller and larger) 300mm. The trade-off in such alternative strategies is between a higher network cost per kilometre when more of the network is subject to Avoid fail (because of the need to do condition assessment and more costly renewals) versus lower failure rates, and less chance that a break or leak will lead to an interruption. We note that average durations of interruptions also tend to be higher under Avoid fail than Run to fail.

In searching for a least-cost strategy, we also consider different numbers of work crew staff than under the status quo. When the staffing levels are higher, there is increased cost, but the duration of interruptions is shortened. To calculate this effect of staff numbers on interruption duration, we assume that the amount of work in person-hours is constant, so an increase in the number of persons will reduce the average number of hours to complete the tasks.

Our spreadsheet model examines various combinations of crew staffing levels and cutoff pipe diameters for the Avoid fail strategy. For each combination, we calculate the total annual social cost across the whole network. We find the combination that leads to the least social cost. For that combination, we calculate the expected number of properties that will be subjected to a service interruption lasting five hours or more. Subject to further realism checks, that number of properties would inform a target that could be used in the system performance standards.

Recognising that a target should not be exceeded (worse than ideal performance for customers) or under-shot (implying more expensive than ideal network management), there would need to be a margin for error before actual performance could be considered a licence breach. Also, we recognise that uncontrollable factors including rainfall, soil moisture,

³ This is a slight oversimplification. There are some water mains classified as critical even though they have smaller diameter than 300mm, because the consequences of a break or leak in those locations would be serious. There were approximately 600 km out of a total 22,000 km of water mains classified as critical with diameter less than 300mm.



temperature, etc will influence the rate of breaks and leaks in any particular year. This consideration should also work to increase the size of the margin for error.

Organisation of the spreadsheet model

Most user-selectable inputs are able to be modified using the blue-shaded cells in the left-hand side of tab “input”. The right-hand side of that tab summarises the results in a manner that compares the status quo with the scenario found to have the least social cost.

The tab “social_cost” calculates the social cost in \$/yr for each type of pipe under each strategy set (combination of smallest avoid fail pipe diameter and staffing # for work crews). Social cost is summed across all pipe types in row 7, where crew costs (common to all pipe types) are added as well.

Tab “pNlong”, row 7, sets out the expected number of properties each year that will suffer a long interruption to water supply (ie, longer than 5 hours) under each strategy set. Tab “pNall”, row 7, sets out the expected number of properties each year that will suffer an interruption of any duration (ie, long or short) under each strategy set.

Tab “CV” calculates the inconvenience value to customers of service interruptions, expressed as \$/year/property affected/km of pipe, for each pipe type under each strategy set. The same formula is used in each of the cells D9:AT74. While this formula is somewhat complex, it needs to be to capture the structure of the customer valuation information produced by the customer engagement work Sydney Water and CIE did.

Tab “AF” contains only 0 or 1 in each active cell. It is 0 if a given pipe diameter is treated as Run to fail under the strategy set for the relevant column, and 1 if that pipe diameter is treated as Avoid fail. Tab “RTF” is also a binary table, which is the mirror image of AF. Cells in RTF are 1 if the pipe diameter is treated as Run to fail in the strategy set and 0 if it is Avoid fail.

Tab “Lognormal” repeats the information provided by Sydney Water on the duration of interruptions (first 8 rows), and then calculates parameters of the corresponding Lognormal distributions in rows 10 – 25.

The remaining tabs summarise information derived from other sources (Sydney Water answers to our questions, costings from AtkinsCardno’s December 2015 expenditure review of Sydney Water’s 2016 price proposal, and system performance standard compliance information provided by Sydney Water at various points in time.) This information is used to estimate some of the input data on tab “input”.

We did not use AtkinsCardno’s estimate of replacement cost rates for critical water mains. Instead, we used their estimate of replacement cost rates for reticulation water mains for all pipe types.

Formulae used in the model

The model examines 66 different types of water pipes (y), each with different diameter. It considers a range of different possible strategy sets (x), each with a unique combination of work crew staffing level and cutoff pipe diameter for the Avoid fail maintenance strategy.

For each combination of strategy set and pipe type (x,y), we calculate the annual social cost using the following formulae:

- ▼ For a pipe type managed to Avoid fail:

$$\text{Social cost } (x,y) = \text{length}(y) * [\#properties_affected(y) * customer_valuation(x,y)/1m \\ + kmreplaf * RCaf + kminsp * IC + VIpkm * ICV/1m]$$

- ▼ For a pipe type managed to Run to fail:

$$\text{Social cost } (x,y) = \text{length}(y) * [\#properties_affected(y) * customer_valuation(x,y)/1m \\ + kmreplrtf * RCrtf]$$

- *Social cost* is in units (\$m/yr)
- *length* is in units (km)
- *#properties_affected(y)* is the number of properties that would suffer an interruption if a pipe of type y broke
- *kmreplaf* is the fraction of km of pipe replaced each year for Avoid fail pipes
- *kmreplrtf* is the fraction of km replaced each year for Run to fail pipes
- *RCaf* is the replacement cost (\$m/km replaced) for Avoid fail pipes
- *RCrtf* is the replacement cost (\$m/km replaced) for Run to fail pipes
- *kminsp* is the fraction of km of pipe inspected each year for Avoid fail pipes
- *IC* is the inspection cost (\$m/km inspected) for Avoid fail pipes
- *VIpkm* is the number of valves inspected each year per km of pipe for Avoid fail
- *ICV* is the inspection cost per valve for Avoid fail pipes

Total social cost for a strategy set, x , is:

$$\text{Total social cost}(x) = \frac{\#crew\ staff * crewcost}{1m} + \sum_{y=1}^{y=66} \text{Social cost}(x, y)$$

- *Total social cost* is in units (\$m/yr)
- *crewcost* is the annual cost per crew member (wages plus equipment) (\$/yr)

The customer valuation of inconvenience associated with supply interruptions is based on the following formulae:

- ▼ When a Willingness to Pay (WTP) customer valuation method is used:

$$\text{customer valuation}(x,y) = (1/UIpct) * [(pr(short,x,y) - pr(short,0,y)) * shortWTP \\ + (pr(long,x,y) - pr(long,0,y)) * longWTP]$$

- ▼ When a Willingness to Accept (WTA) customer valuation method is used:

$$\text{customer valuation}(x,y) = (1/UIpct) * [(pr(short,x,y) - pr(short,0,y)) * shortWTA \\ + (pr(long,x,y) - pr(long,0,y)) * longWTA]$$

- *customer valuation* is the value a single customer places on the expected number of short and long interruptions in a year relative to the status quo, expressed in units (\$/affected property/km of pipe/yr)
- *UIpct* is the baseline change in probability to which the WTP and WTA values refer. *UIpct* is 1%, so $1/UIpct = 100$.
- $pr(short,x,y)$ is the probability that a short interruption (less than or equal to 5 hrs duration) will occur, for pipe type y, given the classification of that pipe type as either Avoid fail or Run to fail under strategy set x
- $pr(short,0,y)$ is the probability that a short interruption will occur, for pipe type y, given the classification of that pipe type under the status quo strategy set x=0
- $pr(long,x,y)$ is the probability that a long interruption (greater than 5 hrs duration) will occur, for pipe type y, given the classification of that pipe type as either Avoid fail or Run to fail under strategy set x
- $pr(long,0,y)$ is the probability that a long interruption will occur, for pipe type y, given the classification of that pipe type under the status quo strategy set x=0
- *shortWTP* is the willingness to pay to avoid a short interruption. The units are (\$/household to reduce the probability of a short interruption relative to the status quo by *UIpct*)
- *longWTP* is the willingness to pay to avoid a long interruption. The units are (\$/household to reduce the probability of a long interruption relative to the status quo by *UIpct*)
- *shortWTA* is the amount of compensation a customer would be willing to accept to endure a short interruption. The units are (\$/household to increase the probability of a short interruption relative to the status quo by *UIpct*)
- *longWTA* is the amount of compensation a customer would be willing to accept to endure a long interruption. The units are (\$/household to increase the probability of a long interruption relative to the status quo by *UIpct*)

Note that the strategy set x influences the probabilities of short and long interruptions in two ways. It determines the number of work crew staff, which influences the time to repair breaks or leaks, and whether a pipe of type y is managed to Avoid fail or to Run to fail.

The formulae for the probabilities are:

$$pr(short,x,y) = blpkm * IFaf * AF(x,y) * p(short,x,AF) + blpkmrtf * IFrtf * RTF(x,y) * p(short,x,RTF)$$

$$pr(short,0,y) = blpkm * IFaf * AF(0,y) * p(short,0,AF) + blpkmrtf * IFrtf * RTF(0,y) * p(short,0,RTF)$$

$$pr(long,x,y) = blpkm * IFaf * AF(x,y) * (1 - p(short,x,AF)) \\ + blpkmrtf * IFrtf * RTF(x,y) * (1 - p(short,x,RTF))$$

$$pr(long,0,y) = blpkm * IFaf * AF(0,y) * (1 - p(short,0,AF)) \\ + blpkmrtf * IFrtf * RTF(0,y) * (1 - p(short,0,RTF))$$

- $blpkm$ is the annual average number of breaks or leaks per km of Avoid fail pipe
- $blpkmrtf$ is the number of breaks or leaks per km of Run to fail pipe
- $IFaf$ is the fraction of Avoid fail pipe breaks or leaks that leads to an interruption⁴
- $IFrtf$ is the fraction of Run to fail pipe breaks or leaks that leads to an interruption
- $blpkm * IFaf$ is the number of interruptions per km of Avoid fail pipe
- $blpkmrtf * IFrtf$ is the number of interruptions per km of Run to fail pipe
- $AF(x,y)$ is a binary variable that takes the value 1 if pipe type y is classified as Avoid fail in strategy set x , and 0 otherwise
- $RTF(x,y)$ is a binary variable that takes the value 1 if pipe type y is classified as Run to fail in strategy set x , and 0 otherwise
- $p(short,x,AF)$ is the probability that, given an interruption has occurred, it will be short for strategy set x if the pipe type is classified as Avoid fail (see Appendix)
- $p(short,x,RTF)$ is the probability that, given an interruption has occurred, it will be short for strategy set x if the pipe type is classified as Run to fail (see Appendix)
- $(1 - p(short,x,AF))$ is the probability that, given an interruption has occurred, it will be long for strategy set x if the pipe type is classified as Avoid fail
- $(1 - p(short,x,RTF))$ is the probability that, given an interruption has occurred, it will be long for strategy set x if the pipe type is classified as Run to fail

⁴ $IFaf$ and $IFrtf$ can and do take separate values because the likelihood that a pipe break or leak leads to an interruption is different when the pipe is managed on an Avoid fail basis than when it is Run to fail. Avoid fail pipes are less likely to suffer an interruption when the pipe leaks or breaks.

We calculate the expected number of properties suffering a long interruption each year using the following formulae:

- ▼ For a pipe type managed to Avoid fail:

$$expected_properties(x,y) = length(y) * \#properties\ affected(y) * blpkm * IFaf * (1 - p(short,x,AF))$$

- ▼ For a pipe type managed to Run to fail:

$$expected_properties(x,y) = length(y) * \#properties\ affected(y) * blpkmrtf * IFrtf * (1 - p(short,x,RTF))$$

The total number of properties suffering a long interruption each year for strategy set x is:

$$Total\ properties(x) = \sum_{y=1}^{y=66} expected\ properties(x,y)$$

The value of this expression for the least-cost strategy set, x^* , would be the target value for the water supply interruption standard.

Appendix

This appendix describes how we calculate $p(\text{short},x,AF)$ and $p(\text{short},x,RTF)$.

We assume that the duration of water supply interruptions follow a lognormal distribution. In other words, this means that the natural logarithm of the duration follows a normal distribution. We estimate separate lognormal distribution parameters for those pipes managed to an Avoid fail strategy and those managed to Run to fail.

The mean of the logarithms of the distribution, $M = \ln(\text{median duration})$.

The standard deviation of the logarithms of the distribution, S , is

$$S = \sqrt{2 (\ln(\text{avg duration}) - \ln(\text{median duration}))^2}$$

The probability that the duration is less than or equal to 300 minutes is the Cumulative Density Function of the lognormal distribution:

$$p(\text{short}) = p(\text{dur} \leq 300 \text{ mins}) = CDF(300) = \frac{1}{2} \left[1 + \text{ERF} \left(\frac{\ln(300) - M}{S\sqrt{2}} \right) \right]$$

Here, $\text{ERF}()$ is the "error function" encountered in integrating the normal distribution. This function can be evaluated using a standard Excel command.

We assume that, relative to the status quo, the duration of an interruption is inversely related to the number of work crew staff available. This would be the case if the number of person-hours to make a repair of any particular type was constant. Therefore,

$$\text{duration}(0) * \#\text{crew}(0) = \text{duration}(x) * \#\text{crew}(x)$$

Implying that

$$\text{duration}(x) = \text{duration}(0) * \#\text{crew}(0) / \#\text{crew}(x)$$

This means that

$$\text{median duration}(x) = \text{median duration}(0) * \#\text{crew}(0) / \#\text{crew}(x), \text{ and}$$

$$\text{avg duration}(x) = \text{avg duration}(0) * \#\text{crew}(0) / \#\text{crew}(x)$$

Therefore

$$M(x) = \ln(\text{median duration}(x)) = \ln(\text{median duration}(0)) + \ln(\#\text{crew}(0) / \#\text{crew}(x))$$

$$\ln(\text{avg duration}(x)) = \ln(\text{avg duration}(0)) + \ln(\#\text{crew}(0) / \#\text{crew}(x))$$

and

$$S(x) = \sqrt{2 (\ln(\text{avg duration}(x)) - \ln(\text{median duration}(x)))}$$

$$= \sqrt{2 (\ln(\text{avg duration}(0)) - \ln(\text{median duration}(0)))} = S(0)$$

Therefore,

$$p(\text{short}, x, AF) = \frac{1}{2} + \frac{1}{2} ERF \left[\frac{\ln(300 \text{ mins}) - \ln(\text{median duration}(AF(0))) - \ln\left(\frac{\#crew(0)}{\#crew(x)}\right)}{2\sqrt{\ln(\text{avg duration}(AF(0))) - \ln(\text{median duration}(AF(0)))}} \right]$$

$$p(\text{short}, x, RTF)$$

$$= \frac{1}{2}$$

$$+ \frac{1}{2} ERF \left[\frac{\ln(300 \text{ mins}) - \ln(\text{median duration}(RTF(0))) - \ln\left(\frac{\#crew(0)}{\#crew(x)}\right)}{2\sqrt{\ln(\text{avg duration}(RTF(0))) - \ln(\text{median duration}(RTF(0)))}} \right]$$