Optimal Asset Management Planning: Advances In Water Mains And Sewers Analysis Within A New Modelling Environment

Jeremy Lumbers*, Tony Conway, Tim Fynn** and George Heywood***

*Tynemarch Systems Engineering, Crossways House, 54-60 South Street, Dorking, Surrey, UK,

Jlumbers@tynemarch.co.uk

**United Utilities Group PLC, Haweswater House, Lingley Mere Business Park, Great Sankey, Warrington, WA5 3LP

Keywords Asset management planning; Water mains; Sewerage; Deterioration modelling

Abstract

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

Background

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

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

A number of key concepts form the basis of the CMPCF as follows:

- capital maintenance should normally be justified on the basis of current and forecast probability and consequence of asset failure, with and without investment
- ‘consequences’ are expressed as direct or indirect impact on service and company costs
- ‘service’ is defined as service to customers and the environment (including all relevant third parties and regulatory requirements)
- service is assessed using suitable indicators, such as interruptions to supply, effluent quality, etc
- opportunities for trade-offs between operating costs and capital costs should be evaluated

- the analysis should recognise the integrated nature of both the water and wastewater systems in order to assess the direct and indirect impacts on customers and the environment.

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

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

Key functionality

The principal components of PIONEER are:

- An Asset Data Store that collects together data from a number of sources for use in serviceability forecasts and optimisations.

- A Serviceability and Cost Forecaster that stores and allows user configuration of models for estimating future values of Serviceability Indicators and costs, with and without maintenance interventions.

- A set of user-configurable Intervention Options to be considered for assets, and the models to be used to estimate their costs and benefits.

- An Optimiser that selects the interventions required to meet a user-defined planning objective.

- A Job Scheduler that allows the user to set up and run a series of forecasts and optimisations.

- Flexible tools for results presentation and reporting.

- The maintenance of an audit trail.

The analysis is based on the principle that future Serviceability Indicators are related to the likelihood of assets to fail and the extent to which they are improved through capital maintenance. The manner in which an asset can fail and the characteristics of the failure are known in the system as a Failure Mode. Failure modes have associated serviceability consequences and costs. Consequences are measured against Serviceability Indicators, which may be environmental, such as pollution, or service, such as poor water taste and odour, or asset performance, such as pipe bursts.

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

A wide variety of model types can be created in the system including:

- Calculation Trees

- Decision Trees

- External Function

- Lookup Tables

- User Tabulated Likelihoods

- User Tabulated Distributions

Water distribution systems analysis

Introduction

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

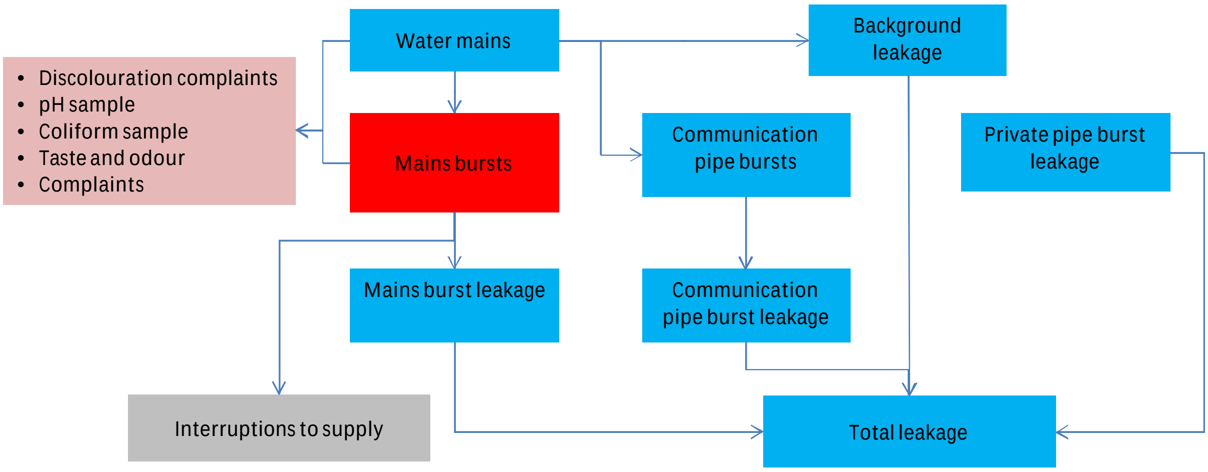

Figure 1 - Integrated approach to water distribution mains analysis

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

The data used to identify and calibrate the sub-models included:

- Mains data such as: age, material, diameter, length, hydraulic characteristics, connectivity, connection density and network configuration.

- Environmental data such as: soil corrosivity, soil fracture potential, temperature variations, water pH, socio-economic data and surface use.

The integration of leakage with other measures of service is an important development that explicitly takes into account the over-lapping benefits of interventions.

Service areas modelled

The service areas selected for consideration were as follows:

- Bursts – as defined for Ofwat June return reporting.

- Interruptions to supply in each of the DG3 duration bands.

- Leakage – including burst-related leakage and background leakage within the distribution system, from both mains and services.

The models were identified from the following data on the mains attributes, failure records, operating environment and service history:

- Burst records, dated and geo-referenced to allow environmental variables (such as weather conditions and soil types) to be taken into account.

- Leakage data, recorded in the form of Net Night Flow for each DMA, used with average customer allowances and Hour to Day Factors to calculate average Night Flow Loss values for each DMA.
- Supply interruptions records linked to address, including the duration of the interruption and the dates over which it occurred together with the recorded reason for the interruption (e.g. mains failure, maintenance, third party).
- Communication pipe (CP) repairs are recorded with dates and a geographical reference as per mains bursts.
- Repairs to leaking supply pipes, meters and stop taps recorded as per communication pipes. The annual numbers of supply pipe, stop tap and meter repairs carried out in each DMA were used in leakage modelling.

Model form

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

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

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

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

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

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

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

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

The burst models assume that the observations (bursts) follow a Poisson distribution and were calibrated using the maximum likelihood estimation (MLE) approach. This involves finding the combination of model parameters that maximises the probability of observing a set of historical records identical to that used for model calibration. For other models, a normal distribution was assumed, and least-squares methods were applied.

Where sufficient data were available (i.e. where material groups had a sufficient length of mains and total number of historical bursts), the burst model was calibrated using half of the mains in that group, randomly selected to avoid bias. The model was then applied to the remainder of the data set, and the results compared with historical burst records for these mains. Figure 2 shows a comparison between the observed and the predicted background leakage.

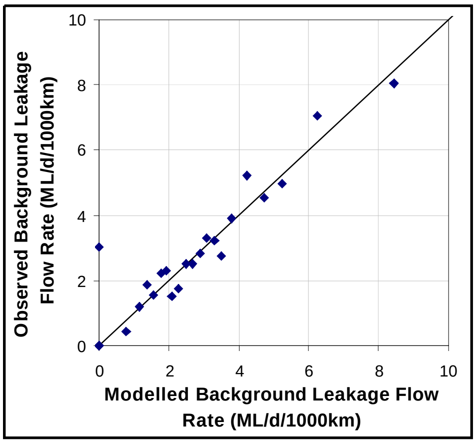

Figure 2 - Observed versus predicted background leakage

Intervention options

The intervention options considered were:

- Mains renewal
- Mains and communication pipe renewal

Interventions can also be linked to material, for example the inclusion of communication pipe renewal in the second intervention type may be defined as being dependent upon the communication pipe material.

The renewal materials applied were polyethylene for mains with a diameter up to and including 300mm, and ductile iron for larger mains.

Results

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

The results can be viewed in various forms, for example as simple time-series plots as in Figure 3 which compares the observed versus the predicted number of bursts for Cast Iron mains laid post 1935.

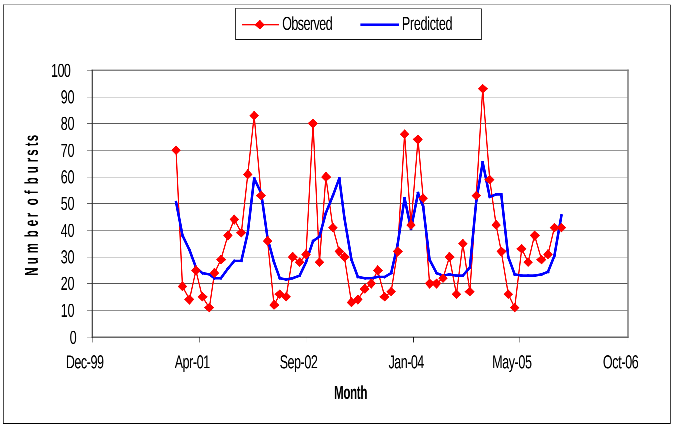

Figure 3 - Observed versus Predicted CI Mains Bursts

Forecasts of average leakage volumes per day associated with different categories of mains and pipes is shown in Figure 4. Figure 5 shows the forecast of total leakage with and without optimal interventions.

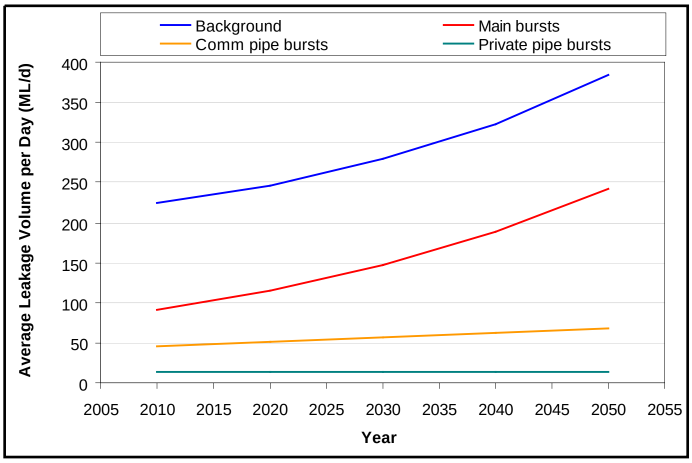

Figure 4 - Forecast interruptions with and without selected interventions

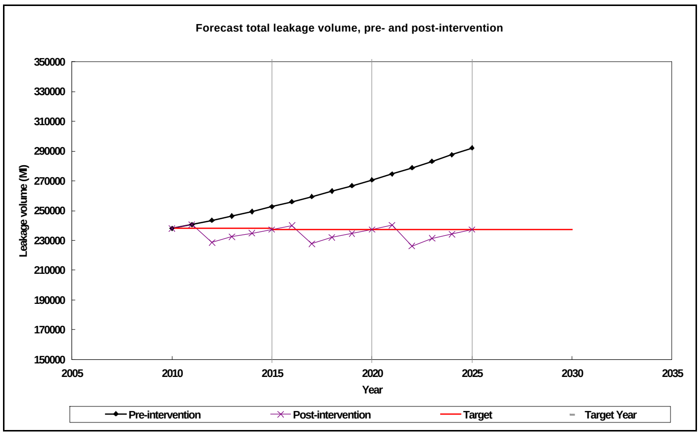

Figure 5 - Forecasts of total leakage with and without interventions

Sewerage systems analysis

Introduction

Models of sewer condition deterioration, collapse rate, blockage rate and flooding and pollution consequences have been developed. The models were identified from data and validated against a separate data set. The data used included:

- Defect data obtained from CCTV surveys
- Sewer attribute data such as estimated age, material, depth, hydraulic characteristics, connectivity, type, manhole locations
- Digital terrain data to calculate overland flow distance to assess pollution and flooding risk
- Historical maps to estimate age of sewers where unknown
- Environmental data such as soil type, depth, surface type

- Socio-economic data including housing type, income, occupancy
- Hydraulic model outputs.

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

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

The digital terrain, address point and watercourse data were used to derive several attributes of potential use in estimating the consequences of a failure. For each pipe, the upstream manhole that would flood in the event of a failure was found from consideration of static hydraulics. Manhole overflows were then simulated and a simple overland flow routing algorithm was used to trace the route of the flow. The algorithm followed the steepest downhill slope between grid points until a flat or sunken area was reached. Various attributes were then calculated:

- flow distance – the longest path of the overflow from the manhole before a flat or sunken area is reached (to a maximum of 500m from the manhole)
- minimum distance of flow to property – the minimum distance between the path of the overflow and any property
- minimum distance of pool to property – the minimum distance between any property and the flat or sunken area at the end of the path of the overflow
- minimum distance of flow to watercourse or pond – the minimum distance between the path of the overflow and a watercourse or pond
- minimum distance of pool to watercourse or pond – the minimum distance between a watercourse or pond and the flat or sunken area at the end of the path of the overflow.

These attributes were made available for inclusion in the models.

Model form

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

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

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

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

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

Intervention options

The interventions considered in the optimisation included:

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

Results

A comparison of modelling and predicted blockage for pipes for different diameters is shown in Figure 6.

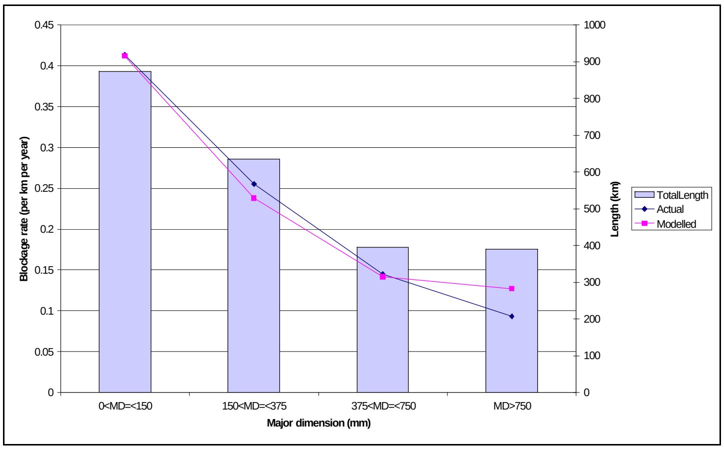

Figure 6 - Blockage rate versus major pipe dimension

The importance of proximity to watercourses regarding the potential for causing pollution incidents is shown in Figure 7 which compares the modelled versus the observed.

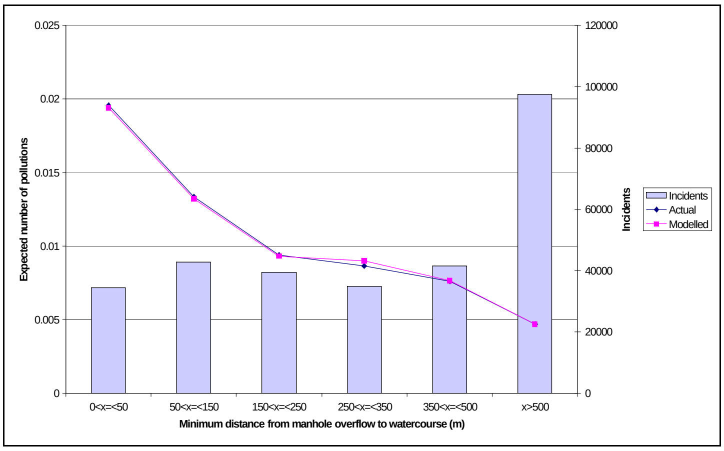

Figure 7 – Probability of pollution given a blockage by minimum distance from manhole to watercourse

Conclusions

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

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

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