Strategic water network rehabilitation planning

R.K. Herz and A.T. Lipkow

Lehrstuhl Stadtbauwesen, Dresden University of Technology, Mommsenstr 13, D-01062 Dresden, Germany

Abstract This paper presents the approach taken and the tools developed and advanced within the European research project CARE-W (Computer Aided REhabilitation of Water networks) for strategic rehabilitation investment planning as a complement to short-term performance monitoring and annual rehabilitation (rehab) budget allocation planning. In a first step, future rehab needs are quantified with a cohort-survival model from the present stock of assets taking into account the specific service lives of its components. Utility managers may choose in the short and medium range from many rehab options: doing more or less, sooner or later, on particular network components and with specific rehab technologies at lower or higher cost. So, in a second step, alternative medium-term rehab programs are specified and tested for their effects. The annual costs and benefits of these alternative rehab programs are forecast with the cohort-survival model beyond the rehab program period to capture the long-term effects of rehabilitating these long-lived assets. Advantages and disadvantages of alternative rehab programs are systematically compared to find out which one is most appropriate under local constraints. However, whereas the survival of network components can be forecast over very long periods with sufficient accuracy, many other characteristics of the water supply system that must be considered for finding the best network rehab strategy may take unforeseeable paths into the far future. Therefore, a scenario writing tool was developed allowing consistent scenarios for particular water utilities to be created and to test whether the alternative rehab programs are robust enough to meet all eventualities of the future. This approach is illustrated by a case study from East Germany.

Keywords Drinking water networks; management tools; rehabilitation; scenarios

Water Science and Technology: Water Supply **Vol 3 No 1–2 pp 35–42** © IWA Publishing 2003

Introduction: the longer perspective on utility assets

As drinking water distribution systems get older, their performance tends to decline. Bursts and leakage increase with the age of the pipelines, water quality problems arise from internal pipe corrosion, and additional pumping energy is required to overcome bottlenecks and to compensate for head losses due to incrustation. Thus measures of pipeline rehabilitation have to be taken in order to maintain the standards of network performance.

An appropriate approach to solving this problem of network deterioration seems to be to monitor a set of performance indicators and to take appropriate measures as soon as these indicators reach a critical value. The measures taken are subsequently monitored again for the effects they have on the performance indicators. Because of the longevity of pipelines and the availability of advanced methods for failure forecasting and pipeline survival modelling, this approach may be regarded as rather re-active and short-sighted. A longer perspective is needed to include the long-term effects of rehabilitation (rehab) decisions into the formulation of medium-term network rehab programs.

Several models have been developed recently that allow the rehabilitation needs of water distribution networks to be forecast. The AWWA Research Foundation published the final report in 1998 of a research project on “Quantifying Future Rehabilitation and Replacement Needs of Water Mains” including software called KANEW based on a mathematical cohort-survival model developed by Herz (1996a,b) in Germany. Whereas this first version of KANEW was restricted to forecasting annual rehab mileage, it was subsequently amended by transforming mileage into investments and by simulating the effects of specified rehab programs in physical and monetary terms (Herz 1998, 2002). Meanwhile it has been applied to about 30 utility networks for gas and drinking water in Europe and abroad (see www: KANEW). At about the same time, Reynolds developed a similar model in Australia, which has received wide publicity as "The Nessie Model" (www.nessiemodel.com), after publication of the AWWA study "Dawn of the Replacement Era – Reinvesting in Drinking Water Infrastructure" (AWWA, 2001; Scharfenaker, 2001). Work on planning models for pipeline rehabilitation is also under way in Australia at CSIRO (Burn, 2002). At the Canadian NRC Institute for Research in Construction in Ottawa, Kleiner and Rajani (1999, 2001) developed another set of models, now combined in the WARP software package, for failure analysis, short-term operational forecasting and long-term renewal planning.

The long-term forecasting methodology of these three models has its origin in demography and financial accounting. Cohort Survival Analysis is widely used in demography for forecasting natural population growth, and the Perpetual Inventory Concept applies the same principle for writing off (linearly) past investments to determine present asset values. There are methodological differences between the three models for:

- the type of density function used to describe failure and service life distributions;
- how the survival functions are calibrated from empirical data;
- how uncertainties of the future are dealt with; and
- to what extent the output is processed for decision making.

Here we present the extended KANEW framework for the exploration of network rehabilitation strategies within the context of CARE-W, an ongoing European research project on "Computer Aided REhabilitation of Water networks" (Sægrov *et al.*, 2003; www.unife.it/care-w).

A framework for network rehab strategy exploration

Within the CARE-W working package on strategic network investment planning, the advanced cohort-survival model of KANEW is supplemented by two new tools: the so-called Scenario Writer and the Strategy Evaluator. They shall be subsequently presented in more detail. The overall framework is shown in Figure 1 and briefly described as follows.

Future rehabilitation needs are derived by a cohort-survival model from the network inventory and from survival curves of pipe types. The latter are determined after analysing the ageing behaviour of pipes, their frequency of failure and rehabilitation by age. This is done in separate studies accounting for local conditions. Different pipe materials and diameters usually show quite distinctive frequency distributions (Herz, 1998). From this pipe lifetime analysis, survival functions are calibrated for the Herz distribution (Herz, 1996a,b, 2002). For each pipe type, there is a lower and an upper bound survival function, within which the service life of most pipelines will end. The lower and upper bound survival functions are then applied to all cohorts, i.e. vintages of each pipe type, resulting in specific annual rehabilitation needs that will occur sooner or later. Rehabilitation should take place within this band of higher or lower annual rehab needs. However, this is just a recommendation for defining a specific rehab program up to a chosen planning horizon.

There are many options for rehab managers. The rehab program could concentrate on particular types of pipe and postpone the rehab needs of others, and choose low- or high-cost rehab technologies providing shorter or longer service lives. This will affect the budget and future failure rates and may cause a dramatic overlap of rehab needs in future years. Thus the effects of alternative rehab programs designed for periods of 10–20 years need to be tested with the cohort-survival model.

In the process of annual network updating, network extension and rehabilitation are simulated as defined by a rehab program for a given period, and forecast by the model beyond this period. Thus the mileage of rehabilitation and extension is calculated year by year, allowing the age and residual lifetime of all pipelines in the network at any point in time to be determined. As the new pipelines have very few failures and leakages, network

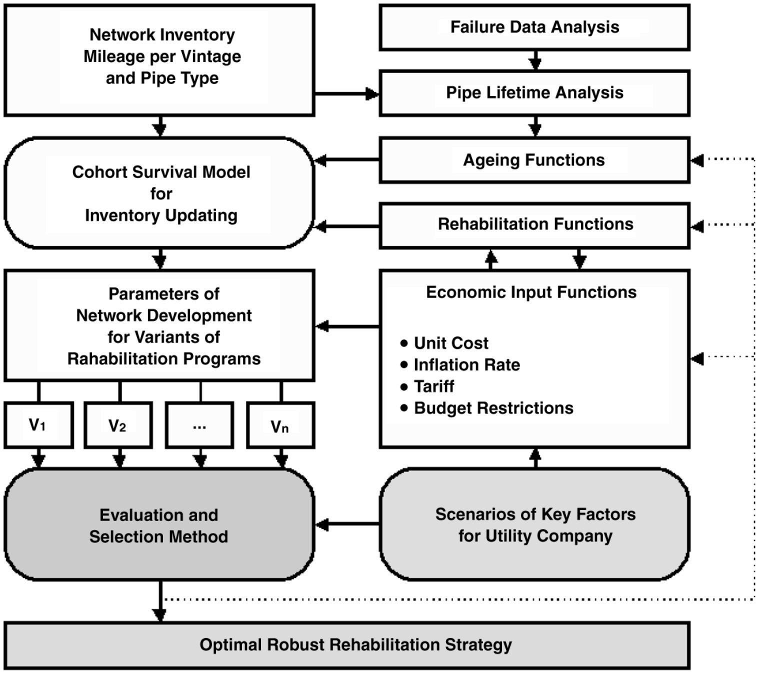

Figure 1 Extended KANEW framework

failure and leakage rates will decline the more rehabilitation is done, whereas they would increase in the do-nothing alternative. With economic input data such as unit costs for rehabilitation and repair, water tariff and marginal cost of water production, the physical outputs of the cohort survival model are translated into monetary terms. As rehab investments come first and the benefits from reduced repair and leakage accrue later, and accumulate over the years, rehab programs do not only have to stay within annual budget limits but also have to prove that they are economically viable in the long run.

To achieve economic viability, the rehab program may have to be modified. Feedback lines indicated in Figure 1 that options other than those mentioned above may have to be changed accordingly. Pipelines may have to live longer (at higher failure rates) and the water tariff may have to be raised to finance the rehab program. Apparently, this will concern the total water supply system. Therefore, we need to look at how some features of the supply system may develop in the future.

Another reason for looking at scenarios of the water utility's development is that some candidates for a rehab program are more adequate in an optimistic rather than in a pessimistic perspective of the future. These uncertainties should be taken into account before settling on the "optimal" rehab program. Thus the rehab program candidates should be compared with each other under different scenarios.

Creating scenarios for utility companies

A network rehab strategy needs to be developed in a wider context on a long perspective. The scenario method appears to be most appropriate for this task. Scenarios are intended to open the "window of opportunities" rather than to forecast the most probable future development (Figure 2). They help to explore in a systematic and consistent way a whole range of complex future states, including paths of future developments which may be quite a bit away from the expected ones, but certainly not including those that definitely will not take place because they are utopian.

Scenarios set the stage for a more detailed analysis and evaluation of rehabilitation strategies by the cohort survival model. Thus they must contain information on factors influencing the choice of network rehab strategies. Such information is part of the IWA Performance Indicators project (Allegre *et al*., 2000) in the form of utility background information and variables used to calculate performance indicators. From a large list, the following 13 key factors were selected because they appear to be most relevant for network rehab strategies and because they are useful for writing water utility scenarios:

W1 Population supplied
W2 Total per capita consumption
W3 Residential per capita consumption
W4 Percentage of revenue water
W5 Yearly water production capacity
W6 Annual network extension
W7 Pipe length per capita

E1 Domestic water tariff
E2 Industrial water tariff
E3 Percentage of running costs
E4 Inflation rate
E5 Average per capita income
E6 Average number of persons per household

The following three additional key factors were included, although they will be more accurately forecast by the cohort-survival model as a function of specified rehab programs:

R1 Network failure rate
R2 Network leakage rate
R3 Network rehabilitation rate

The Scenario Writer allows us to place the development of these network performance indicators in a consistent context with the other key factors, in a bright and dark future.

One of the difficulties in scenario writing is to account for the interrelationships between the various factors and to create consistent combinations of factor values that are not just wishful or fearful thinking on future states of the system. Therefore the Scenario Writer checks on an impact matrix (see Figure 3) containing the direction and intensity of relationships between each pair of factors. These relationships are also classified as proportional or inverse. In case of inconsistent input values, the user is asked to reconsider and modify his first estimate. Impact matrices allow us to identify active and passive factors, which is useful in writing scenarios.

The Scenario Writer tool developed in CARE-W provides an impact matrix for up to 20 key factors, where the above mentioned 16 factors have been checked for logical consistency and support is given to create a consistent matrix for any further 4 key factors that may be added by a particular water utility company.

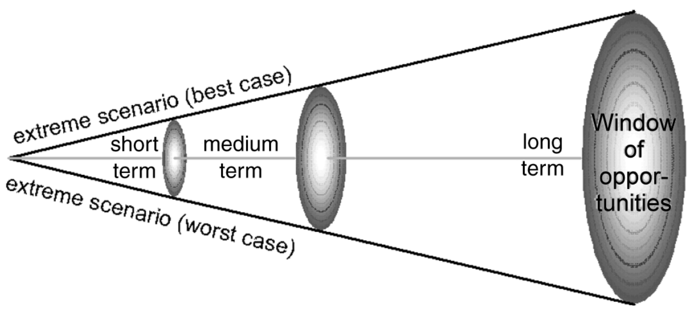

Figure 2 Scenarios open up a window of opportunities in possible futures. Scenarios start from the present situation. Usually two extreme developments are projected that define the shape of a funnel opening up into the far future and containing possible future states. These future states are characterized by a set of consistent values of closely interrelated variables. The extreme scenarios are usually thought as best/worst cases or labelled as bright/dark futures. Scenarios in between are more realistic. As time goes by, the funnel moves forwards.

	KF1	KF2	KF3	KF4	KF5	KF6	KF7	KF8	KF9
KF1									
KF2	**←**								
KF3	←	**←**							
KF4	←	←	0						
KF5	←	**↑**	←	↑					
KF6	←	↑	0	←	**↑**				
KF7	0	**←↑**	**←**	**↑**	0	**↑**			
KF8	↑	←	←	0	←	←	0		
KF9	↑	0	0	**↑**	↑	0	←↑	**←**	

Figure 3 This impact matrix shows the direction and intensity of relations between 9 key factors. There are $n(n-1)/2$ relationships, including zero-relations (0). The arrows are pointing from the affecting key factor to the affected one. In case of an interaction, the cell contains two opposite arrows. Bold arrows indicate strong impacts. By counting the number of arrows pointing to or from key factors, active and passive key factors are distinguished. Another useful category is whether relationships are proportional or inverse.

Results from an East German case study

The water supply system of the city of Erfurt serves as an example to illustrate how future needs of network rehabilitation are forecast with KANEW and what the long-term effects of specific rehabilitation programmes will be.

Present situation

The water supply system of Erfurt serves about 160,000 people through 550 km of water mains plus 250 km of service pipes. Service pipes lie within the responsibility of the property owners. Water consumption of households plus industry is about 170 l per day. Before German re-unification it was twice as much. About one third of the water fed into the system is non-revenue water, amounting to water losses of the order of 1 m^3 per hour and per kilometre of water mains. Probably about two thirds of these water losses are due to bursts and leakage at cracks, corrosion holes, joints, valves and hydrants. The failure rate (with water extrusion) is about 0.55 per km and year for water mains and 2.35 for service pipes. So almost half of the leakage may occur on service pipes. These figures are significantly higher than the average for East German water distribution networks, which again is about twice as high as the West German average, where rehabilitation has received much more attention in recent decades. The future need of network rehabilitation depends on the aging behaviour of the existing stock. In the following we concentrate on water mains.

Ageing behaviour of pipe types

Pipe age alone cannot justify rehabilitation. However, age in combination with other characteristics of the pipe can be used to produce reasonable and consistent estimates of the service life of types of pipe (Figure 5). Based on local experience and on the analysis of failure and rehabilitation statistics, ranges of age are estimated that would be reached by 100, 50 and 10% of a particular type of pipe under more or less favourable circumstances. Usually this is done in an interactive way including research, engineering and management staff of the particular water supply company. For new types of pipe, the Delphi method is applied. Survival curves from other water utilities give some orientation.

Defining rehabilitation programmes

As the results of the cohort-survival model depend very much on the estimates of specific service life distributions or survival functions, simulation runs are performed by KANEW with lower and upper bounds and with median survival functions to delimit the range of future rehabilitation rates. KANEW then allows us to specify annual rehabilitation rates for types of pipe within a defined rehabilitation period and calculates, beyond this programme

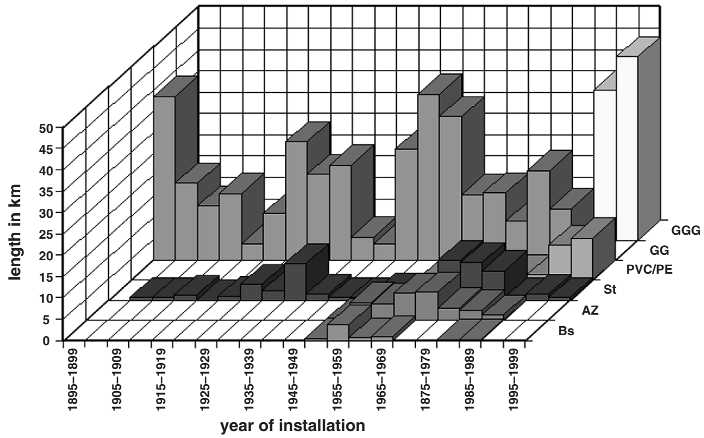

Figure 4 Length of water mains in the city of Erfurt by period of construction and by material. Six categories of water main are shown by 5-year periods of installation. Two thirds are cast iron (GG) pipes. After German re-unification, almost 100 km of new ductile cast iron (GGG) pipes and some PE pipes have been laid. In addition to cast iron pipes, there are some older steel (St), asbestos (Az) and concrete (Bs) pipes approaching the end of their service lives. During the past decade, almost 2% of the network has been rehabilitated per year, mostly by replacing old cast iron and steel pipes. There has been little cement-mortar relining of old cast iron pipes although most of them show heavy incrustation, but there were no problems with discoloured water.

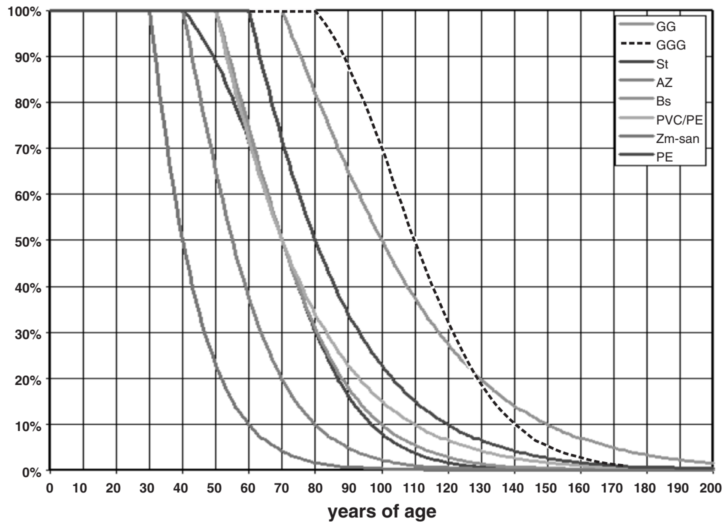

Figure 5 Survival functions of types of water mains under optimistic service life assumptions. Survival curves of the Herz distribution are shown for the six existing types of water mains and the new generation of PE pipes as well as the low-cost rehab technology of cement mortar relining. As a rule, most water utilities do not replace a pipeline before it reaches a certain age. Up to this age, in case of failure, there will be just spot repair. This threshold age varies with pipe material. Ductile iron pipes are assumed to be more resistant and to get older than cast iron and PE pipes. Renovation with cement mortar relining will prolong the service life of a pipeline under optimistic assumptions by 40 ± some years, for 10% of them even by 60 years. These survival functions are applied to each cohort of water mains.

horizon, the over- or unfulfilled rehabilitation need of types of pipe up to the time horizon of the analysis. For this case study, several rehabilitation programs were defined and tested. Here we present two, one that fulfills the forecast network rehabilitation rates, the other one setting rehab, targets for specific pipes.

The other tentative rehab program is fulfilling all rehab needs as forecast with median survival curves. It is more specific on the new pipelines. So specific unit costs could be

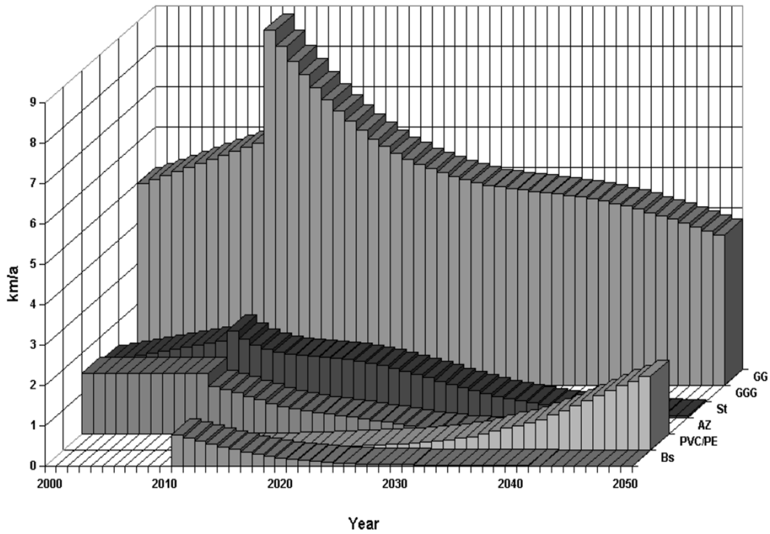

Figure 6 Forecast rehabilitation needs of categories of water mains according to a rehab program for the period from 2000 to 2010. In this tentative rehab program up to the year 2010, targets were defined for annual rehabilitation of the most failure prone types of water mains, i.e. gray cast iron, steel and asbestos cement pipelines. Assuming median service lives of these pipes, apparently, the rehab rates for GG and St are not sufficient and lead to arrears of rehabilitation at the end of the rehab program. Pipelines in need of rehabilitation remained in the stock, where they got older and their failure rate increased. After 2010, the pipes that need rehabilitation are forecast with the cohort-survival model on the basis of specific service life distributions without constraints.

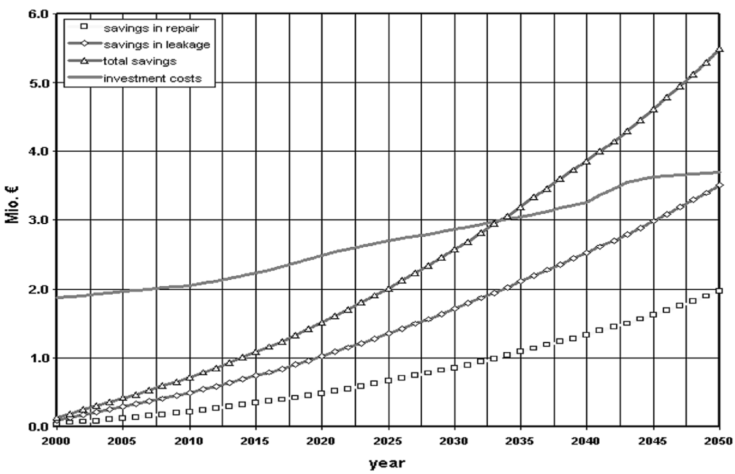

Figure 7 Annual rehab investments and cost savings from reduced water leakage and repair. In this tentative rehab program it is assumed that 20% of cast iron and steel pipes in need of rehabilitation are renovated, 60% are replaced by ductile iron and 20% by PE-pipes. Old PVC/PE-pipes are replaced by new more resistant PE pipes, concrete pipes by ductile iron pipes of larger diameters. 60% of asbestos pipes are replaced by ductile iron, 40% by PE-pipes. This will lead to a slight increase of rehab investments, mainly due to inflation, and progressively increasing cost savings from reduced repair and leakage. Leakage was valued with 20% of the water tariff. In this case, it takes 23 years until the accumulated cost savings surpass the annual rehab investments.

applied and cost savings from rehabilitated pipelines calculated according to reduced failures and leakage. The development of rehab investments and cost savings is shown in Figure 7. Note they do not contain social costs of rehabilitation, repair and leakage.

Finding the best rehab strategy

Alternative rehab programs should be compared with each other on multiple criteria in the short, medium and long term. KANEW generates a variety of decision criteria, such as network age and residual pipe life as well as present values of rehab investments and cost savings up to particular points in time. By comparing advantages and disadvantages of alternative rehab programmes, the best strategy evolves in an iterative process. This process could be supported by an efficient multi-criteria evaluation tool. Within the CARE-W project, such a tool, called the Strategy Evaluator, is being developed at Dresden University.

Conclusions

Rehabilitation of water networks should be planned with a long perspective. Cohort-survival models allow us to forecast rehabilitation needs in the long run. Softer forecasting tools like the Delphi method and Scenario Writing should be applied where empirical findings do not carry that far. To bridge the gap between long-term and short-term rehab activities, a two-tier approach is required: the network level for the long term and the project level for short-term activities such as priority setting for rehab projects (Baur and Herz, 1999; Baur and Kropp, 2002; Baur *et al*., 2003).

Acknowledgements

Parts of this research have been completed within the CARE-W project financed under the Fifth Framework Programme for Research and Development of the European Union. We express our gratitude particularly to our project partners who contributed to developing the Scenario Writer tool.

References

Alegre, H., Hirner, W., Baptista, J.M. and Parena, R. (2000). *Performance indicators for water supply services*. Manual of Best Practice Series, IWA Publishing, London.

AWWA-RF (1998). *Quantifying Future Rehabilitation and Replacement Needs of Water Mains*. Denver, CO.

AWWA (2001). *Dawn of the Replacement Era – Reinvesting in Drinking Water Infrastructure. An Analysis of Twenty Utilities' Needs for Repair and Replacement of Drinking Water Infrastructure*. Denver, CO.

Baur, R., LeGauffre, P. and Sægrov, S. (2003). Multicriteria decision support for annual rehabilitation programmes in drinking water networks. *Wat. Sci. Tech: Water Supply*, **3**(1–2), 43–50 (following article).

Baur, R. and Kropp, I. (2002). Selecting and scheduling infrastructure rehabilitation projects. *Wat. Sci. Tech: Water Supply*, **2**(4), 43–50.

Baur, R. and Herz, R.K. (eds) (1999). *Service Life Management of Water Mains and Sewers*. Decision Criteria and Strategies for Rehabilitation. Proc. 13th Junior Scientist Workshop, Dresden University of Technology.

Burn, S. (2003). Asset planning for water reticulation systems – the PARMS model. *Wat. Sci. Tech: Water Supply*, **3**(1–2), 55–62 (this issue).

Herz, R.K. (1996a). Ageing processes and rehabilitation needs of drinking water distribution networks. *J Water SRT Aqua*, **45**(5), 221–231.

Herz. R.K. (1996b). Dégradation et renouvellement des infrastructures: un modèle de survie par cohorte. *Flux*, **23**, 21–36.

Herz, R.K. (1998). Exploring rehabilitation needs and strategies for water distribution networks. *J Water SRT Aqua*, **47**(6), 275–283.

Herz, R.K. (2002). Developing rehab strategies for drinking water networks. Paper presented at the 9th International Conference on Durability of Building Materials and Components, Brisbane, 17–21 March 2002.

KANEW in: *www.tu-dresden.de/biwiss/stadtbau/KANEW.html*

Kleiner, Y. and Rajani, B.B. (1999). Using limited data to assess future pipe replacement needs. *J AWWA*, **91**(7), 47–61.

Nessie Model in: *www.nessiemodel.com*

Rajani, B.B. and Kleiner, Y. (2001). WARP – Water Mains Renewal Planner. Paper presented at International Conference on Underground Infrastructure Research, Waterloo, Canada.

Sægrov, S. *et al*. (2003). Computer Aided Rehabilitation of Water Networks (CARE-W). *Wat. Sci. Tech: Water Supply*, **3**(1–2), 19–27 (this issue)

Scharfenaker, M.A. (2001). Mythic monster aids first scientific assessment of nationwide water infrastructure needs. *J AWWA*, **93**(7), 20–32.