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Approaches to sewer maintenance: a review

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Abstract

Sewer maintenance and rehabilitation strategies developed in a number of countries are reviewed. Comparisons are made between those approaches that focus on a predefined subset of strategic sewers and those that consider proactive maintenance of the whole system to address the wider consequences of failure such as customer satisfaction, social disruption and environmental damage. A number of diverse methods are described which can be used to optimise and prioritise proactive maintenance by analysing sewer performance, and lessons are drawn from maintenance strategies developed for other buried infrastructure assets. Limitations in existing sewer databases are discussed and new methods of obtaining sewer condition information are described. The paper concludes that to be cost effective, proactive maintenance involving inspection and repair must be focussed on those pipes which can be shown to have an early predisposition to failure.

Keywords: Asset management; Maintenance; Sewers; Urban drainage

1. Introduction

Engineers worldwide are coming to the view that proactive and preventive repair strategies for urban drainage systems are often more cost effective than the traditional approach of reactive sewer maintenance. Existing infrastructure assets are continuously increasing in age, and at current replacement/renewal levels have an inferred average asset life of several hundred years. However, age-related deterioration of sewers is unclear. In many cases the failure of clay and concrete pipes can be related to the practices at the time of construction or subsequent third-party damage, rather than simply their longevity. Nevertheless a "bathtub" shaped pattern of performance has been suggested by some authors (Dakers, 1980; Rostum, Baur, Saegrov, Horold, & Schilling, 1999; Davies, Clarke, Whiter, & Cunningham, 2001) in which there is a relatively high probability of a defect occurring at the end of construction when backfill, traffic and soil loading is introduced to the pipe, followed by a period of relative stability. Much later there will be a period of increasing probability of a defect as the material properties and transport capacity of the sewers decline.

Inevitably, as the assets in the ground continue to age, concern will grow about their continuing performance and the risks of future failure. In order to preserve the functionality of this ageing infrastructure, strategies need to be developed to focus maintenance activity on those parts of the network where it will be most effective. Increasing customer and political pressure, together with more stringent environmental regulations, are adding to the requirement that maintenance of these systems is managed in a more sustainable and comprehensive way. Macaitis (1994) has pointed out that these new circumstances are challenging the efficacy of traditional urban drainage crisis management.

Sewer maintenance and rehabilitation are processes which can and should be optimised (Burgess, 1994), because operating at or near the boundaries (e.g., only emergency repairs at the lower boundary and complete system rehabilitation at the upper boundary) is clearly more costlier than operating in at least part of the region between these boundaries. Grigg (1994) has reported that whilst many cities in USA have elements of maintenance management systems, many lack a cohesive plan for managing urban drainage infrastructure. The management strategy of choice being "to clean the inlets as you can afford and fix the system if and when it fails".

In order to plan sewer maintenance activity more effectively, tools are required which can optimise and prioritise any proactive work by predicting sewer

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condition and performance. New technologies such as robotics, ground piercing radar, sonar and infrared thermography can help provide enhanced information relating to the condition of underground pipes and the advances in computerised databases and geographic information systems can help manage the condition data more efficiently. Valid condition assessments are the key to developing good planning and programming for urban drainage maintenance and rehabilitation operations, and these require good record keeping and proficient information systems. In many countries, however, there is a general lack of good information on the condition of infrastructure assets such as sewers and water mains. No one knows where the pipes are, what their type is, when they were last inspected, etc., and there is often the absence of a linkage between fixed asset financial databases and maintenance management records (Grigg, 1994).

This paper reviews different approaches to tackling this problem which have been taken in a range of countries and notes that the choice of an appropriate technique is often determined by the quality and extent of data available. The data requirements for these techniques are discussed and some new challenges are posed for the future.

2. Established approaches using selective rehabilitation

The UK Water Industry National Assessment (National Water Council/ Department of Environment Standing Technical Committee, 1977) of its underground assets revealed alarmingly high estimates of the cost of repairs. In the early 1980s, Peters (1982) reported on research which showed that a small proportion of incidents (<20%) accounted for a disproportionate amount of the repair costs. Hurley (1994) describes how this led to the development of the Sewerage Rehabilitation Manual (SRM) (Water Research Centre, 1983), which used new developments in computerised hydraulic modelling and data-processing techniques to assess sewer system performance on a catchment wide basis. In order to be cost effective the SRM recognised the need for a selective rehabilitation strategy, which was achieved by directing survey and rehabilitation work to the "critical sewers", defined as those sewers where collapse repair costs could be expected to be the highest. These sewers represent about 20% of the UK network and have been identified based on the criteria of their economic consequences of failure rather than on their likelihood of failure. The remaining 80% of "non-critical" sewers, not explicitly dealt with under the SRM strategy, remain subject to reactive maintenance only.

After an initial planning phase the SRM recommends allocating a structural condition grade (1–5) for each critical sewer using manual or CCTV inspection, together with an assessment of hydraulic performance using computer models to simulate flows in the system. This analysis leads to the development of a Drainage Area Plan in which options and priorities for rehabilitation are evaluated and an integrated strategic plan is developed.

Similar approaches have been taken up in other countries based on the principle that 20% of the sewer network will cause 80% of the severe financial, social or ecological problems. For example, in Belgium a Hydroplan procedure has been developed which uses a cumulative frequency analysis of sewer characteristics to group sewers into three categories, where Category A is not strategic, Category B is less strategic and Category C is strategic. Weight factors are used to reflect financial, social and ecological policies and priorities (Cobbaert, Huberlant, Provost, & Swartenbroekx, 1998). Field surveys are then carried out which concentrate on the highly strategic sewers, the hydraulic core area and the hydraulic structures and these are used to update existing databases, build validated hydrodynamic models and indicate the structural condition of the strategic sewers. The performance of the sewer system is then evaluated against its ability to transport storm and wastewater without hydraulic overload, as well as creating minimal ecological damage and retaining good structural integrity. This is achieved by judging performance against the following defined criteria: water quantity standards, maximum water levels, allowable discharges, water quality standards, overflow frequency and structural condition standards. An asset management plan is then produced which defines areas where direct intervention is necessary to achieve a straightforward and technically acceptable solution, areas where direct intervention is not possible (with further work needed to assess the optimal solutions) and areas where direct intervention is not yet necessary but where special attention is required through the maintenance programme.

Anderson (1999) has described a drainage management system in Australia which uses UK and Australian standards to develop a 1–5 condition grading score for each manhole-to-manhole length of sewer, based on a selective CCTV inspection. Such work is limited to critical or important sections of drainage pipeline, old brick or concrete pipes more than 50 years old, hydraulically stressed sewers as well as for operational needs to determine causes of blockage and localised flooding during storms. A decision matrix, which combines condition with criticality, is then used to prioritise work on the elements of the network which require attention because of deteriorating structural condition and hydraulic performance and their relative importance to the drainage authority. Once again it is the critical assets (defined as criticality A or B in a condition and criticality matrix, using criteria previously described by

Anderson & Scott (1997)) which are recommended to receive the highest attention for maintenance, inspection or renewal because the consequences of these assets failing are high from an operational repair, business, political and financial viewpoint.

A more complex method for awarding condition grades has been developed by Hasegawa, Wada, and Miura (1999) in Japan which claims to predict a time when the sewer pipe should be repaired based on the knowledge of pipe diameter, pipe length, materials and other sewer characteristics, and is based on the accumulated knowledge and experience of those professional engineers involved with sewer maintenance and management. CCTV inspection is used to classify pipe defects into three levels and decreases in flow capacity are evaluated arising from observed reductions in the cross sectional area of the pipe (due to sediment accumulation, slipped jointing, etc.). Pipes are then ranked according to a flow capacity reduction ratio. A road collapse probability index is judged based on the following defects: Infiltration/Inflow (I/I), breakage, cracks, unconnected joints, slipped joints, and defective lateral pipes. This allows pipes to be ranked into three groups ranging from high collapse possibility, high collapse possibility if no action is taken to low collapse possibility. The sewer properties and circumstances are then considered using the following information: the age and material of the sewer, cover depth, groundwater levels, traffic volume, soil properties and proximity of other underground installations. Each of these factors is then attributed a rank **a**, **b** or **c** and the probability of road collapse is based on those pipes with a higher proportion of factors ranked **a**. A matrix is then produced which shows the necessity for sewer repairs and is based on the relationship between the degree of flow capacity reduction and the possibility of road collapse. This information is translated into priority numbers on a 1–4 scale which can be used as a tool for the premeditated management of the network.

The procedure is complex and limited by the large amounts of data required, which in many catchments will not exist, and is dependent in formulating the rankings on the experiential judgement of engineers. Such a procedure may lead to anomalous results if expected default values are entered where real values are missing.

Engineers in several American cities have reported their approaches to directing maintenance and rehabilitation activities, often based on scoring techniques similar to those described above. For example, Galeziewski, Edmonson, and Webb (1995) describe a prioritisation procedure based on a photographic inspection and CCTV survey for the rehabilitation of large diameter unlined concrete sewers in Phoenix, Arizona, which were prone to hydrogen sulphide corrosion damage. This uses an algorithm which combines the corrosion and structural condition of each pipe with other observed defects and an impact factor to produce an overall score which is used to rank pipes in order of deteriorating condition, allowing pipes to be grouped into five condition categories. These condition categories are plotted on colour coded maps from which a series of rehabilitation projects can be developed.

Stalnaker (1992) describes the sewer rehabilitation methodology used in Dallas, Texas. An algorithm has been developed as an objective decision-making process to determine whether a sewer be replaced, repaired or rehabilitated. The system uses data from recent CCTV inspections and flow surveys and applies a number of pre-set rules to formulate maintenance decisions. The technique is extremely labour intensive and no criteria are offered for the initial selection of the sewers to be surveyed. However, the use of expert rules can make the interpretation of surveys more straightforward and less subjective.

All these methods rely on some agreed set of evaluation criteria which tend to define pipes with specified characteristics as high or low risk, critical or non-critical. Although using this kind of generalised criteria can be a useful pragmatic guide, such approaches may not universally apply to all catchments. For example, the criteria used to define critical sewers in the UK Sewerage Rehabilitation Manual were largely derived from collapse studies conducted on ageing inner city networks. Critical sewers in newer (post-war) catchments are often found to be in good condition (partly as a result of improved construction standards for these more expensive facilities), and experience has shown that maintenance activity in these circumstances is often better focussed elsewhere. Further, once the structural condition of these critical facilities have been improved, overall maintenance of the system becomes more important. Thus there are dangers in concentrating all activity on a pre-selected subset of sewers and more efforts should be made to identify the correct subset for each catchment for which maintenance will be most effective. This requires the development of suitable analytical techniques to analyse past performance in the whole catchment in an attempt to better direct future proactive maintenance activities. Some alternative approaches to this problem are described in the following sections of this paper.

3. The need for change

Many problems such as blockage, odour and collapse continue to occur on the part of the system which has not been systematically rehabilitated through the procedures described above. This is usually made up of the non-strategic sewers which are usually smaller diameter pipes, often laid at slack gradients where serviceability problems of siltation, protruding connections, infiltration, fat deposition, encrustation and root infestation tend to have a disproportionately greater effect on their performance than on larger core area sewers. These sewers are increasing in age and if no form of pre-emptive measures are taken it is inevitable that they will be subject to a higher risk of failure in the future (Oliphant, 1993).

Following privatisation of the Water Industry in England and Wales in 1989, Eadon (1994) noted that the overall management of sewers had become more positive. The conditions of licences granted to Sewerage Undertakers and the new regulatory framework created a need for information about the condition of all sewerage assets. This need arose from balancing the provision of a good level of service to customers and a reasonable return for shareholders. Hence water companies now have to show that all the assets in their care are being maintained in good order and the promised improvements delivered. The UK regulatory body OFWAT requires continued improvements in the performance of sewerage assets through more accurately focussed maintenance work using better information systems and better utilisation of existing data (OFWAT, 1999). This has led to a new set of drivers for rehabilitation, with customer satisfaction now a high priority for all water companies. This trend will move the need for maintenance away from the high value core area sewers, already addressed through established procedures, to the upper reaches of the network which are made up of the smaller local sewers which impact more directly on the customer.

4. Recent developments

4.1. Non-critical sewers

Studies in UK have considered the feasibility of extending proactive maintenance to non-critical sewers, whilst recognising that the planned maintenance of all non-critical sewers cannot be justified as survey costs would outweigh any benefits. Orman and Clarke (1994) have discussed methods for targeting well-defined groups of sewers that are more likely to collapse or become blocked, based on either existing condition and failure data or on attributes of the sewers derived from other records. Their economic appraisal was restricted to comparing the costs of surveying all sewers with a high consequence of collapse (as identified only using the depth of the sewer) to the savings arising from the planned repair of the comparatively few failures found. On this basis they found that pre-emptive inspection and repair of non-critical sewers was unlikely to be economic (except in a small number of cases) but that a pre-emptive approach to removing the cause of recurrent blockage would be cost effective in a significant proportion of cases. No consideration was given to customer issues or the wider disruption costs caused by failure and they conceded that their economic model was highly sensitive to the planned repair costs, which had been assumed or estimated in their analysis. A modest reduction in planned repair costs was sufficient to make a number of methods economic. They concluded that planned maintenance of non-critical sewers should only be considered to reduce the number of collapses in a small number of areas where failure rates are abnormally high, and where blockages are recurring more than once per year.

More recent work by Fenner, Sweeting, and Marriott (2000) accepted that the UK water industry attitude to proactive maintenance was changing and so a decision support model was developed by analysing historical sewer event data and asset information. This approach highlighted some of the causal factors of sewer failure on the non-critical part of the system. A data availability survey of water companies revealed the limited extent of information held in asset databases, with little systematic recording of factors such as pipe age or surrounding soil type, which restricted the type of analysis which could be undertaken.

The first stage of this model was based on the analysis of pipe data contained in a series of 500 m $\times$ 500 m grid squares defined using GIS software. Algorithms were developed to predict the likelihood of sewer failure in each square (based on the number of past events in the square) and to allocate a consequence factor to each square (based on global and local metrics which affect the community and individual customers, respectively). Likelihood and consequence values were combined in two-dimensional risk plots which enabled the identification of "critical grid squares" (Fig. 1). A simple cost model was then applied to highlight those grid squares containing sewers which would be cheapest to rehabilitate so that most cost-effective actions could be identified and prioritised accordingly. Validation was achieved by successfully predicting those squares exhibiting failures in the latter part of the data record. The method provides a coarse screening tool for the water industry which can be used systematically to evaluate "hotspots" of sewer failure.

A second stage applied a Bayesian statistical model (Fenner & Sweeting, 1998) to analyse the performance of individual pipe lengths in those grid squares identified as the most at risk. This adjusted the catchment wide probability of failure based on the characteristics of each pipe. The significant characteristics were identified using a diagnostic ratio to determine whether pipes with certain characteristics had a higher than average incidence of past failure. Significant characteristics were grouped together in a series of combinations (condition states) and their overall probability of failure was

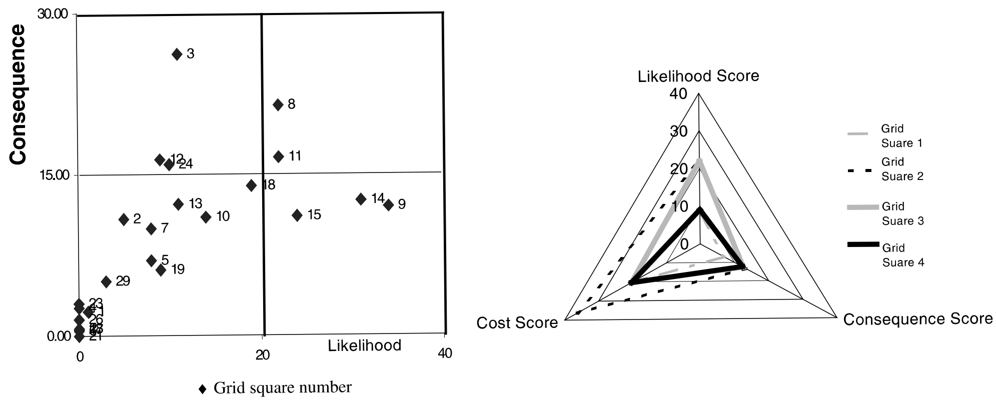

Fig. 1. Risk plot showing critical grid squares in top right quadrant and radar plot combining likelihood, consequence and cost factors.

computed by applying the Bayes theorem. Pipes could then be ranked according to these probabilities. By applying this technique to data from several catchments, it was found that similar condition states and associated probabilities arose in each of the data sets studied. The results have shown that when more of the significant characteristics are found in an individual pipe length, a higher probability of future failure can be anticipated. On this basis, pipes can be screened to help prioritise any given pipe into a planned maintenance programme.

The analysis described above showed that pipes which were most prone to failure had the following characteristics: long lengths, small diameter, shallow depth, slack to moderate gradients, and foul sewers. Repeated events were found to be the best indicator of future sewer failure, suggesting that current reactive maintenance practices of rodding and jetting are tackling the symptoms of the problem and not the cause. An advantage of the technique is that it allows an analysis of the whole sewer network based on typical limited levels of data availability. A disadvantage is that to achieve an individual ranking considerable data manipulation is necessary which may involve the need to manually link asset and event information, where sewer records and complaint data have traditionally been stored in separate paper archives.

4.2. Cohort survival models

In Norway novel methods for assessing the technical state of wastewater (and water) pipes have been developed using the results of CCTV inspections to group sewers into condition classes (Rostum et al., 1999). The transition between these condition classes is then used to describe the deterioration process of sewers. This is possible because in Norway 90% of all water and wastewater pipes are digitally recorded in the GIS database Gemini VA in a common format, including information on year of construction, pipe material, pipe dimensions, soil condition. Additionally, quite long records of failure data (e.g., break type, time to break) and CCTV inspections exist.

A pipe state rating S is calculated according to the formula

$$S = K(P_1L_1 + P_2L_2 + \cdots + P_NL_N)/L,$$

where L is the total inspected length, L_N the length with one or several faults, P_N the weight of fault no. n and K is a constant equal to 100.

This includes an analysis of pipeline functionality and the consequences of failure such as environmental and property damage. The values of S are then used to assign a class indicating the structural/operational state of each sewer ranging from Class 1 (very good: $0 < S < 5$) to Class 5 (useless: $70 < S$). This classification is based on a Norwegian standard procedure used by many Norwegian municipalities (NORVAR, 1998). The prediction of the deterioration process is based on a cohort survival model for urban infrastructure networks (Herz, 1998), where cohorts are defined as a set of elements installed in the same year with a particular failure probability. The state survival functions of a sewer system specify the probability of a transition between the various classes in the form of a Herz distribution (Herz, 1996)

$$S(t, a, b, c) = \frac{a + 1}{a + \exp[b(t - c)]}$$

where $t > 0$, a is the ageing parameter (no ageing takes place when $a = 0$), b the failure parameter (the larger the parameter the steeper the graph) and c is the resistant parameter (the duration of life before the ageing process starts). For sewers the value of c is set to zero in this function, on the assumption that ageing starts at the beginning of the pipe's life.

Using the information on the database the state survival functions are calibrated and used to describe the transition from one condition class to the next in a given catchment. In this way the percentage of pipes which still remain in each class at a given age can be

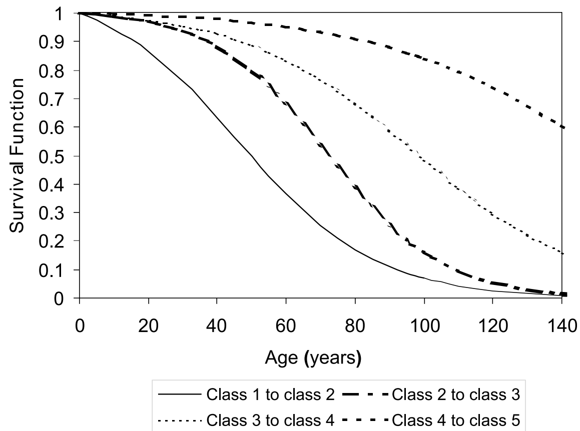

Fig. 2. State survival functions showing transitions between condition classes (after Rostum et al., 1999).

determined (Fig. 2). The technique has been applied to districts of Trondheim and it has been found that after 35 years 50% of all sewers have reached a condition class of 2 or worse (Horold, 1998). This approach allows a time based forecast which will predict when a sewer pipe will reach a critical state (e.g., transition from class 3 to 4). From this knowledge proactive inspection strategies can be developed for the sewer network and the residual lifetime and the value of the network can be estimated. The technique can be refined by using CCTV inspections to improve the first calibration of the state survival functions, and it offers attractive possibilities in helping to guide the long-term asset management of sewer networks. However, the authors concede that a major limitation is the need for a complete and long-term knowledge of failure data. This kind of data has been extensively recorded in Norway, in contrast to other European countries, and so the adoption of this approach may be limited elsewhere.

4.3. Performance indicators

In Portugal, Cardosa, Coelho, Matos, and Matos (1999) have developed a standardised performance assessment for sewer systems based on a system of performance indicators, which provides a clear framework for decision support in the diagnosis and rehabilitation of sewerage systems. The methodology is based on three components for each aspect of performance to be analysed. Firstly the numerical value of a network property or state variable is either generated by hydraulic or water quality simulation models, or found from reliable data records. Secondly, an (arbitrary) penalty curve translates how the decision variable is rated over a given operational range between a no-service (0 rating) and an optimum service (4 rating) situation. Finally, a network operator allows the performance values at each elemental level to be aggregated across the system (e.g., by using averages, weighted averages or maximum/minimum values depending on the purpose of the analysis). In this way the method can produce a performance evaluation for every element of the system as well as for the system as a whole, which can form the basis for a statistical analysis. Performance can thus be plotted against a series of operational conditions, typically either for a range of return periods (system graph) or the simulation of a specific event (event graph).

The performance indicators may be used to support immediate decisions about the need for rehabilitation and to understand the current system behaviour and compare alternative design solutions. The authors recognise that in modern societies the performance of a sewer system cannot be exclusively based on technical aspects and that economic, social and environmental points of view are increasingly becoming important. They suggest a range of useful indicators based on the following five performance domains: *hydraulic* (water level, flow velocity, overflow volume, peak and duration, ratio between maximum wet weather flow and maximum dry weather flow); *environmental* (concentration of pollutants, polluted overflow discharges, septicity); *structural* (damage rate, leakage); *economic* (maintenance costs, power costs) and *social* (disruption to street traffic and activities, public complaints and odours).

The parameters for each of these performance indicators must be defined by the analyst, according to local characteristics, legal constraints, operational and management strategies and the objectives of the analysis. So, for example, water level in a pipe should not exceed its pipe diameter D more than once in T years. Thus the best performance is obtained when the water level is D (performance level 4); lower levels mean unused capacity (performance level linearly reduces to a value of 1 when the pipe is empty), water levels greater than D will be undesirable with performance level 2 set at overflow level. When the water level reaches either the ground surface or basement levels, clearly minimal levels of service have not been achieved and so the performance level is set at 0 (Coelho & Alegre, 1998) as demonstrated in Fig. 3. Each pipe can be graded this way for maximum water level during a simulated event. A generalising function using $k \cdot Q_{\mathrm{in}} \cdot L$ takes the form of a weighted average, where Q_{in} is the flow capacity of the pipe, L is the pipe length and k is a risk coefficient translating the consequences of flooding in that section. System graphs can then be obtained by the calculation for different return periods (T) of the performance indicators, with the curve peak indicating the return period associated with optimum system performance. The benefit of this approach is that it shifts the focus of technical management of urban drainage systems to a wider, more rigorous, performance oriented view based on a standardised means of diagnosis. A clear advantage, in comparison to the other methods described here,

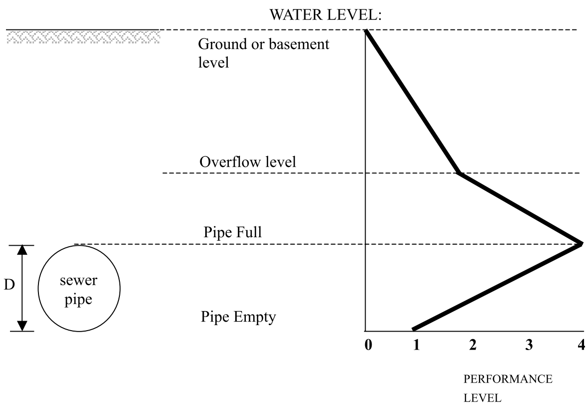

Fig. 3. Performance values for water level (after Cardosa et al., 1999).

is the potential for rationalising the often complex output from hydraulic models and for integrating the hydraulic, structural and environmental diagnosis of sewer system performance. However, much work is still required in understanding which are the most appropriate performance indicators to be monitored, and whether the cost of measuring these can be justified.

4.4. *Risk of sediment build-up*

In France attempts have been made to analyse the role played by the structure of the network itself (shallow slope, loops, geometry of pipes, special structures, etc.) and the risk of sediment build-up (Gerard & Chocat, 1999). The development of a diagnostic model can then direct de-silting operations to areas of the network most prone to sediment build-up.

A conceptual model was developed using monthly measurements of sediment levels from seven representative sites in the Lyon drainage network. These data indicated the general deposition tendency in the sewers under study, depending on their structure and their environment, and led to an assessment of the build-up risk recorded for each section. The work involved the analysis of vulnerability factors (slope, loop system, geometry, singularities, cross-section, etc.), followed by hazard factors (local surface problems, obstructions, liability to flooding, nature and quantity of upstream contributions, flow, state of repair) that may explain sediment build-up. Logistic regression was used to quantify the relative importance of each of the causes identified (based on 280 validation sections) and the relative risks for each factor was calculated.

Their theoretical model determines the risk of sediment build-up by using a set of simple parametrised expert rules (and/or, if/then) based on the fact that silting-up is mainly a conjunction of several causes and therefore occurs in preferential locations. The rules are implemented in three stages. The first stage involves the analysis of the specific vulnerability of each section based on slope, loop system, geometrical aggravating factors (such as changes of capacity or slope), the presence of singularities (such as a trap, valve, pumping station, weir or siphon) and shape of section (favourable: gutter or ovoid; unfavourable: circular, flat). When each of these has been assessed the sections are classified according to their vulnerability: very high, high, average, low and very low.

The second stage involves a separate assessment of the different factors used to estimate hazard (i.e., the probability that there are some solids to be trapped). This is based on the knowledge of the surroundings of the network and the catchment area being drained, such as its liability to flooding, local surface problems (such as markets, dense shopping areas and heavily planted areas), possible obstructions to flow from roots etc, and the state of repair of the pipes (particularly of the invert). In addition, the upstream contribution is also considered, with contributions assumed to be proportional to the active length of the upstream collector. When these factors have been assessed the sections are classified into five groups as before.

The third stage uses logical "and/or" operators to combine factors for vulnerability and hazard, and ranks the theoretical risk of sediment build-up into: very high, high, average, low and very low. Here the hazard criteria refine the vulnerability criteria, thus a high hazard figure or a high vulnerability figure alone will not constitute a high risk.

The theoretical risks of sediment build-up provided by the model were compared with the measured build-up of sediment at the 280 locations, and the model was shown to underestimate the risks, performing better when predicting very low to average risks rather than high or very high risks. Performance was improved with the inclusion of the hazard factors in the analysis. Whilst accepting that further improvements can be made in the model, the authors claim that it can provide the basis for thematic maps of the network showing the distribution of the theoretical risk of sediment build-up for each section, thus improving the planning of maintenance and cleansing operations.

In UK a recent survey of sewerage operators found that sediment deposition was very often associated with operational problems, and these were attributed primarily to slack pipe gradients restricting sediment capacity. This provides further evidence to suggest that inherited system or topographic features cause most sediment deposition problems (Frasier, Ashley, Sutherland, & Vollertsen, 1998). The most common maintenance strategy for dealing with these problems has traditionally been periodic cleaning out by jetting or other methods. Recently, however, the use of on-line invert traps to provide some form of preventative measure is being considered, but suitable locations for their installation need to be determined. Linking the physical attributes of a sewer system to the risk of sediment build-up may help in optimising the siting of these devices.

4.5. Cost optimisation

Burgess (1994) has used Markov chain theory (Rau, 1970; Benjamin & Cornell, 1970) to probabilistically model the structural condition of sewers. He evaluated a large number of potential rehabilitation strategies by attempting to minimise the following function based on the present value of all sewer condition dependent costs over the planning term, (N periods of Δt years):

$$\sum_{k=1}^{N}[T_k = R_k + W_k + C_k + I_k + O_k](1 + r)^{-k\Delta t},$$

where R_k are the rehabilitation costs, W_k the water quality degradation, C_k the damages resulting from sewer collapse, I_k the treatment of clear water entering as infiltration through pipe defects, O_k the operation and maintenance costs, T_k the total cost at each time step and r is the annual rate of interest (as a decimal). Collapse costs were computed using a failure probability (on an annual basis per unit length) assigned to each state multiplied by the average damage costs associated with observed sewer collapse incidents. A heuristic procedure was developed to minimise the above cost function and repeated iteratively until the optimal region was reduced to an acceptable size. The model was tested on the City of Hamilton Ohio, which showed that a very aggressive programme of rehabilitation was nearly as costly as the absence of a programme, demonstrating the need to optimise sewer rehabilitation planning.

Another cost optimisation methodology has been proposed by Sydney Water Corporation (Mohanathansan & McDermott, 1998) which seeks the optimal least cost solution from a range of sewer rehabilitation and treatment works extension options to reduce unacceptable high sewage overflow discharges during wet weather. The method is designed to compare every combination of sewer rehabilitation in each sub-catchment versus capacity expansion through pipe renewal and treatment plant extension (amplification). The optimal algorithm used is based on a Dynamic Programming Technique using information on design flow, existing subcatchment data, existing system component's capacity and configuration and cost functions. It does this first using a forward calculation by starting at the upstream end of the system, moving downstream and looking at each possible rehabilitation versus amplification possibility, keeping a memory of the cumulative cost of each possible option combination. Upon reaching the furthest point downstream the option with the lowest cost combination is identified and this is traced back on the decision tree to define the location and extent of the works required. The approach has been designed for planning the wider upgrading of a drainage network to meet, for example, specified percentage reductions in rainfall ingress and I/I peak flows based on a consideration of the engineering costs involved. As such it allows the possibility of testing the cost effectiveness of millions of possible improvements and option combinations, and the sensitivity of the optimal solution to strategy assumption changes.

Both of these methods are largely restricted to a consideration of engineering costs and fail to take into account social costs of disruption or customer satisfaction, which if included in an analysis may lead to a different range of optimal solutions being adopted.

5. Lessons from other buried infrastructure assets

Much related work has been carried out to determine the continuing functionality of other buried infrastructure assets, with some of the techniques described above having been pioneered, for example, on water distribution mains or gas pipelines. However some caution should be exercised in considering how transferable some of these techniques might be as failure patterns and the availability of field data are different for sewers and water pipes (Rostum et al., 1999), leading to different methods for predicting their technical state. So, for example, historical failure records for water pipes can be used directly in lifetime models which can estimate the probability a pipe will fail within a given time horizon, or counting process models which can show the deteriorating or improving trend in time of a group of "identical" pipes and their rates of occurrence of failure, (Lei & Saegrov, 1998). In contrast, sewers which have not yet collapsed but are nevertheless in a poor condition and need rehabilitation will not be identified simply from sewer failure records because only breaks which lead to complete collapse are recorded. Thus CCTV inspections will be more suitable for modelling the technical state of wastewater pipes.

5.1. Water mains

Saegrov et al. (1999) have reviewed the on-going efforts in the rehabilitation of water networks in Europe and North America. They discuss the use of statistical methods for estimating existing and future rehabilitation needs and the use of software tools for prioritising actions. The review centres on the high level of activity which has been undertaken with respect to water distribution systems, and the need to predict leakage and breaks. For example, the German "Karlsruhe Procedure" analyses failure and rehabilitation statistics to determine the length of water mains that will reach the end of their useful lifetime in future years (Herz, 1996) and can analyse the long-range effects resulting from specific rehabilitation strategies.

Over recent years there has been considerable research activity in the area of reliability assessment and improvement for water distribution networks (Xu, Goulter, & Tickle, 1998). A comprehensive review of these reliability measures and algorithms is given in Goulter (1995). Much of this work has focussed on the reliability aspects arising from the structural failure of components (e.g., Jowitt & Xu, 1993; Bao & Mays, 1990; Goulter & Coals, 1986; Wagner, Shamir, & Marks, 1988; Khomsi, Walters, Thorley, & Ouazar, 1996). Xu et al. (1998) describe two algorithms for assessing the capacity reliability of deteriorating water supply infrastructure. In USA Jackson, Gray, Padilla, and Arakaki (1999) have presented a proactive approach to water distribution system maintenance based on (i) a failure trend analysis for different categories of pipes, (ii) physical condition of extracted pipe materials and (iii) an economic break-even analysis that compares the costs associated with maintaining an existing pipe in service, to the cost of replacing or rehabilitating the pipe. On this basis the economical optimum future year to schedule a pipe's rehabilitation can be determined.

These relatively advanced techniques contrast with the comparative lack, to date, of parallel activity in developing appropriate systems for the maintenance of sewerage infrastructure. This, in part at least, is a consequence of the more limited availability of information relating to drainage networks.

Saegrov et al. (1999) argue that proactive techniques have greater "up-front" costs for the inspection, while reactive techniques imply greater "follow up" costs for the repair of failures that have occurred. If social costs, such as delayed journey times caused by a pipe failure, are taken into account, the amount of proactive maintenance that can be justified will be correspondingly increased. The outcome of any analysis to determine the most appropriate balance between proactive and reactive maintenance will be dependant on a number of critical factors which indicate a trend towards "failure". This failure may be structural or related to the performance or level of service attained by the network. Saegrov et al. note that research is required to ascertain what the critical factors are and to establish their relationships with network failures. They conclude by identifying knowledge gaps and research possibilities, mainly relating to data collection and how to best use existing data for the development and calibration of predictive deterioration models, risk assessment methods, etc.

5.2. Gas pipelines

Much work has been completed concerning priority maintenance strategies for gas pipelines in USA including estimates of probabilities of pipe defects based on asset and performance information by Kulkarni, Golabi, and Chuang (1986) and Kulkarni and Patwardhan (1990), a simple risk analysis approach using event history to predict future events (Ahmad, 1988), and the use of linear discriminant analysis to determine the probability of breakage on any pipe length (Dugovic, 1980). Harwood, St. John, and Bauer (1982) have also used discriminant analysis to rank leak prone gas mains and developed three linear models to predict future leakage rates, with varying success rates being reported. In Canada probabilistic models have been developed to assess the condition of oil and gas pipelines and to determine the optimal inspection interval and the repair strategy that would maintain adequate reliability throughout the service life of the pipe (Pandey, 1998). Cooke and Jaeger (1998) comment upon probabilistic models to find failure frequencies of underground gas pipelines and note that previous studies have developed ranking tools providing qualititative indicators for prioritising inspection and maintenance activities, but as pipelines are often quite homogenous (e.g., same material) these are not sufficiently discriminatory to be of great value.

5.3. Asset management

Rimmel (1998) describes the asset management planning of a UK electricity company and the lack of data available to evaluate the link between asset condition and business risk. He notes that present databases for overhead electricity networks have more extensive condition data than for underground mains. This is a typical picture which emerges in relation to most buried infrastructure assets. Several UK authors have described the development of asset databases and GIS systems for asset management in the water industry (Thomas et al., 1994; Glasbrook, 1994; Bainbridge, 1997; Seager & Woods, 1998; Banyard & Bostock, 1998) with, in some cases, performance indicators being used to display graphically those parts of the system performing within targets and those failing targets. The developments here again have been led from the water supply side of the industry.

6. Data requirements and challenges

Many of the approaches described earlier rely on the ready availability of reliable data about the pipe's physical attributes and its failure or performance history. With sewerage databases often not as complete as their water mains counterparts this can place significant restrictions on the level and type of analysis which can be achieved. As Cardosa et al. (1999) point out, the accuracy of any methodology cannot be greater than that of the original information about the networks state variables. The methods reviewed above cannot compensate for poorly calibrated models or other sources of data inaccuracy. Considerable efforts need to be made in standardising data records and until reliable and consistent databases are in widespread use then the methods used to drive proactive sewer maintenance need to be simple and robust within the prevailing information environment. Dangers exist of producing misleading results if models operate to a large extent on default or assumed values.

Standardisation of information is important if a widely usable decision support system, which makes use of existing information, is to be created. The storage of information in several kinds of databases presents a number of complex problems when these need to be integrated. For example, issues relating to naming variables, classifying objects and distinguishing differences in dimensions of variables often need to be resolved. Standardisation of the description of the information is therefore very useful (Van de Looij & Brouwer (1999)). Data should also be stored in a suitable digital exchange format such as the National Transfer format (in UK) which describes how to write (geo)graphic and alphanumeric data into an ASCII file, but then this data can only be subsequently read sequentially making it suitable only for off-line data exchange. In the Hierarchical Data Format the data is self-describing and can be accessed directly (binary format) making it suitable for on-line alphanumerical data exchange.

Burns, Hope, and Roorda (1999) have noted that in Australia until recently few records of public infrastructure condition and value existed, reflecting the past philosophy of "build and forget" for infrastructure. Despite recently being required to keep asset registers, only a few Australian Councils have rigorously attempted to collect all their stormwater drainage assets on a manhole-to-manhole basis recording physical attributes such as pipe and channel sizes and depths and even less have recorded manhole and pipeline condition data (Anderson, 1999). The privatisation of the water utilities in UK has driven the establishment of documentation systems for water and sewer network condition (Saegrov et al., 1999). However Fenner and Sweeting (1999) identified limitations in the storage of sewerage asset data in UK after conducting a detailed investigation of the records commonly held by drainage departments. This revealed that for the purpose of retrospective analysis the majority of historic data existed only as an address recorded on a paper record, and in many cases did not provide adequate information to automatically link a past event such as a blockage to the relevant pipe in the ground. The main sources of information identified included digitised sewer line plans, manhole cards, customer contacts data, blockage reports completed on site, individual collapse and flooding databases and OFWAT returns. The specific data fields consistently available from these sources were found to be: pipe material, sewer type, pipe size, pipe depth and event history. Other data sets such as gradient could be inferred but were not recorded in standard databases. Little systematically recorded information data was held on pipe age, soil type, pipe loading or on costs of pipe repairs. Furthermore, it was realised that design or record drawing information may be inaccurate when checked against field data and so should not be relied upon when building models as it may not be a true representation of the as built system. For a drainage management system to be of value Anderson (1999) has suggested the data requirements shown in Table 1 should be required.

The key physical attributes which need to be collected are manhole cover levels, pipe sizes, invert levels of in-

Table 1
Data requirements for a data management system

Requirements	Description
Accuracy	All pipe and channel sizes and other physical attributes are known and the connectivity of the system is confirmed
Completeness	All constructed works are identified with no gaps existing in the pipe and channel networks unless confirmed by field study
Spatially defined	The location of the network should be referenced to the cadastral or property and road base to the nearest meter for presentation of the data in a GIS and for accurate development of hydraulic models
Known system condition	Moves to condition based depreciation rather than straight line depreciation on design life make condition assessment essential
Data transfer	Information must be easily transferred to the format required by modern hydraulic modelling products and GIS software
Asset management	Business decision rules using asset condition (likelihood of failure) and asset criticality (consequences of failure) should be used to define proactive maintenance, inspection or rehabilitation programmes
Maintenance management	The drainage information system should link to a maintenance management system for recording incidents and for recording the nature of field operational work undertaken
Quality Assurance	The procedures for editing existing information or adding in more information need to be covered by sound QA and incorporate security on who can edit the data

coming and outgoing pipes and pipe material. Much important information can be collected during field visits by maintenance operatives such as the condition of manholes, overall integrity of the manhole structure, and the degree of tree roots, silt and evidence of surcharge levels. Other useful information which can help inform decision support models are:

- pipe shape,
- function/location/upstream catchment conditions,
- hydraulic load/frequency of surcharge,
- drift/underlying geology/groundwater levels,
- traffic and surface loadings,
- age/construction techniques,
- event history/frequency of CSO operation,
- years since last inspection/previous maintenance/rehabilitation history.

The most widely used method of collecting information on the internal condition of sewers is CCTV inspection. This, however, depends on the skill and experience of the operator, together with the reliability and quality of the TV picture and can be misleading because of the obscuring of vital defects such as cracks by mud.

Wirahadiskusumah, Abraham, Iseley, and Prasanth (1998) have reported on the use of other non-destructive, remote-sensing tools for diagnosing the condition of sewers. They describe an infrared thermography system used in St. Louis to locate pipeline leaks (existence of cooler surfaces), voids caused by erosion (giving a warmer signature), deteriorated pipeline insulation and poor backfill. However, a major drawback in the use of this technology is that inspection relies on the use of a single sensor and experience is crucial in interpreting the thermograms. Sonic distance measurement can also be used for sewer condition assessment to give indications of pipe wall deflection, corrosion loss and the volume of debris in the invert. This system can be used in plastic, clay, concrete or brick pipes of small or large diameters and operated in air or water (although not both simultaneously). Ground penetrating radar can provide information regarding the type of sewer material, pipe thickness and structural condition of the pipe, the condition of the sewer–soil interface (ground water and voids) as well as the condition of the surrounding soil and the presence of other nearby pipelines, (Foillard, George, & Schwarze, 1995).

A German prototype for a remotely controlled and highly manoeuvrable robot inspection system (KARO) has been designed to automatically detect the type, location and size of defects in sewer pipes (Kuntze, Schimdt, Haffner, & Loh, 1995). It carries intelligent multi-sensors for on-line sewers inspection purposes, including a three-dimensional optical sensor, ultrasonic sensors, and a microwave sensor. The system applies a sensor fusion based fuzzy-logic system for conducting damage diagnosis. The developers claim that it can detect damage up to 10 cm behind the pipe wall and is also able to detect leakage holes in adjacent soils and cracks in pipe walls, even if they are obscured by mud layers because the system is supported by air ultrasonic sensors.

Other developments in Australia have led to a new multi-sensing technology called PIRAT (Campbell, Rogers, & Gilbert, 1995). This uses an instrument system which collects the pipe geometry data and an interpretation system which detects, identifies and rates each defect. Sewer condition is automatically assessed, eliminating subjective judgements needed when using other techniques. In Japan, Sewer Scanner and Evaluation Technology (SSET) utilises CCTV, scanner and gyroscope technology (Abraham, Isley, & Prasanth, 1997). The SSET provides information including CCTV video record, a full circumference scanned image of the pipe from one end to the other, a computer generated colour coded print out of the defects together with a written description, and horizontal and vertical pipe deflections. Importantly, the machine does not have to stop within the sewer to allow the operator to assess each defect, so field work can be expedited.

Wirahadiskusumah et al. (1998) describe on-going research based on fuzzy set theory and fuzzy logic to interpret the sensor information from these systems to identify defects. In similar work, Moselhi and Shehab-Eldeen (1999) describe image analysis and pattern recognition techniques, based on a neural network analysis of digitized video images, to automate the identification and classification of surface defects in sewer pipes. Loke, Warnaars, Jacobsen, Nelen, and do Ceu Almeida (1997) have also suggested there is considerable potential for using artificial neural networks as a tool for classifying sewer defects and producing an assessment of the overall condition state of a sewer, using video inspection data.

These technological developments are extending the quality of condition information on which maintenance decisions can be based but they do not solve the fundamental problem posed at the beginning of this paper which is deciding where they should be deployed and which pipes should be inspected. It remains not cost effective to collect inspection information on pipes which are revealed to be in good condition. It is important therefore to use these tools in conjunction with some of the strategies reviewed earlier to focus on those parts of a drainage network most at risk from future failure.

In highlighting the need for better data it is essential to precisely define the objectives of any monitoring programme. As Bertrand-Krajewski, Barraud, and Chocat (2000) point out, the first question should not be "what should or can we measure?" but "what question do we want to answer?". The temptation to measure a lot of things in the hope that some meaningful conclusions can be drawn, should be avoided. Unfortunately, for both technical and financial reasons, field measurements in urban drainage systems are limited in both space and time. It follows that operational and maintenance decisions are often made on insufficient and unrepresentative data, leading to investment and operational costs far in excess of the costs of making the necessary field measurements.

7. Conclusions

A number of issues emerge from the above review. It appears that the lack of information on which to conduct a meaningful analysis of system performance is common to many (though not all) cities in Europe, Australia and North America. Whilst modern information systems are being rapidly introduced their use has often appeared to lag behind similar developments in water supply and other infrastructure assets with the emphasis too often being on data presentation rather than effective analysis. Many drainage authorities have developed their own scoring systems to indicate structural condition or hydraulic performance but these are often only applied to a small subset of the system for which inspection information is available or which are deemed strategically important or costly to repair. Increasing customer and regulatory pressures will force a more comprehensive approach in the future where sewer maintenance will need to become more proactive to protect customers from the consequences of failure on increasingly ageing networks. A range of techniques is being developed to target maintenance work most effectually, based on statistical appraisals of past system behaviour, broadly defined performance indicators to ensure acceptable levels of service are maintained, cost optimisation of rehabilitation strategies and improved understanding of the influence of the pipe structure and layout itself on contributing to blockage and flooding episodes.

The challenge for the future is to develop holistic management strategies which allow maintenance activities to be planned across all the sewer pipes in a network by achieving a greater understanding of which pipes have a greater predisposition to early failure than others. Only then can sewer maintenance activity move to a truly proactive basis from its traditional and historic reactive past.

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