SEWER NETWORK ASSET MANAGEMENT DECISION-SUPPORT TOOLS: A Review

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ABSTRACT

This paper presents a review of selected sewer asset management decision-support tools. The tools are grouped according to their functionalities and capabilities. The central concept behind each tool is described and its corresponding data requirements are identified. In addition, this paper looks into the issues surrounding the use of the current available tools and presents an outlook on further research needs in the field of sewer asset management decision-support tools.

Key words: sewer, asset management, decision-support tools

1 INTRODUCTION

Sewer network systems are considered an essential part of the urban water infrastructure, which have to be carefully operated and maintained in a rational, sustainable and scientifically based manner (Ertl and Haberl, 2006). Currently, however, many cities are being serviced by deteriorating sewer infrastructure which leaves communities vulnerable to unexpected catastrophic failures that disrupt not only sewer service but above-ground activities as well (Hahn et al., 1999).

Owing to the importance of sewer networks in the functioning of society, the current state of the networks, and given the enormous cost of replacement of these systems, actions need to be taken to restore and/or improve the systems and to prolong their service-lives; these goals can be attained with the implementation of sewer asset management systems. Similar to other infrastructure asset management, efficient information management is key to better decision-making in sewer asset management. Asset managers are required to assess critically their agency's operating environment and its competency. Moreover, they are required to make difficult decisions that have long-term and often critical consequences for their agency and/or stakeholders; decision-support tools will improve the accuracy and the soundness of their decisions (NSW Asset Management Committee, 2003). Vanier (2001) has acknowledged that engineers, technical staff, administrators and politicians all benefit if decisions about infrastructure maintenance, repair and renewal are based on reliable data, solid engineering principles and accepted economic values.

This paper provides a review of selected sewer asset management decision-support tools. The tools are grouped according to their functionalities in relation to the complete infrastructure asset management system. The central concept behind each tool is described and its corresponding data requirements are identified. In addition, this paper looks into the issues surrounding the use of the current available tools and presents an outlook on further research needs in the field of sewer asset management decision-support tools.

2 DESCRIPTION OF TOOLS

At present, there are several sewer asset management decision-support tools available. These tools are varied in their scope and focus. Figure 1 shows the currently available tools and the stages they cover in the complete infrastructure asset management system. The left-hand side of the figure shows the primary components of a complete infrastructure asset management system. The main concepts of each tool are described in the succeeding text.

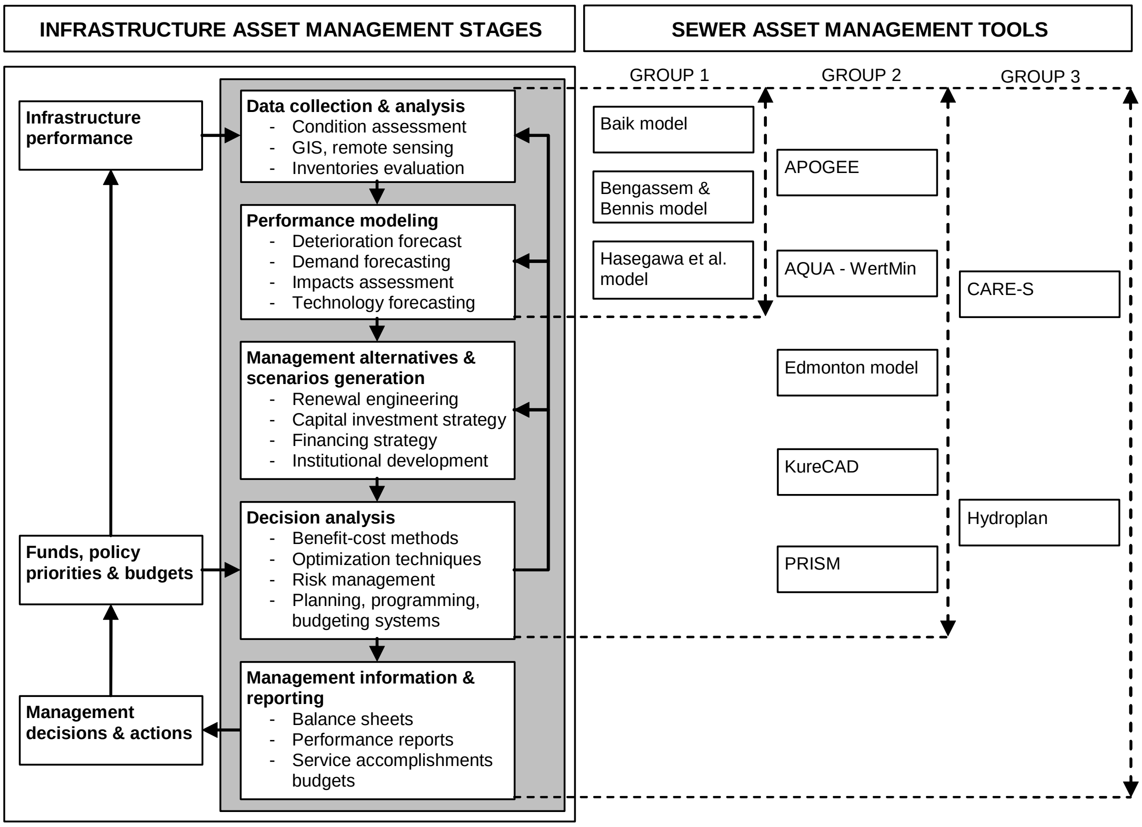

Figure 1. The generic infrastructure asset management system (Lemer, 1999) with the corresponding sewer asset management tools applicable at different stages.

2.1.1 Group 1: Performance analysis tools

The asset management decision-support tools under this category refer to those tools that deal mainly with performance modeling (Fig. 1).

Baik model (US)

The Baik model estimates the transition probabilities of different condition states in Markov chain-based deterioration models for wastewater systems, using an ordered probit model (Baik et al., 2006). The idea is to predict the future condition of the sewers so that managers can prepare inspections, rehabilitation and replacement activities in a timely and cost-effective fashion. To estimate transition probabilities, the model requires data from the condition assessments of the existing system: for structural assessment, internal inspection is required and for hydraulic assessment, models are used. Infiltration and inflow are also investigated. The pipe condition rating is calculated based on maintenance and structural points (evaluated using 108 criteria, e.g. deformation, presence of roots) from the inspection.

Bengassem and Bennis model (Canada)

This model is a systematic methodology to evaluate the structural and hydraulic conditions of a sewer system, using fuzzy inference system as an aid in the development of a rehabilitation program (Bengassem and Bennis, 2000). The method encompasses structural inspection and hydraulic simulation to evaluate the condition of the components of the sewer network. Fuzzy theory is then applied at the pipe sections level to integrate all the evaluation factors, to come up with a performance assessment of the sewer network. Three aspects are considered in the evaluation of the structural performance: 1) intrinsic (i.e. pipe defects), 2) extrinsic (i.e. pipe characteristics and environment characteristics affecting pipe degradation, e.g. geotechnical factors, hydro-geological factors and various factors including seismic or tectonic activity), and 3) site vulnerability (i.e. nature of site, soil density,...). Each pipe is then scored from 0 to 100 to indicate its condition based on the three different aspects. Evaluation of the hydraulic performance of the system is focused on the conveyance capacity of the system and is assessed using the formula of Bennis (Bennis et al., 1999), which determines the surcharge responsibility factor of a pipe.

To determine the level of performance of the sewer network, three fuzzy systems are built: a fuzzy structural system (FSS), a fuzzy hydraulic system (FHS) and a fuzzy global system (FGS). FSS and FHS calculate the structural performance index (based on intrinsic, extrinsic aspects and site vulnerability) and the hydraulic performance index (based on site vulnerability, SRF and SEF values) respectively. FGS then combines all the different factors to determine the global performance index (GPI) for each pipe section in the sewer network.

Hasegawa et al. model (Japan)

This model estimates the degree of necessity of repairs for existing sewer pipes, based on four viewpoints: 1) decrease in flow capacity, 2) road collapse possibility, 3) sewer overflow and flooding as influenced by inflow/infiltration, and 4) increase in treatment cost due to inflow/infiltration (Hasegawa et al., 1999). The degree of necessity for repair is evaluated at the pipe level.

Using the results of CCTV inspection, the reduction in flow capacity is calculated. Based on the flow reduction capacity value and on the type of pipe (i.e. sanitary or combined), the pipes are ranked into three categories: rank 1 – a little flow capacity left, rank 2 – left flow capacity is half the original one, and rank 3 – left flow capacity is more than half of the original. The possibility of road collapse is evaluated using a road collapse probability index, which was constructed based on observed pipe defects such as breakage, defective lateral, disconnected joints, etc. An index is assigned to a given sewer, based on observed defects from CCTV inspection. The sewers are classified into three categories, based on the index values: rank 1 – high possibility of road collapse, rank 2 – high possibility of road collapse if no measures are taken, and rank 3 – low possibility of road collapse. The influence of sewer surroundings is factored in the determination of the possibility of sewer collapse. Using pipe profile (age and material) and circumstances surrounding it (depth of cover, groundwater level, type of road, traffic, soil type and presence of other underground structures), pipes are assigned a rank; the possibility of road collapse is then considered to increase in proportion of this ranking. The influence of inflow/infiltration on sewer overflow and flooding is determined using a simulation model. The possibility of overflow/flooding is evaluated based on the relation of the wet weather peak flow (Q) and the design (Q_d) or maximum pipe flow (Q_{max}) capacities: rank 1 - $Q \geq Q_{max}$, rank 2 - $Q_d \leq Q < Q_{max}$, and rank 3 - $Q < Q_d$. Then, the associated increase in treatment cost for excessive inflow/infiltration is calculated. To come up with the final repair priority, the ranking of each sewer based on the four viewpoints are combined; the pipe with the highest combined rank is prioritized first.

2.1.2 Group 2: Performance and decision analyses tools

The tools under this category cover the first three stages of the complete asset management system – from data collection, to performance modeling and decision analysis (Fig. 1).

APOGEE (France)

APOGEE is a decision support system developed with the aim of optimizing the annual planning and rehabilitation of sewer networks (Rommel et al., 1989). It has three basic components:

1. *a database* – this contains relevant information gathered through inspections about the symptoms of degradation at different sections of the network;
2. *an expert system* – this makes a diagnosis on the state of the sewer network, based on the entries in the database. Its knowledge base concerns the modeling of mechanisms affecting sewer network failure based on five categories: hydrology and hydrogeology, excess loading on the network, abrasion and agressivity of the effluent, pressurized flow in the collector, and history of the

construction modes. Its inference engine is implemented in Prolog; it is capable of mixed chaining and is able to carry out reasoning based on a first order logic, i.e., predicate calculus;

3. *a planning module* – this schedules the interventions to repair the network and prescribes the manner of repair. It employs a multi-criteria approach in defining, evaluating and selecting rehabilitation actions based on technical and environmental criteria.

<u>AQUA-WertMin (Germany)</u>

AQUA-WertMin (Baur and Herz, 2001) is a computer program designed to assist utilities with the planning of TV-inspection, renovation and new construction strategies for wastewater networks. Its driving force is the application of the Herz distribution (Herz, 1996), which calculates the transition of sewers from one condition class to the next lower condition class over time. Users enter pipe condition scores into the application based on inspections (e.g. CCTV). The software then delineates pipes into six classifications: from excellent condition or no observed defects to failed pipe or needs for immediate replacement. Next, the software calculates the probability of a pipe section transitioning from one condition to the next lower condition class. As such, deterioration of pipes and future rehabilitation needs of the sewer systems is forecasted. The tool also contains modules wherein users can compare the costs of different rehabilitation strategies based on an economic analysis of costs and time of repairs.

<u>Edmonton models (Canada)</u>

Three models, each using a combination of rule-based simulation and probability analysis, were created to assist the city of Edmonton to plan its sewer maintenance expenditure (Ruwanpura et al., 2004). The main aim is to forecast the cost of repair or rehabilitation of existing pipes based solely on pipe condition. The first model uses rule-based Monte Carlo simulation to predict the condition rating (CR) of a pipe, based on pipe age, material, length and the actual probability of existence (APE). APE values are determined from constructed cumulative probability distribution curves of sewer condition ratings obtained from CCTV inspections with respect to age. The second model utilizes the Markov theory to predict the future CR (in 5 years time) of a pipe, given the current condition and considering age, type of material, length and transitional probabilities, which are based on calculated APE values. The third model pertains to forecast the present and future costs of sewer renovation, based on the results generated by models 1 and 2. The cost forecast model develops a range of costs, based on the method and costs of repair using rule-based Monte Carlo simulation. From this, the user can decide the cost of rehabilitation/replacement in the range based on the preferred confidence.

<u>KureCAD (Finland)</u>

KureCAD is a GIS-based tool for managing sewer pipe rehabilitation with the following functionalities: 1) storage of asset information, 2) sewer pipe rehabilitation prioritization, and 3) provision of documents for the implementation of rehabilitation plans (Stone et al., 2002). Data on structural condition (strength and shape), functional condition (its ability to transport water) and leakage rates (estimated leakage from the pipes) are the three basic types of data in KureCAD. Using the results from internal inspections or maintenance records, the user can specify a score, from 1 (good condition with no repairs) to 4 (very bad condition needing immediate repair). Denoting the condition of the pipe with respect to the three basic data types. KureCAD then combines the scores into one condition index and converts it to a GIS display. From this result, the assessment of the pipe condition – including sewer rehabilitation prioritization and rehabilitation strategy selection and cost calculations – can be done. In addition, KureCAD generates planning and design documentation – detailed site maps, detailed construction specifications and contract conditions – necessary to start the rehabilitation work.

<u>PRISM (Canada)</u>

PRISM (Proactive Rehabilitative Infrastructure Sewer Management) is a computerized financial outlay model for prioritizing sewer pipe rehabilitation planning, based on a horizon of budgetary constraints (Ariaratman and McLeod, 2002). PRISM minimizes capital expenditure over a planning horizon, while utilizing the full annual budgets and allocating rehabilitation investment to the most important pipe classes first; this is done with the use of linear programming. Pipe classes are defined based on age, diameter, material, waste type and average depth of cover. A deficiency probability, which is the likelihood of a sewer being in a deficient structural state derived from historical data using a log-linear statistical model, is calculated for each pipe class. To delineate two or more pipe classes with similar deficiency probabilities, a pipe importance factor is calculated based on deficiency probability, type of pipe (combined, sanitary, storm) and pipe size. The pipe class with the highest importance factor is the first one to consider in the rehabilitation planning.

2.1.3 Group 3: Total sewer asset management tools

The tools classified under this group represent total sewer asset management system that covers all the stages of the complete infrastructure asset management system (Fig. 1).

CARE-S (Europe)

CARE-S (Computer-Aided Rehabilitation of Sewer Networks) is a decision support system designed to give guidance to municipal engineers to establish and maintain an effective management of the sewer networks (Saegrov, 2006). Its ultimate goal is to ensure that only the right sewer is rehabilitated at the right time, with the application of the right technology. The CARE-S methodology in assessing the sewer network and in developing a rehabilitation plan is in accordance with EN752-5:1997 procedure (EN, 1998). The CARE-S procedure consists of four stages:

1. *initial planning* – this stage involves the establishment of the framework for sewer rehabilitation, the identification of relevant performance indicators (PIs) and the identification and prioritization of the areas to be rehabilitated. At this stage, CARE-S offers a tool generating PIs that are pertinent to rehabilitation decision;
2. *diagnostic study* – this involves investigations on structural, hydraulic, environmental and operational performances of the prioritized sewer subsystem (as determined from step 1). CARE-S offers a number of network level models and detailed pipe-specific models that allow the hydraulic (e.g. InfoWorks, FLUENT), environmental (e.g. CSO Assessment Tool) and structural condition (e.g. GompitZ, WATS 2.0) of the network to be assessed, including also their change over time;
3. *development of solutions* – the development of a possible solution to a given sewer problem as identified in step 2 involves drawing-up integrated solutions. CARE-S utilizes multi-criteria decision making tools in ranking priority pipes for rehabilitation (using Interactive Elimination Process; see Kropp and Baur, 2002) and in selecting appropriate rehabilitation techniques (using Balancing and Ranking Procedure; see Strassert, 2000). Prioritization of rehabilitation projects is based on structural, hydraulic, environmental and socio-economic criteria and other associated criteria. The selection of the rehabilitation technology is aided by the CARE-S rehabilitation technology information system, which contains an extensive database of rehabilitation and repair technologies. In addition, it has also a tool for the development of a long-term rehabilitation strategy, based on forecasted future sewer conditions, as predicted in step 2;
4. *implementing and monitoring* – this involves carrying out the rehabilitation works, implementing the operational plan, revising hydraulic and environmental models, monitoring key performance indicators (kPIs), continuing a condition inspection program, reviewing the success of the rehabilitation plan and revising the plan as necessary. To carry out these tasks, the CARE-S rehabilitation manager module provides general guidelines for their implementation.

Hydroplan (Belgium)

Hydroplan is an integrated approach to sewer asset management based on structural, hydraulic and environmental risk assessments carried out on the strategic elements of the sewerage network. The procedure (Van Herzeele et al., 2006) starts with an inventory of the current situation and historical data, to set-up an initial asset database. Next, a strategic analysis is performed at the pipe level. The pipes that will cause the greatest consequential damage in case of failure are scored based on several factors, which include financial, social and environmental damages. Weighting factors are applied to the scores to designate the global strategic level of a given sewer. After estimating the impact of failures, the probabilities of sewer failures are calculated. This is done at structural level (pipe condition) using aging models (e.g. Herz distribution) and inspection results, and at the hydraulic and ecological levels using a calibrated hydrodynamic model (e.g. InfoWorks). Scores are attributed for the different aspects of failure, according to fixed criteria, such as probability of collapse (or estimated residual lifetime), frequency of flooding, etc. The results from the strategic analysis and the failure probabilities are combined to come up with the global risk score. This step gives the set of critical pipes where proactive rehabilitation investments are most cost efficient. The final outputs of the procedure are 1) a short-term action list that would take the network to a higher performance and 2) a mid- and long-term operation and maintenance strategy that would maintain the high level of performance. The long-term investment is determined using a total life cycle model, using Monte Carlo simulations, that integrates all costs by monetizing the risks and preventive investments. The sewerage database is continuously updated with newly gathered information and the procedure is looped through to ensure the timely detection of new problems and allow better planning of most cost-effective solutions.

3 DATA REQUIREMENTS

Summarized in table 1 are the relevant data for each of the sewer asset management decision-support tools described above.

Table 1. Sewer asset management decision-support tools relevant data.

TOOLS		DATA DESCRIPTION																								
		Pipe material	Pipe age	Pipe length	Pipe diameter	Pipe thickness	Pipe shape	Depth of pipe	Type of pipe	Pipe roughness	Pipe slope	Pipe location	Condition data	Defects/ History	Flow data	Leakage rates	Soil data	Land use	Traffic/ Road	Tree location	Groundwater data	Population	Geotechnical	Type of joints	Economic data	Rehab tech/cost
Group 1	Baik	x	x	x	x			x	x		x		x		x	x	x		x		x					
	Bengassem & Bennis			x	x			x			x	x	x	x	x		x						x			
	Hasegawa et al.	x	x	x	x			x			x		x		x	x	x		x		x				x	
Group 2	APOGEE	x	x	x	x		x	x	x	x	x	x	x	x		x	x	x	x		x		x			x
	Aqua-Wertmin	x	x	x	x		x		x		x	x	x	x		x	x		x					x	x	x
	Edmonton	x	x	x	x			x					x				x						x			x
	KureCAD	x	x	x	x						x	x	x	x		x	x		x	x				x	x	x
	PRISM	x	x	x	x			x	x				x													x
Group 3	CARE-S	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
	Hydroplan	x	x	x	x		x	x	x		x	x	x		x		x	x	x	x		x				x

4 DISCUSSION, SUMMARY AND PERSPECTIVES

The adoption of sewer asset management system and the use of decision-support tools in the operation, maintenance and rehabilitation of sewer networks are seen to gain more importance in the coming years due to various reasons such as the aging of the existing systems, changes to regulations, demand for more transparency in decision-making and interfacing with customers and climate change.

Based on the review conducted, it places Europe and North America on the forefront of the development and use of decision-support tools for sewer network asset management. This is not surprising, considering the extent and age of sewer networks in these areas, not to mention the technological capability to develop such tools. However, Stone et al. (2002) note that these tools are applied only in selected areas but not on a large national scale.

The sewer network asset management decision-support tools currently available differ in their capabilities and functionalities (refer to Fig. 1). Some tools are integrated, covering data management, performance and deterioration analyses to rehabilitation plan developments (e.g. CARE-S, Hydroplan). They satisfy most of the primary requirements of a complete asset management system, as shown in Fig. 1; others are more specific and cover only part of these requirements. All reviewed tools possess data storage capabilities and most use GIS display functionalities – an important tool in the inventory of the utilities assets portfolio (Vanier, 2001). The core of most tools is the performance analysis and deterioration prediction – a crucial factor in any asset management system (Lemer, 2000); deterioration (e.g. Herz distribution, Markov chain) and hydrodynamic models are utilized to this end. A handful of tools also deal with the production of appropriate rehabilitation plans for the deficient and deteriorating sewer networks by using multi-criteria or cost analysis techniques.

In terms of complexity, most sewer asset management decision-support tools are rather complex in their architecture. The use of hydrodynamic models, deterioration models and multi-criteria analysis tools may require several persons to implement and run the system. Between utilities, US EPA (Stone et al., 2000) notes that sophisticated tools are used only by large utilities. With respect to data, most of the tools require extensive datasets. As one goes from more specific tools (e.g. performance analysis tools) to more integrated tools (e.g. CARE-S), the amount of data required increases (see Table 1). Data is always a bane when it comes to the use and implementation of these tools, as the required datasets are often not available at the utilities level. In Europe, water services data collection normally just include pipe age, length, material, diameter and location (Stone et al., 2002).

Most of the reviewed tools are products of university research, while some originate from large research consortiums. They therefore mainly reflect a research or scientific point of view (Hahn et al. (2002). In a study commissioned by the US EPA, Stone et al. (2002) have found that current prototypes of some water and wastewater asset management tools are too rigid and too complex, and often require amounts of data that are unaffordable to collect and use. This is especially true with the tools developed by large research consortiums, as different groups with specific specializations tend to develop their part to the hilt, making the whole product more complicated than it should be, while requiring enormous amount of data.

More research is therefore needed towards the development of sewer network asset management decision-support tools, specifically, "light-versions" that can easily be applied at the utilities level, requiring only available and easily obtainable data. The research should deal with finding an optimum balance between the data requirements and the results that can be obtained from asset management tools. Although good data is important, gathering and collecting them requires enormous investments. With such "light-versions", it should be possible to already take many important decisions in a sound way – a case of Pareto principle – saving the utilities scarce resources, which could be redirected to actual rehabilitation and renewal works instead of being spent on data collection alone. This development will especially be beneficial for smaller collection companies.

A different track is hereto imperative for the development of new tools: to closely coordinate with the utilities and develop tools that address their needs, based on their perspective. As the name implies, decision-support tools should facilitate discussion among decision-makers and hence should be developed in such a way that they should be able to grasp what goes on inside and what comes out of it, giving them confidence in the interpretation of the results – in other words, tools should be handy and less complicated.

In addition, due to the central role played by deterioration modeling in the success of asset management, more research has to be conducted in this field to find new ideas that would result into better understanding of the process leading to better deterioration forecasts and in more reliable tools. Parallel studies in other fields (e.g. medicine, highway engineering) can be looked into, to get ideas in the development of aging models. Research dealing with finding plausible and economical techniques for data gathering should also continue.

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