Expert System for Prioritizing the Inspection of Sewers: Knowledge Base Formulation and Evaluation

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Abstract: This paper describes the development of the knowledge base expert system denoted as Sewer Cataloging, Retrieval and Prioritization System. This computer support system prioritizes sewer pipeline inspections used to target critical areas within a sewer drainage system. This system addresses a growing need of municipalities. The sewer infrastructure of many cities is in a state of disrepair due to budgetary constraints, a history of neglect and, often most importantly, a lack of critical information about the aging and complex system of sewers that convey wastewater for 75% of the population. The knowledge base was assembled with input from a national group of experts from both the public and private sectors. Input from the experts assesses the overall need to inspect based on both the line's consequence and likelihood of failure. In turn, consequence and likelihood of failure are based on six mechanisms describing failure and two mechanisms predicting the impact of failure. Prioritization is accomplished using a Bayesian belief network that allows the uncertainty of the experts’ beliefs to be propagated through the decision process. The knowledge base is evaluated with a series of case studies and is shown to be effective at mimicking the knowledge of experts.

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Introduction

Wastewater collection and conveyance systems are extremely important, yet invisible components of our nation’s urban infrastructure. In the United States, approximately 19,000 wastewater collection systems provide service to 75% of the population (Clean 1999). Unfortunately, many wastewater collection systems are in a state of disrepair and fail to convey sewage as intended. The failings of the degraded systems burden society with possible pathogen exposure, beach closures, waterway pollution, road and building damage, and disruption of critical services and commerce. In a recent study, the EPA concludes that performance of a collection system is directly linked to the operation and maintenance (O&M) program (Arbour and Kerri 1998). Improvement of the O&M strategy for a sewer system naturally improves the effectiveness of the system.

Efficient and successful O&M programs must have detailed information with which to make informed decisions and strategic plans for capital expenditures. Sewer system evaluation surveys (SSES) are the standard for gathering such information. These surveys include activities such as closed caption television filming, flow monitoring, and manhole inspections. Performing an SSES for an entire sewer network is an expensive and time-consuming process. The budget constraints of many utilities allow only a portion of their sewer systems to be investigated annually (E. Cox, Facilities Inspection Coordinator, King County, Wash., personal interview, 1998; D. Singleterry, Portland Bureau of Environmental Services, personal interview, 2000). Therefore, it is necessary to develop inspection schedules that prioritize the system’s most critical sections (those with a high likelihood or consequence of failure) to ensure they are inspected first and frequently.

This paper presents the development of the knowledge base for an expert system that predicts the criticality of sewer pipelines. The expert system, denoted as SCRAPS (Sewer Cataloging, Retrieval and Prioritization System), considers information about the environment and state of a sewer line through an extensive set of relationships that describe failure impact mechanisms. This paper briefly discusses the constraints faced by sewer utility operators and managers and the tools developed to help these operators better manage their systems. The paper discusses the development of the SCRAPS’ knowledge base, describes the calculus used by the tool to reach a decision, and presents an evaluation of the knowledge base by examining the tool’s failure and failure impact mechanisms with a group of sewer pipeline case studies.

Existing Decision Support Tools

Little effort to date has focused on devising methodologies for gathering information about the condition of pipelines. It was not until the mid-1980s that the use of decision support tools emerged as an important element in pipeline rehabilitation. The tools range
from simple ranking algorithms to information management systems and rehabilitation models. The simplest approach is the Water Research Center’s condition assessment algorithm (WRC 1986). This algorithm has become the industry standard used in SSES, rehabilitation models, and rehabilitation plans by public utilities, regulation agencies, consulting firms, and sewer evaluation related industries (USHUD 1985; WRC 1986; Burgess 1990; Reyna et al. 1994). The algorithm is a set of simple statistical calculations that can be easily automated as demonstrated by the several software programs designed to aid in condition assessment (ADS 2000; WRC 2000).

Researchers have developed more complex tools to assist decision makers in developing rehabilitation plans. These tools have been developed primarily in academic settings and focus on the development of rehabilitation plans. Burgess (1990) developed a probabilistic Markov based model in which the specific conditions or values used in the state transition matrices are determined with a comprehensive system investigation and the WRC condition assessment algorithm. The transition matrix is updated to reflect rehabilitation performed in the system. The Multi-Attribute Rehabilitation of Sewer Systems (MARESS) model develops a rehabilitation strategy with a multiobjective optimization model (Reyna et al. 1994). Similar to the Burgess model, the MARESS model requires information from a completed sewer system evaluation survey that has been assessed using the WRC algorithm.

The most recent tool developed is an EPA benchmark study (Arbour and Kerri 1998). Similar to the previous tools, the benchmark study requires that the utility complete a system evaluation. Rather than focusing on the condition of a sewer line, the benchmark focuses on the characteristics of the system, the level of O&M activity, and the overall condition of the system. The benchmarking process allows the utility to question to compare their characteristics, activity levels, performance levels, and overall condition to these factors in other well-managed systems.

Decision support tools, such as those described here, require that the utility have information available to develop a plan for rehabilitation or to make a benchmark comparison. The tools do not incorporate advice that can inform utilities on how to efficiently collect information about their systems. SCRAPS is intended to complement the efforts of other decision support tools by providing a means to collect necessary information and target critical pipelines.

**Tool Formulation**

SCRAPS has two primary components: (1) an inference engine; and (2) a knowledge base. An inference engine defines the mathematical algorithm by which a decision is reached. The knowledge base is the body of information that represents the topic of interest. The other components of SCRAPS, a graphical user interface and a database, are developed with Microsoft Visual Basic and Microsoft Access, respectively. These components are not described here.

**Inference Engine**

SCRAPS is implemented in an expert system shell (Hugin 2000) using a Bayesian belief network (Heckerman and Wellman 1995; Jensen 2000). A Bayesian belief network is a probabilistic model that conditionally relates two or more independent variables. Relationships among variables in a Bayesian belief network are described graphically and probabilistically. Graphically, a belief network is represented as a series of nodes connected by directional arcs. Nodes represent the variables, and arcs indicate relationships among the variables (Fig. 1). The node from which the arc originates is the parent node, and it influences the node where the arc terminates, the child node.

The relationship among the connected variables is further described by conditional probabilities associated with the state of the parent variables and the child variable (Grzymala-Busse 1991; Shafer 1996). All variables have a discrete set of states (or values) that they can assume. The relationship between a set of parent variables and their child is described by the state of the parents and the conditional probabilities that relate the state of the parents to the state of the child. The conditional probabilities that describe the relationships in SCRAPS were obtained through extensive interviews with experts and through the process of system calibration.

The calculations performed in a Bayesian network inference engine propagate the uncertainty, inherent in conditional probabilities, throughout the node network. A formal description of the propagation of uncertainty is described as follows (Heckerman and Wellman 1995):

Let $Y$ be a vector which represents the set of nodes $(y_1, y_2, y_3, \ldots, y_n)$ influencing a specific node $X$. Let the states of the variable at node $X$ be defined as $X^k$. The confidence that $X$ assumes a specific value $k$ is defined as

$$p(X^k) = \sum_{i=1}^{n} p(X^k | y_i) p(y_i)$$

where $p(X^k)$ = confidence associated with the node $X$ assuming the state $k$; $p(X^k | y_i)$ = confidence that node $X$ assumes the state $k$ when causal node $i$ assumes a value of $j$; and $p(y_i)$ = confidence that causal node has assumed state $j$. 

![Fig. 1. Sewer Cataloging, Retrieval and Prioritization System relationship](image-url)
Knowledge Base

The knowledge base of an expert system is developed through a process of “knowledge acquisition.” Knowledge was acquired and incorporated into SCRAPS by domain familiarization and interviewing sewer infrastructure experts, operators, and managers. The knowledge acquisition process was facilitated with a rapid prototyping process that entailed developing a simplified prototype of the tool after each information gathering session (McGraw and Harbison-Briggs 1989). This facilitates rapid feedback of the domain experts’ suggestions and effective testing of the accuracy of the knowledge base.

Domain Familiarization

Over time, considerable effort has been invested in understanding the factors that contribute to the criticality of sewer lines. One of the most influential efforts that contributed to a lasting paradigm was the work of the United Kingdom’s Water Research Center (WRC 1986). The approach developed by WRC organized contributors in two primary groups—consequence of failure and likelihood of failure. Each of these primary groups was further divided into subgroups. This paradigm has been incorporated into the logic of rehabilitation strategies (Brown and Caldwell 1998a, b, c) and models (Burgess 1990; Reyna et al. 1994) in addition to SCRAPS’ knowledge base. Table 1 summarizes the key points in the following discussion of the factors that contribute to the consequence and likelihood of failure.

The consequences of failure (releases, overflows, and surface collapses) are assessed by considering the socioeconomic impacts and the reconstruction impacts. Because of its breadth, socioeconomic impacts are of greater importance than reconstruction impacts. Socioeconomic impacts consider the threat to human health and environmental quality and the costs associated with a loss of commerce, critical services, and sewer service.

The consequences of overflow failures are typically greater to human health than surface collapse failures, because the wastewater leaves the system in an overflow failure. Surface collapse failures are immediately evident, and efforts are made to reroute the wastewater. Human health is threatened when treatment plants, unable to treat all incoming wastewater, discharge untreated wastewater to receiving waters. Overflows prior to treatment occur at manholes in streets, public parks, private yards, and basements. The location of failures is also important. Failures expose people to pathogens if the overflow occurs in areas where people live, work, and recreate, where food is grown, or where critical services, such as police and fire protection and hospitals, are located (G. Knott, Assistant Director, Oscar Faber, Hertfordshire, U.K., personal interview, 2000).

Impacts on the environment are important and related to impacts on humans. However, from an environmental health perspective, the larger the body of water to receive the wastewater, the greater the probability the ecosystem will be able to return to its original state (E. Cox, personal interview, 1998). Therefore, streams, wetlands, and floodplain areas are the most sensitive to wastewater from overflows (EPA 1994).

Sewer failures economically impact society by limiting access to businesses, disrupting traffic, and disrupting sewer services to businesses. Locations that are economically critical are those in central business districts, suburban commercial hubs, or industrial parks. Traffic-related economic impacts result from delays in transporting people, goods, and services and the inaccessibility of businesses to customers.

Reconstruction impacts consider the costs to the sewer utility to repair or replace failed sewers. The cost of an emergency repair of a failed sewer can be two to ten times greater than that of preventative repair of a damaged sewer (B. Isaac, Senior Facilities Inspector, King County Dept. of Natural Resources, Seattle,

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Table 1. Summary of Knowledge Base

<table>
<thead>
<tr>
<th>Consequence of failure</th>
<th>Overall Structural Defects</th>
<th>Likelihood of failure</th>
<th>Overall Operational Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socio-Economic Impacts</td>
<td>Interior corrosion</td>
<td>Material</td>
<td>Erosion</td>
</tr>
<tr>
<td>Reconstruction Impacts</td>
<td>Exterior corrosion</td>
<td>Material</td>
<td>Structural defects</td>
</tr>
<tr>
<td>Human health</td>
<td>Installation history</td>
<td>Material</td>
<td>Material</td>
</tr>
<tr>
<td>Environmental</td>
<td>Wastewater temperature,</td>
<td>Soil acidity</td>
<td>Presence of</td>
</tr>
<tr>
<td>Commerce</td>
<td>Age</td>
<td>Stray currents in ground</td>
<td>Natural stream</td>
</tr>
<tr>
<td>Traffic</td>
<td>Soil type</td>
<td>Previous inspection assessment</td>
<td>Previous inspection</td>
</tr>
<tr>
<td>Groundwater levels</td>
<td>Pipe structure</td>
<td>Cathodic protection</td>
<td>assessment</td>
</tr>
<tr>
<td>Surface loads</td>
<td>Wastewater velocity</td>
<td>Previous inspection assessment</td>
<td>Known surcharging</td>
</tr>
<tr>
<td>Exfiltration</td>
<td>Previous inspection assessment</td>
<td>Known overflows</td>
<td>Previous inspection</td>
</tr>
<tr>
<td>Previous inspection assessment</td>
<td></td>
<td></td>
<td>assessment</td>
</tr>
</tbody>
</table>

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Wash., personal interviews, June 1998–January 2000). Included in these costs are: unscheduled requests for pipe materials; construction materials and equipment, such as trenching structures, bypass pumps and tunneling equipment; unscheduled requests for heavy equipment; and increase in labor requirements and resurfacing costs (G. Knott, personal interview, 1998).

The likelihood of failure is divided into the characterization of structural defects and operational defects. Structural defect failure mechanisms consider factors that cause a change in the forces that surround the pipeline or a change in the pipe material’s ability to resist forces in the surrounding soil. Operational failure mechanisms consider processes that restrict wastewater flow due to either an increase in flow or a decrease in pipe capacity.

Properly manufactured and installed pipelines can resist natural changes in their environment. However, when the forces around a pipe are not uniform or the pipe material cannot accommodate the forces, structural defects, such as cracks, fractures, broken sections, open joints, or sags, occur. Lateral support forces from the soil are more important to flexible pipe materials, because they have low tensile strength, and to brick sewers, which depend on forces normal to the pipe perimeter to keep the bricks in place (ASCE 1994).

The forces surrounding the pipe become dynamic, and the pipe material becomes vulnerable to defects when voids form in the pipeline’s surrounding soil. A poorly installed pipeline can experience settling or shifting that can create voids in the soil (Delleur 1994). The infiltration of groundwater through existing structural defects creates or increases the size of voids as the infiltrating water carries particles from the soil into the pipeline (Delleur 1994). The soil’s weakening makes the land above the pipe vulnerable to surface collapse. The effects of infiltration on void formation are made worse by the process of exfiltration. Exfiltration occurs when water leaves the sewer line through structural defects during periods of hydraulic surcharge. Surcharged wastewater can scour or loosen more fines at the perimeter of the voids (Delleur 1994; J. Zubia, Brown, and Caldwell, personal interview 1999).

Static forces in the soil surrounding a pipeline also change due to dynamic forces in or above ground. Dynamic forces that cause structural defects are large, one-time events or smaller cyclic events that occur at a variety of frequencies (daily or seasonally, for example). Large, one-time events include periods of heavy surface construction, in-ground utility construction, or nonconstruction events, such as earthquakes or landslides. These events are especially significant when coupled with weakened material or voids in the soil. Many surface collapse failures are associated with degraded but functioning sewers that fail due to a large one-time event (WRC 1986; Delleur 1994). Smaller, cyclical dynamic loads include load transfer from above ground activities, such as routine truck, machinery, bus, or train traffic or in ground movements, such as those caused by expansive soils or frost heave (E. Cox, personal interview, 1998).

Biochemical, electrochemical, and physical reactions can degrade the pipe material and make it vulnerable to structural degradation, even if the pipeline is installed properly and the risk of dynamic forces is low. These reactions lead to a thinning or weakening of the pipe material, which causes the material to lose its ability to resist the forces in the surrounding soil. The three primary types of material degradation are identified here as; (1) corrosion of the interior of the pipe; (2) corrosion of the pipe exterior; and (3) erosion of the invert.

The risk of interior corrosion depends upon the susceptibility of the pipe material to corrosion and the amount of corrosive chemicals in the wastewater. Interior pipe corrosion typically occurs from the formation and release of hydrogen sulfide. The conditions that form hydrogen sulfide are different than those that cause its release. Corrosion by hydrogen sulfide is most common in a pipeline when the conditions for forming hydrogen sulfide are upstream of the conditions that release it. Hydrogen sulfide is formed in anaerobic conditions, such as those found in force mains, continually surcharged gravity pipes, debris piles, or pools caused by sagging lines. It is assumed that anaerobic conditions exist in open channel flow at the wetted perimeter and, therefore, a small amount of hydrogen sulfide is generated, and some corrosion can occur if the conditions allow for release (ASCE 1989). Hydrogen sulfide gas is released in turbulent conditions. Such conditions occur at siphon outlets, drop structures, discharge of forcemains, interceptor intersections, a change in slope and during high wastewater velocities (J. Zubia, personal interview, 1999). Exterior pipe corrosion depends upon the susceptibility of the pipe material to acidic substances and galvanic corrosion (Delleur 1994). Acidic soils or groundwater attack unprotected cementous or metal pipe materials, whereas stray currents in the ground cause a galvanic corrosion with metal or metal reinforced pipes. Pipe materials can be protected with exterior coatings, sacrificial anodes, or other cathodic protection (P. Bellows, Vice President, Brown and Caldwell, personal interview, 2000).

The risk of erosion of pipe material is also dependent upon the material type. The materials that are at the highest risk of erosion are concrete, asbestos cement, metal, orangeburg pitchiber, and wood stave (L. Jones, Vice President, Brown and Caldwell, personal interview, 2000). Both high velocity wastewater and the presence of cobbles or manmade debris contribute to erosion of the invert of a pipe. Sources of cobbles and large destructive debris include open manholes and construction sites (WRC 1986).

Operational failure mechanisms originate from an increase in demand and a decrease in capacity. Infiltration and inflow are the two types of demand on a sewer system. A distinction is made between the two, because the processes that create them are different, as well as the processes to reduce them. Infiltration contributes to the demand on the sewer system as groundwater enters the system through structural defects. Inflow is the demand on the system from service connections and storm waters. Sanitary systems, although not designed to carry storm water, carry storm water inflow through system defects, such as manhole covers, illegal drain connections, and unintended cross connections with storm sewers. Inflow increases the demand as the number of service connections grows. For sanitary systems, inflow can also increase as the number of system defects that allow storm water to enter increase (EPA 1991; ASCE 1994). A distinction between infiltration and inflow can be seen on a hydrograph, as well. Infiltration will be constant throughout the year, whereas inflow will increase during storm events (B. Isaac, personal interview, 2000).

A decrease in capacity is the result of a decrease in the effective diameter of the pipeline and an increase in the roughness coefficient (Mannings’ number). The effective diameter is reduced by structural defects, such as open joints, broken pipe sections, root masses, or collected debris (WRC 1986). Root masses are common in areas with older trees and often enter a sewer system through service connections or defects in joints and pipe material (ASCE 1994). It is estimated that 300,000 annual blockages are attributed to root growth in the sewer lines (Urban Institute 1981). Debris accumulation also decreases the effective diameter of a pipeline. Debris accumulates in sections of the line with low velocity. More debris enters a combined sewer system, because the system intakes contain surface runoff. The high ve-
locities of combined sewer systems during storm events can scour debris from the conveyance systems, but the velocities also have the ability to move larger pieces of debris into the system. Wastewater from restaurants and industry can contain large amounts of grease and other debris, which can accumulate in pipelines and create a restriction in the line size (ASCE 1994).

**Interviewing Experts**

In addition to domain familiarization, knowledge acquisition for expert systems typically requires extensive interviews with domain experts. For SCRAPS, interviews were performed with both private and public sector experts. The private sector group contained sewer rehabilitation experts from Brown and Caldwell, Inc. This group contributed information based on extensive experience in sewer rehabilitation gained from hundreds of sewer system evaluation surveys, inspections, and rehabilitation performed in the United States and abroad. The public sector experts include sewer utility managers from one agency in Canada and seven agencies in North America: (1) Portland, Ore., Bureau of Environment Services; (2) Cleveland, Northeast Ohio Regional Sewer District; (3) Toronto, Ontario, Infrastructure Planning and Transportation Division; (4) Boston, Water and Sewer Commission; (5) Miami-Dade, Fla., Water and Sewer Department; (6) Eau Claire, Wis., Department of Public Works; (7) King County-Metro, Wash., Department of Natural Resources; and (8) Phoenix, Water Services Department. These experts provided breadth to the knowledge base, because they represented a variety of characteristics, such as age of sewer network, potential of system expansion, budget constraints, predominant system material, and soil type. Input from the public sector experts helped to build a knowledge base that considers regional issues and the budgetary constraints imposed on public decision making.

The interview process was conducted in four stages with each stage representing the contribution of one expert group and resulting in a prototype with which to test the knowledge base. In Stage 1, the interview process resulted in the private sector experts developing the initial logic scheme of the knowledge base, including the likelihood and consequence of failure concepts, failure mechanisms, impact considerations, and levels of prioritization. A graphical representation of the relationships and factors that contribute to the consequence and likelihood of failure was developed and served as a framework for the inference engine of the first prototype.

In Stage 2, an introductory questionnaire was developed based on the initial logic scheme to solicit comments from the public sector experts about the scheme and the utilities’ processes for prioritizing sewer inspection. The questionnaire contained three sections. The first section sought statistical information about sewer systems, such as size of system, percentage of pipe diameters material types and ages, and industrial contribution. The second section focused on the utility’s current inspection process. The third section defined the criteria used to rank the factors that are thought to contribute to the consequence and likelihood of failure. The questionnaire served as an interviewing tool that allowed information gained from the questionnaire, concepts, anecdotes, and lessons from previous experiences to be incorporated into the knowledge base.

In Stage 3, the knowledge base developed by the private sector experts was evaluated and refined. This stage of development focused on testing the prototype with numerous case studies to refine the relationships, redistribute priorities within the relationships, adjust the conditional probabilities, and test the overall assessment of the tool.

In Stage 4, a calibration questionnaire developed around Brown and Caldwell pipeline case studies was distributed to the public sector experts. The public sector experts were asked to comment on the tool’s results based on four criteria: (1) the assumptions and factors considered in the tool; (2) characteristics of the problem; (3) the tool’s ability to determine the consequence

![Fig. 2. Interior corrosion portion of Sewer Cataloging, Retrieval and Prioritization System belief network relationship](image-url)
and likelihood of failure; and (4) the sensitivity of the results to changes in case study characteristics. The knowledge base was calibrated based on the results of this final interviewing stage and was then validated with the following tool evaluation procedure.

**Tool Evaluation**

SCRAPS was evaluated on: (1) the two impact mechanisms that develop the prediction of the consequence of failure; (2) the six failure mechanisms that contribute to a prediction of the likelihood of failure; and (3) the tool’s decisions for consequence of failure, likelihood of failure, and the overall prediction on the need to inspect (Fig. 1). The mechanisms describing failure and its impacts were developed in great detail, but are not presented here with the exception of the failure mechanism, interior corrosion (Fig. 2), which is presented as an example of the level of detail.

**Evaluation Process Components**

A set of sewer pipeline case studies was developed with the aid of four utilities: King County-Metro, Wash.; Seattle Public Utilities; Boston Sewer and Water Commission; and the Portland Bureau of Environmental Services (Table 2). Each utility representative developed three case studies from pipelines with which they were familiar. An initial set of 12 case studies was developed using this procedure. Each case study included the tool’s decisions and its impacts which were developed in great detail, but are not presented here.

**Table 2. Description of Validation Case Studies**

<table>
<thead>
<tr>
<th>Validation Case Studies</th>
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</tr>
</thead>
<tbody>
<tr>
<td>AI—2.5 m×2.5 m (99°×99°) combined brick, built 1920. No observed overflow; groundwater varies above and below the invert; line surcharges more than once per year; high risk interior corrosion inspection assessment; structural defects; unknown surcharge; no debris; moderate resurfacing costs; and located in commercial district. 7% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>AI—0.3 m (12&quot;) combined clay, &gt;20 years old. No observed overflows; &lt;305 m (1000 feet); recent low risk interior corrosion inspection assessment; construction practices known okay; groundwater above invert; cover depth 3–12 m (10°–40°); recent moderate risk structural defects inspection assessment; no surcharge; no debris; moderate resurfacing costs; and located in commercial district. 11% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>AII—2.6 m (102&quot;) combined brick. No observed overflows; known debris but no maintenance; &gt;305 m (1000 feet); recent moderate interior corrosion risk inspection assessment; ground water varies above/below invert; surcharges &gt;once per year; expansive soil; tidal influence on groundwater; heavy surface loads; moderate risk structural defect inspection assessment; inconvenient access; high traffic levels; and located in a commercial/industrial district. 10% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>BI—0.8 m (30&quot;) poured-in-place concrete, built 1909. Portion of line is under building (elementary school); rehabilitated after inspection; moderate risk interior corrosion inspection assessment; cover depth 3–12 m (10°–40°); high risk structural defects inspection assessment; no surcharge; groundwater below invert; and located in moderate density residential area. 15% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>BII—0.3–0.6 m (10°–24&quot;) combined concrete, 1920. No observed overflows; no debris; no roots; recently rehabilitated; &lt;305 m (1000 feet); velocity 1–5 fps; no surcharge; groundwater varies above/below invert; cover depth 3–12 m (10°–40°); convenient access; moderate traffic; and located in moderate density residential. 18% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>BIII—0.4 m (16&quot;) combined clay, 1909. Root problem and insufficient maintenance; 15 years since low risk interior corrosion inspection assessment; groundwater below invert; recent high risk structural defect inspection assessment; soil type unknown; moderate resurfacing costs; convenient access; low traffic levels; and located in a high density residential area. 14% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>CI—0.4–0.5 m (16°–20&quot;) sanitary cast iron pressure, 1963. No observed overflows; no root or debris problems; &gt;305 m (1000 feet); forcemain; velocity 1–5 fps; no interior coating; recent moderate risk exterior corrosion inspection assessment; groundwater above invert; cover depth &lt;3 m (10°); inconvenient access; and located in sensitive habitat; recreation and moderate density residential. 13% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>CII—0.6–0.7 m (24°–48&quot;) combined brick ovoid, 1903. No observed overflows; root problems with insufficient maintenance; &gt;305 m (1000 feet) [forcemain]; recent low risk interior corrosion inspection; no surcharge; soil type unknown; 15 years since moderate risk structural defect inspection assessment; 5–15 years since moderate risk infiltration inspection assessment; unknown groundwater levels; tunneling required in reconstruction; inconvenient access; low traffic levels; high resurfacing costs; no redundancy; and located in sensitive habitat; low density residential; and recreational area. 15% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>CIII—1.1 m (42&quot;) sanitary ductile iron, 1984–1986. No observed overflows; known debris problems; no debris maintenance; &gt;305 m (1000 feet); low risk interior corrosion and structural defect inspection; groundwater below invert; and located in industrial/business district. 19% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>DI—0.5 m (21&quot;) combined, vitrified clay, 1919. Known debris problems; insufficient debris maintenance; low risk interior corrosion; unknown groundwater levels; recent high risk structural defects inspection; recent low risk infiltration inspection; observed subsidence; inconvenient access; and located in commercial/business district. 25% variables unknown.</td>
<td></td>
</tr>
<tr>
<td>DII—0.2 m (8&quot;) combined concrete, age &gt;20 years. Root problems with sufficient maintenance; no debris problems; &gt;305 m (1000 feet); &gt;15 years since low risk interior corrosion; infiltration and erosion inspection assessment; unknown surcharge; unknown groundwater levels; inconvenient access; no redundancy; and located in moderate environmental impact and moderate density residential. 39% variables unknown.</td>
<td></td>
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<tr>
<td>DIII—0.2 m (10&quot;) combined vitrified clay, 1906. Unknown observed overflows; root problems with sufficient maintenance; 5–15 years since low risk interior corrosion; structural defects; infiltration, and erosion inspection assessment; unknown surcharge; unknown groundwater levels; heavy surface loads; cover depth 3–12 m (10°–40°); soil type unknown; no redundancy; and located near moderately sensitive habitat, a heavily used arterial and business district. 38% variables unknown.</td>
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experienced. All twelve case studies were assessed: (1) by the author of the case study—the case study expert (CSE); (2) using SCRAPS; and (3) by the pool of experts. The pool of experts consisted of both public sector (King County, Seattle, Boston, and Portland) and private sector experts from Brown and Caldwell. For ease of comparison, the assessment of the pool of experts was represented by the average of the expert pool (AEP).

The experts were asked to assess the relationship decisions in terms of their “confidence” that the decision or mechanism is in a particular risk state (high, moderate, and low). For example, an expert could assign confidence values of 100% high, 0% moderate, and 0% low (100, 0, 0) for the operational defect mechanism if the expert was very confident that the pipeline was at high risk for operational defects (such as frequent dry weather overflows).

If the expert was confident that the risk was moderate, values of (0,100,0) could be assigned. However, if the expert was less confident that the risk was moderate and believed that there was also support (in the case study) for the pipeline being at high risk, confidence values of (20,80,0) might be assigned.

Comparisons made among the assessments of the CSE, the AEP, and SCRAPS determine if the assessments are similar, and if the assessment decisions and case studies were analyzed consistently. The test for similarity was performed by comparing the criticality of each participant’s assessment. Criticality is a single characterization of the three states’ assessments and is calculated by multiplying each of the states by a weighting factor and summing the product. The weighting factors assigned to the three states—high, moderate, and low risk—are 3, 2, and 1, respectively. For instance, a three state assessment of (20,80,0) has a criticality value of 20*3+(80*2)+(0*1)=220. A pipeline’s criticality is categorized into one of three ranges: high (300 to 250), moderate (250 to 175), and low (175 to 100).

Analysis of Similarity by Criticality Values

Fig. 3, 4, and 5 compare the criticality for the CSE (y-axis) and the AEP and SCRAPS (x-axis). Each point on the graph represents a particular assessment decision. The points represent the comparison of the criticality value of the CSE to SCRAPS (triangular points) and the CSE to AEP comparison (circular points). Pairs are identified by their case study identifier and their common y-coordinate. The area within the diagonal band on the graphs represents assessments that are “similar” to the CSE. The area below the diagonal band represents assessments that are “more conservative” than the CSE, and the area above the diagonal band represents assessments that are “less conservative” than the CSE.

Table 3 summarizes the overall performance of SCRAPS and the AEP in replicating the assessment of the CSE. The table indicates SCRAPS makes more “similar” and “more conservative” and less “less conservative” assessments than the average of the expert pool. This would indicate that overall the tool is more conservative than the average of the expert pool.
Table 3. Distribution of Criticality Values for Sewer Cataloging, Retrieval and Prioritization System (SCRAPS) and Average of Expert Pool (AEP) based on Similarity to Case Study Expert

<table>
<thead>
<tr>
<th></th>
<th>SCRAPs</th>
<th>AEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar</td>
<td>55%</td>
<td>36%</td>
</tr>
<tr>
<td>More conservative</td>
<td>37%</td>
<td>20%</td>
</tr>
<tr>
<td>Less conservative</td>
<td>8%</td>
<td>44%</td>
</tr>
</tbody>
</table>

All but case study DII (CSE criticality 220) were considered to be high criticality pipes. The cluster of points in the upper left corner of Fig. 3 shows that the set of case studies all had a high criticality for this term. In general, SCRAPS assessed the consequence of failure term similar to the CSE, whereas the AEP assessed the term less conservatively than the CSE.

In terms of criticality, all but two of SCRAPS criticality values for consequence of failure are within the similar diagonal band area. The remaining two are assessed as more conservative. The majority of the AEP criticality values are less conservative assessments. SCRAPS and the AEP assessed 92 and 58% of the case studies similar to the CSE, respectively. The more conservative assessment for case study DI by SCRAPS is attributed to the location of the pipe in a commercial district. SCRAPS considers pipe failures in commercial districts to have a high economic impact. Also, this case study is described by variables that SCRAPS assumes contribute to high reconstruction costs, such as high resurfacing costs, heavy use arterial, major by-pass pumping requirements, and unknown soil and groundwater information.

For the likelihood of failure decision, SCRAPS assessed two case studies much more conservatively, case studies CIII and BII (Fig. 4). SCRAPS’ conservative assessment for CIII is attributed to the pipeline’s overall risk for material degradation. Material degradation combines interior corrosion, exterior corrosion, and erosion. SCRAPS conservative assessment of the interior corrosion mechanism strongly influenced overall likelihood of failure outcome. The tool assessed the BII pipeline with a high criticality due to the description of high surface loads, a tidal influence on the groundwater, a history of ground movement, and previous inspection of moderate structural risk. Reasons for the assessment being more conservative than the CSE may be due to the expert’s information about the case study that is not an input value for the tool or simply the tool’s probability state values are too conservative.

For the tool to inspect decision, SCRAPS assessed two of the case studies as more conservative—BII, CSE criticality 125, and DI, CSE criticality 200 (Fig. 5). This seems reasonable for case study BII, because SCRAPS assessed the likelihood of failure as more conservative, and SCRAPS uses the result of likelihood of failure to determine need to inspect. For case study DI, however, SCRAPS more conservative criticality does not seem reasonable, because SCRAPS was similar to the CSE in its assessment of both consequence of failure and likelihood of failure. The CSE appeared to have erred, as they assessed both the consequence of failure and likelihood of failure with a high criticality value of 300, and then assessed the need to inspect with a moderate criticality value of 200.

Conclusions

The maintenance of the United States’ sewer infrastructure is a problem of growing significance. As the average age of this infrastructure increases, the more cost-effective inspections must become. Utilities’ budgets allow inspection of only a small portion of pipes annually, and it is important to develop inspection schedules that target those portions of the system that are most at risk. This paper has described the development and evaluation of the knowledge base of a decision support system developed specifically to assist small to medium sized utilities to operate and maintain their systems by focusing their inspection efforts on their most critical pipelines.

The knowledge base contained in SCRAPS is based on the WRC (1986) paradigm of assessing the pipes within a sewer system using the consequence and likelihood of failure. This basic framework has been supplemented with knowledge derived from extensive interviews with public and private sewer inspection experts. This information includes mechanisms that define key modes of sewer failures and degradation and impacts relationships. The knowledge base was developed and calibrated using over 100 case studies of sewer pipelines, then evaluated with 12 actual sewer pipeline case studies. In the evaluation process, SCRAPS’ knowledge base was shown to be adequate in assessing failure mechanisms in pipelines similar to experts. However, SCRAPS was found to be more conservative than human experts. This paper has not focused on the usability of SCRAPS in the field, which is the topic that will be explored in further studies. In addition, future calibration and validation of the model should focus on case studies that describe pipes that are not highly critical with the intent of decreasing the current conservative bias of SCRAPS.

References


Brown and Caldwell. (1998b). Large diameter sewer inspection, for City of Portland, Oregon, Bureau of Environmental Services, June.


