By Mike Homenuke, P.Eng., Infrastructure Planning Engineer, Kerr Wood Leidal Associates Ltd.

Using predictive modelling to support collection system renewal

The City of Victoria (the City) is in the process of completing a full cycle of CCTV inspections on its 500 km of sanitary sewers and storm drains, which has been managed by Kerr Wood Leidal Associates (KWL) for the past five years. The CCTV program identified a significant amount of rehabilitation work that is required due to the aging of the system. The City's sewers and drains are primarily vitrified clay pipe, and are approximately 100 years old. A long-range projection of renewal costs and understanding of risks was needed to inform decisions about how to fund sewer renewal over the long term. For this reason, KWL developed a program for evaluating different management scenarios using predictive modelling software. This will allow the City to assess tradeoffs between funding and risks of sewer failures.

Asset management context

Establishing a sustainable level of funding to maintain service levels and reduce lifecycle risk should be a key goal of all municipal sewerage and drainage utilities. The implementation of asset management programs in municipalities is making this goal easier to achieve thanks to improved data, standardized sewer condition assessments and advanced software. While condition assessments provide valuable information about the current state of assets, the long-term deterioration of sewer systems is difficult to predict without either a detailed historic record of pipe condition or use of mathematical algorithms to model deterioration over time.

In order to avoid unexpected inflationary pressures on sewer rates, asset managers must understand the long-term costs of system maintenance and renewal that are needed to maintain required service levels. This means being able to assess current service levels and costs, and also to predict future service levels and costs given a range of potential management strategies. With this capability, it becomes much easier to clearly communicate the implications of various funding and management strategies to decision makers. It should be noted that to effectively use predictive modelling in asset-related decision-making, basic asset management practices should already be in place. This is the means to collect, track and produce the necessary data to enable reliable predictive modelling.

> "Establishing a sustainable level of funding to maintain service levels and reduce lifecycle risk should be a key goal of all municipal sewerage and drainage utilities."

Predictive modelling for sewer collection systems

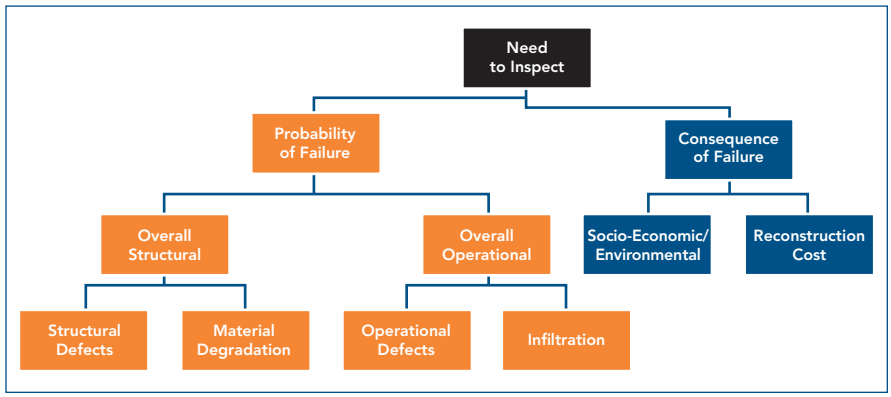
There are a number of ways to conduct predictive modelling for sewer collection systems: hydraulic models based on future populations; deterioration models such as Markov or Cox; or multi-objective approaches. Each of these different types of models describe ways that collection systems may fail, including insufficient capacity, structural failure or blockages causing backups. Generally, these all describe a likelihood (probability) of failure, and may also consider the consequence of failure. The product of likelihood and consequence is the risk of failure, which can be a way to describe the overall service level. A risk matrix, shown in Figure 1, assigns a risk level based on the likelihood and consequence of failure.

The risk matrix can be programmed into models and populated with user inputs to assign risk to individual assets within a collection system. Using advanced software, it becomes possible to develop a database to track the factors that contribute to the risk of asset failures. When linked with geographic information system (GIS), particular attributes and failure mechanisms can be mapped to provide a spatial context for issues that require attention of asset managers. Ideally, predictive models should be suitable for conducting multiple scenario analyses, which means the effort to adjust key parameters should be minimal relative to the value of the results. A sensitivity analysis is recommended for gaining a complete understanding of how certain factors may affect costs and risks. Validating

FIGURE 1: Typical Risk Matrix

Consequence		Likelihood: Low	Likelihood: High
	Low	Low Risk	Moderate Risk
	High	Moderate Risk	High Risk

FIGURE 2: SCRAPS Decision Tree Structure



predictive models is also important in order to have confidence in the results, and ensure that consistent results will be generated. One such model that fits these attributes is discussed below.

Sewer Cataloging, Retrieval and Prioritization System (SCRAPS)

SCRAPS is a software model developed by the Water Environment Research Foundation (WERF) in 2001. SCRAPS is based on a Bayesian belief network calculation engine built around a database that stores inputs and outputs. The intent of SCRAPS was to develop software that could mimic the decisions of expert sewer asset managers in determining which pipes are of the highest priority for inspection based on an assessment of the likelihood and consequences of failure. The model is based on a decision tree structure that assesses conditional probabilities at each decision node. The decision nodes are described as "child" and "parent" nodes, in which the product of the parent nodes is used to determine the conditional probability of the child node being in a high, medium or low risk state. A high-level overview of the decision tree model is shown in Figure 2.

SCRAPS breaks the decision tree into likelihood and consequence branches, which can be further broken down into structural condition, operational condition, infiltration, material degradation, reconstruction cost and socio-economic and environmental impacts. Each of these conditions are represented as a percentage likelihood of being high, medium or low risk in the results calculations for each pipe, which allows the user to understand what factors are driving the risk of failure. At the highest level, a single overall score called "Need to Inspect" (NTI) is generated, which is a weighted composite calculation. Alternately, the user may wish to refer to the likelihood of a pipe being in a high, medium, low or very low overall NTI state. These states roughly translate into a recommended inspection frequency of 2, 5, 10, and 20 years, respectively.

SCRAPS uses a data structure oriented around individual pipes, and can be used for gravity and pressure pipes, as well as storm, combined or sanitary sewers. Most of the information used by SCRAPS will come from the city GIS, CCTV data, hydraulic model and/or flow monitoring. Some pre-sorting and processing is generally needed to adapt the native format data to align with the SCRAPS data schema. A single .mdb file stores all of the inputs and outputs, which makes the software compatible with other systems and relatively simple to manage. SCRAPS includes three general data categories:

1) Pipe physical attributes and design characteristics.
2) Inspection, condition and maintenance history.
3) Pipe environmental characteristics.

The SCRAPS model was tested and validated by conducting a risk profiling exercise, in which a pool of experts (Expert Pool) was compared against SCRAPS. Twelve sewer utilities (Case Study Experts) provided examples of pipes in their systems that ranged in priority for inspection. The Case Study Experts then completed a risk profile of their own pipes, and this was used as the reference for the Expert Pool and SCRAPS comparison. The result was that SCRAPS generated similar scores as the Case Study Experts 87% of cases compared with the Expert Pool, which generated similar results in only 15% of cases.

City of Victoria case study

KWL developed an approach for using SCRAPS as a scenario analysis tool to evaluate the resulting risk of failure against a range of management strategies for the City. The overall approach was to modify the SCRAPS inputs to reflect different management strategies, and then compare the model results against the estimated costs for these strategies.

The first step in the case study was to test the impact of CCTV data. This was an important step because the scenario evaluation was based on future conditions in which CCTV data would not be available, so the model needed to perform well in the absence of this information. The model was tested by comparing the NTI results between 2009, prior to starting the latest CCTV inspection cycle, and 2014, after completing the inspection cycle. It was determined that the overall NTI ratings remained similar before and after CCTV inspections were included in SCRAPS, but the spatial distribution changed. Structural and operational condition data have a strong weighting in the SCRAPS model, as do pipe age and material. However, in this case, it was concluded that the pre-inspection results were reliable enough to use the model for future predictions in addition to assessing current risks. Figure 3 shows the change in NTI as a result of introducing the CCTV data to SCRAPS.

Next, future scenarios were developed based on 20-year projections of capital renewal and emergency repair costs. The sequence of scenarios included:

2009 Pre-Inspection
2014 Post-Inspection
2034 Run to Fail
2034 Fix Major Defects
2034 Proactive Rehabilitation

Once the baseline 2009 and 2014 cases were established, the SCRAPS inputs were adjusted to reflect 20 years of aging on the system and the different management strategies. Capital costs for inspection, sewer renewal and emergency repair costs from unplanned failures were estimated based on the current sewer condition ratings and the NTI results from SCRAPS. Table 1 provides an overview of the cost breakdown. The NTI profiles from the various scenarios are shown as Figure 4. As of 2014, about 65% of the collection system is considered high-risk. With a Run to Fail strategy, the savings from not inspecting or maintaining the system would go toward increased emergency repairs, and the number of high risk pipes would increase to about 75%. This strategy would not be recommended because the level of service decreases though the direct costs stay about the same. Fixing major defects will require a significant increase in the budget for inspection and rehabilitation, but would reduce the number of high-risk pipes to about 55%. By doubling the renewal funding yet again, the high-risk component could be reduced to as low as 40% with a pro-active rehabilitation program.

TABLE 1: Sewer System Renewal Strategies

Strategy	Includes	Inspection Cost ($000s/yr)	Rehabilitation Cost ($000s/yr)	Overall Budget ($/m/yr)
Current Baseline	Flushing, Cleaning, Inspection	350	150	1.9
Run to Fail	No Inspections or Maintenance, Emergency Repairs Only	0	400	1.7
Fix Major Defects	Continue Current Inspections + Maintenance, Fix Grade 5 Defects	400	1,000	6
Proactive Rehabilitation	Continue Current Inspections + Maintenance, Fix All Grade 2 and worse Defects	400	2,500	12

FIGURE 3: Effect of Introducing CCTV Data to SCRAPS Inputs

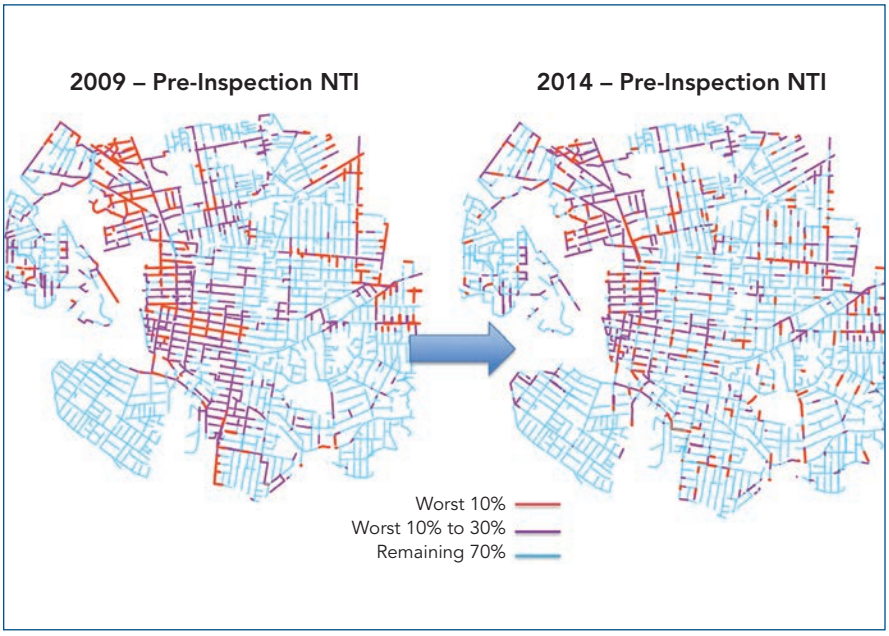
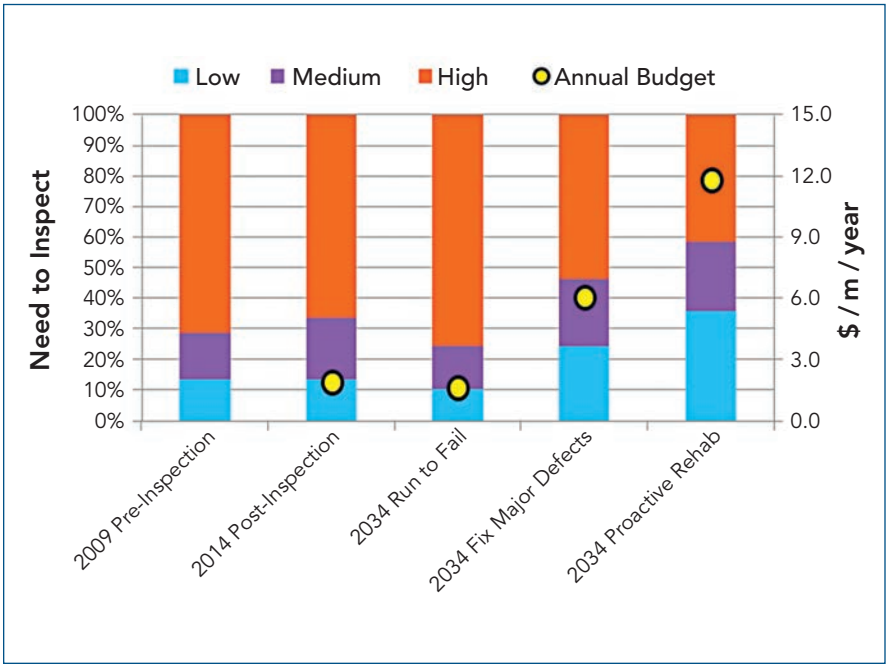


Figure 4: Need to Inspect and Cost Results for City of Victoria



Conclusion

Predictive modelling can be a useful tool for asset management practitioners as it allows for forecasting a range of service levels relative to the cost of service. This paints a clearer picture for senior managers and decision-makers in setting service and funding levels. SCRAPS offers a holistic modelling approach that lends itself well to evaluating different scenarios with a rich dataset.

Through the City case study, a proof-of-concept has been established for using SCRAPS as a predictive modelling tool. The different management scenarios establish a clear means of understanding the trade-offs between costs and service levels. The next steps will be to conduct a more detailed sensitivity analysis and extend the scenario timeline to reflect a longer-term asset management program. This will eventually lead to an optimization of funding levels that reflects the abilities of the City to fund sewer rehabilitation and the overall risk tolerance for asset failures. Since SCRAPS also provides asset-by-asset results, funding can be targeted toward the assets that are most in need based on both the likelihood and consequences of failure.

About the Author

Mike Homenuke has been with KWL since 2003, after graduating from UBC Civil Engineering (B.A.Sc.). Mike has focused his career on planning municipal utilities and energy infrastructure, and has worked on a wide range of projects including strategic planning, master infrastructure plans, feasibility studies, detailed designs and construction management. Mike's approach to infrastructure planning involves linking project outcomes to strategic objectives, with a strong focus on data, leading-edge technologies such as GIS and computational models, and management of infrastructure over the entire lifecycle. Mike's current technical focus is in developing asset management programs and long-range infrastructure plans for water, wastewater, district energy, and other municipal infrastructure.