CONFIDENTLY PREDICTING EFFECTIVENESS OF SEWER REHABILIATION

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ABSTRACT

NSCC has to date rehabilitated 32 mini-catchments, the rehabilitation effectiveness results are currently available for 14 of these catchments. Each of these mini-catchments has been rehabilitated from the outset with the view towards determining the effectiveness of the rehabilitation undertaken within the catchment. Because of this, the process and data capture has been carefully managed for the last 10 years.

NSCC now have a small database of I/I reduction results that (most importantly) has been collected and measured using the same process and methodology. A model that predicted the percentage reduction in RDII and peak wet weather flow was developed using this data. Confidence intervals were determined to help accommodate the variation in the reduction in I/I not explained by the models. The confidence intervals enable the model outputs to be used with a known degree of confidence.

Also presented within the paper are the measured reductions in RDII% and PWWF from all 14 catchments with rehabilitation effectiveness results; NSCC's current forecast of the point at which a catchment may be too watertight to achieve a significant reduction in I/I; and a thorough description of how sewer rehabilitation fits into the wider trunk sewer network cost-optimization program.

KEYWORDS

Rehabilitation, RDII, I/I, Wastewater, Sanitary Sewer, Cost Optimization, Peak Wet Weather Flow

1 INTRODUCTION

1.1 PURPOSE OF THIS PAPER

Two important questions that are almost surely asked by every wastewater network operator who has contemplated trying to reduce excessive levels of inflow and infiltration (I/I) through network rehabilitation are:

> "How much will rehabilitation reduce the inflow and infiltration (I/I) by?"
>
> "What confidence can we have that the proposed rehabilitation works will reduce I/I to our performance target ?"

This paper will discuss the work done by Methodical Enginuity and NSCC to enable NSCC to confidently predict the effectiveness of sewer rehabilitation by developing an understanding of the answer to these two questions.

1.2 PREDICTING WITH CONFIDENCE BY UNDERSTANDING THE VARIATION

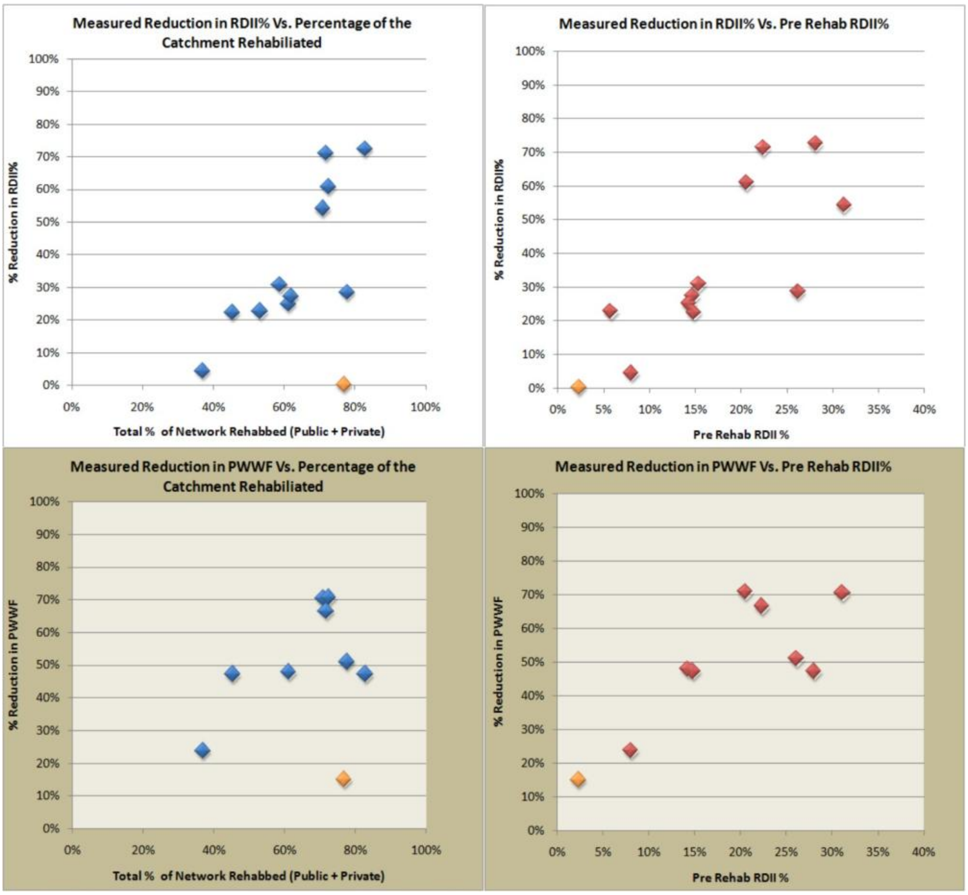
For nearly 10 years North Shore City Council (NSCC) has been actively rehabilitating the wastewater network and gathering rehabilitation effectiveness data. Rather than being run as a cause-and-effect type of study, NSCC adopted a rehabilitation methodology around 10 years ago, and has tried to consistently rehabilitate the network in the same manner in order to achieve consistent and predictable rehabilitation results. However, even after the rehabilitation methodology was kept constant, the measured reduction in I/I varied considerably (Figure 1).

The purpose of this project was to enable NSCC to confidently predict the effectiveness of sewer rehabilitation, and this meant developing an understanding the observed variation in the I/I reduction effectiveness results. Understanding the variation meant:

- Identifying the causes of variation in the effectiveness of I/I rehabilitation that could be used to predict the rehabilitation effectiveness using a model; and,

- Understanding the magnitude of the variability in the effectiveness of the I/I rehabilitation that could not be predicted, so that this variability could be appropriately accounted for in subsequent planning work.

Figure 1: Measured I/I Effectiveness Results to date show significant variation



All of the measured rehabilitation effectiveness results available to date are presented in each of these four charts (measurements with low confidence have been removed). The effectiveness is expressed in terms of the percentage reduction in RDII% and the percentage reduction in Peak Wet Weather Flow (PWWF). Significant variation in the percentage reductions can be seen in the figures. Examples include:

- *Top Left-Hand Chart: When between 70-80% of the total network was rehabilitated, the % reduction in RDII varied from approximately 25-70% (ignoring orange dot).*
- *Two Left-Hand Charts: The orange dot (mini-catchment C026-01) looks like an outlier, but;*
- *Two Right-Hand Charts: The orange dot (mini-catchment C026-01) fits the general trend.*

Conclusion: The 2D- plots only show the change in rehabilitation over one-factor (the x-axis), and therefore do not provide a complete picture of what is happening with the rehabilitation because the actual reduction is dependent on a number of factors. To get a complete understanding, a multi-dimensional view would be required. Multi-dimensional plots of the measured results were extremely difficult to visualize, and therefore have not been presented in this paper.

1.2.1 VARIATION THAT CAN BE PREDICTED

In an ideal world, if 50% of a catchment were consistently rehabilitated, the percentage reduction in I/I would be the same every time. NSCC's measured rehabilitation effectiveness however; showed that the actual reduction for any given percentage of the catchment area varied significantly. If the cause of this variation could be identified, it might then be able to be included in a model to enable better forecasts of the rehabilitation effectiveness to be made.

The initial focus of this study was therefore to identify factors that might have contributed to the measured variability in the rehabilitation effectiveness results. Once identified, the factors could be turned into predictor variables for a model to forecast the reduction in I/I through network rehabilitation.

1.2.2 VARIATION THAT CANNOT BE PREDICTED

Even complex mathematical models are but simple reflections of the physical world we live in. With something as complex as the effectiveness of sewer rehabilitation there will always be a number of physical factors that influence the actual reduction in I/I that cannot ever be realistically included in a mathematical model. Therefore, once the model to predict the effectiveness of the reduction in I/I was developed, the second focus area of the study was to develop an understanding of the variation in the rehabilitation effectiveness that could not be predicted by the model.

1.2.3 VARIABILITY SUMMARY

In summary:

- By understanding predictable sources of variation in the rehabilitation effectiveness; a better model could be produced to forecast the most likely reduction in I/I; and

- By understanding the unpredictable variation, confidence intervals could be developed around the rehabilitation effectiveness model outputs. The confidence intervals enable the model outputs to be used with confidence.

1.3 NSCC'S REHABILITATION EFFECTIVENESS DATABASE

Over the last 10 years North Shore City Council (NSCC) has rehabilitated 32 mini-catchments. A mini-catchment is NSCC's terminology for the smallest catchment that is gauged by sewer flow monitoring and is used for detailed catchment plans.

The rehabilitation effectiveness results are currently available for 14 mini-catchments. Measuring the reduction in I/I due to rehabilitation takes several years to complete, and projects are underway for all of the remaining 18 mini-catchments rehabilitated to date.

Each of the mini-catchments has been rehabilitated from the outset with a view towards determining the effectiveness of the rehabilitation undertaken within the mini-catchment. Because of this, the process and data capture has been managed carefully for the last 10 years.

NSCC now have a small database of I/I reduction results that (most importantly) has been collected and measured using the same process and methodology. Aside from the improvements in techniques and technology, NSCC's rehabilitation methodology has remained relatively consistent for the last 10 years.

Throughout the entire 10 years of the program, the following factors have been kept relatively consistent:

- The same selection criteria to determine what is and what isn't rehabilitated;

- The same companies and people doing the work;

- The same methods of rehabilitation civil work;

- The same method to measure any reduction in I/I.

As described in the previous section, even after all these factors were kept constant, the measured reduction in I/I varied considerably. However, one of the main advantages that NSCC's small database has over other studies and databases is that because the rehabilitation process has been kept relatively consistent, the causes of the variability should be somewhat easier to isolate and understand.

1.4 NSCC'S REHABILITATION CIVIL WORKS PROGRAM

1.4.1 BACKGROUND

To improve beach water quality, North Shore City Council undertook Project CARE (Council Action in Respect for the Environment) in the year 2000. A key outcome of Project CARE is a Wastewater Network Strategic Improvement Program (WNSIP) to reduce the overflows from the wastewater network caused by the Inflow and Infiltration (I/I) of rainwater into the wastewater network during wet weather events.

The WNSIP program is cost-optimized to meet the North Shore City Council's wastewater network performance target of no more than two overflows per year by the year 2021 (a 6-month Average Recurrence Interval, ARI). This target was agreed with the North Shore City community after extensive community consultation as a part of Project CARE, and continues to receive strong support from the North Shore community.

Project CARE strives to ensure the WNSIP program achieves the wastewater network overflow target at the least cost to the North Shore community. The least cost capital works are determined by a cost optimization model that assists in identifying the optimal balance between:

- Conveyance (bigger pipes and pumps);
- Storage, and;
- Reduced inflow and infiltration (by wastewater network rehabilitation).

To ensure the WNSIP program is on-track to reaching its targets, Project CARE includes a review every 6-years. This review includes an assessment of the benefits of the capital-works projects completed to date, and a revision / update of the upcoming WNSIP projects. It is this requirement for a 6-yearly review cycle that has driven NSCC to maintain a program of monitoring and measuring the effectiveness of I/I reduction for the last 10 years. It was recognized that a better understanding of the effectiveness of rehabilitation would improve the accuracy of the cost-optimization and associated network planning during the subsequent review cycles of the WNSIP program.

1.4.2 COST-OPTIMIZED WASTEWATER NETWORK REHABILITATION

The cost optimization assessment described above is undertaken city-wide for the trunk-sewer. The flow gauge catchments of the trunk sewer are relatively large, in the order of 250ha (approx. 7,000 people) (average size). In this paper, the trunk sewer flow gauge catchments are called "CARE-catchments".

The first step in NSCC's rehabilitation processes is to determine what targets were established for rehabilitation in North Shore City's optimized WNSIP program. As described above, the WNSIP program determines the most cost-optimal balance of increased conveyance; storage; and reduction in I/I at the trunk sewer level through Project CARE trunk sewer modelling and optimization. If a CARE catchment is identified for rehabilitation, the cost-optimization model will also have set a target reduction in I/I for the CARE-catchment.

A CARE-catchment may have high levels of I/I, but this does not necessarily mean that it will be recommended for rehabilitation by the city-wide cost-optimization process. If a CARE-catchment has high levels of I/I, but has not been identified for rehabilitation in the Project CARE WNSIP program, this is because it has been identified to be cheaper to accommodate the I/I via an alternate means, mostly likely either: increased capacity to the wastewater treatment plant, or by storing the wet-weather inflow in a storage tank that is emptied after the rainfall has passed.

1.4.3 THE REHABILITATION CIVIL WORKS PROGRAM

Once a mini-catchment has been identified for rehabilitation; NSCC's policy is to fully rehabilitate the network within the mini-catchment. NSCC attempts to rehabilitate all public wastewater pipes within the mini-catchment, and in addition to the public wastewater pipes, the Council inspects all the private wastewater pipes within the area.

The owners of the privately owned pipes that fail inspection are required to repair their pipes to the satisfaction of the Council. NSCC keeps records on the privately owned pipes and whether they have been repaired or not to ensure identified faults are not overlooked.

NSCC's policy to fully rehabilitate a mini-catchment was based on both extensive reviews of international literature undertaken during the year 2000 Project CARE study, and field tests under taken by NSCC. The key findings of this review were:

- The entire public network needs to be rehabilitated, because once a leak is plugged, the water will simply find the next weakest point in the network to infiltrate;

- Even pipes and manholes that appear "good" on CCTV camera can leak;

- Both the public and private networks need to be rehabilitated. Back in the year 2000, when the international literature review was undertaken, the overseas studies had found that measured reductions in the levels of I/I were "hit and miss" if the private network was not rehabilitated in conjunction with the public network.

1.4.4 DETERMINING THE EXTENT OF THE REHABILITATION REQUIRED TO ACHIEVE A TARGET REDUCTION IN I/I

1) The Project CARE catchment (the trunk sewer catchment) is broken up into many smaller catchments (called mini-catchments). The mini-catchments are flow-gauged to measure how leaky they are.

2) A hydraulic model of each mini-catchment within the CARE-catchment is built and used to calculate the RDII % and the Peak Wet Weather Flow (PWWF) in each mini-catchment;

3) The mini-catchments are ranked in order from the leakiest to the most watertight.

4) The engineer uses an I/I reduction effectiveness model to predict how much I/I will be reduced if the mini-catchments within the CARE-catchment are rehabilitated.

5) Starting with the leakiest mini-catchment, the engineer then increases the number of mini-catchments to be rehabilitated until a sufficient number of the mini-catchments are being rehabilitated in order to achieve the I/I reduction target for the CARE-catchment.

6) Physical rehabilitation of the public and private network is then carried out in the specified mini-catchments;

7) Approximately two years after the public network is first repaired, a sufficient number of the private properties will have had the identified defects repaired. At this point in time the engineer organizes flow gauges to be reinstalled in the same locations in the wastewater network that they were installed in for the pre-rehabilitation flow gauging. The purpose of this second phase of detailed (mini-catchment) flow gauging is to measure any reduction in flows due to the rehabilitation.

8) With the flows now measured, the engineer hires a specialist hydraulic modeller to build a hydraulic model of the wastewater network that will simulate the network before and after the rehabilitation work was carried out.

9) With the models built, a rainfall series with over 200 historical storms is run through the pre and post models. The outputs from the two models are then statistically analyzed to determine if any reduction in wet weather flows has occurred as a result of the rehabilitation work undertaken.

1.4.5 SUMMARY

- NSCC's trunk sewer wastewater capital works program (WNSIP) is determined by a cost-optimization model. The goal is to achieve a containment standard of no more than two wet weather overflows per year, for the minimum cost to the community;

- Rehabilitation of the network to reduce the levels of I/I is one of the options considered by the cost-optimization model. The model needs cost-benefit data for rehabilitation as an input. The rehabilitation effectiveness models described in this paper will be used to produce those cost-optimization tables.

- Trunk sewer catchments are called CARE-catchments. If a CARE-catchment is identified for rehabilitation, a target reduction in I/I will have been set for that CARE-catchment. The CARE-catchment is then broken down into smaller catchments, called mini-catchments to provide detailed information about local sewer network within.

- The sewer rehabilitation effectiveness models described in this study will be used to help NSCC plan the number of the mini-catchments that require rehabilitation in order for the CARE-catchment's target I/I reduction to be achieved.

1.5 DEFINITIONS

Different organizations attach different meanings to industry terminology. The following sections have been prepared to clarify the definition attached to the measures by which NSCC describes the leakiness of a wastewater network.

1.5.1 AVERAGE RECURRENCE INTERVAL (ARI)

The average recurrence interval (ARI) is estimated using a frequency distribution formula for a partial series, as recommended by *Australia Rainfall and Runoff (1987)*. The ARI is calculated from the rank of the event, as per the formula below:

$$ARI_{years} = \frac{n + 0.2}{m - 0.4} \tag{1}$$

Where:

n = the number of years in the simulation, and

m = rank of the particular event.

1.5.2 RDII% (THE VOLUME OF RAINFALL IN THE SEWER)

Definition: The average percentage of rainfall entering the wastewater sewer, with unit: (% rainfall)

The RDII (Rainfall Dependant Inflow and Infiltration) is the rainfall-derived flow response in a wastewater sewer network. The RDII% is the volume of rainfall dependant inflow and infiltration in the sewer during and after a rainfall event, divided by the volume of rainfall that fell in the catchment.

The formula for RDII% is:

$$RDII\% = \frac{Volume\ of\ Rainfall\ in\ the\ Sewer\ during\ the\ event\ (m^3)}{Area\ of\ the\ Catchment\ (m^2)\ \text{x}\ \text{Depth of rainfall during the event (m)}} = \frac{m^3}{m^3} = \% \tag{2}$$

The reported RDII% leakage for each mini-catchment in North Shore is the average RDII% for storms between 2-month to 2-year ARI. The ARI of storms is calculated as follows: NSCC has a predefined set of 237 rainfall events in an official 17-year rainfall time series that is used to calculate the performance of the wastewater network planning projects. The use of these same storms ensures continuity across every catchment. The RDII% volume is calculated for each of these storms. The response is then ranked, and the ranking is used to calculate the return period (ARI) of each storm.

The reason that the RDII% is calculated from the storms with an ARI between 2 month to 2 year is that NSCC considers that the errors in the calibration of the hydraulic models for storms larger or smaller than this are too large in most hydraulic modelling studies to include in the calculations.

1.5.3 PWWF

Definition: The peak wet weather flow rate from the catchment during the 6-month storm, with units: (L/sec/ha)

The Peak Wet Weather Flow (PWWF) is the peak RDII (Rainfall Dependant Inflow and Infiltration) flow during a 6-month ARI storm event. It does not include the normal diurnal flow that occurs if it is not raining, the dry weather flow (DWF). The PWWF is standardized to a per-hectare value, to enable the peak wet weather flow to be compared across catchments of any size.

The formula for peak flow is:

$$\begin{aligned} PWWF &= \frac{Peak\ Instantaneous\ flow\ rate\ during\ the\ 6\ month\ storm\ \left(\frac{L}{second}\right)}{Area\ of\ the\ Catchment\ (ha)} \\ &= L.second^{-1}.hectare^{-1} = L/sec/ha \end{aligned} \tag{3}$$

Where: The peak instantaneous flow rate is the wet weather (RDII) component of the flow only.

As for the RDII%, NSCC's predefined set of 237 rainfall events from their official 17-year rainfall time series is used to standardize the reported ARI of each mini-catchment. The instantaneous peak flow is calculated for each of the 237 storm events. The response is then ranked and the ranking was used to calculate the return period (ARI) of each storm.

1.5.4 PERCENTAGE OF "TOTAL CATCHMENT" REHABILITATED

The final rehabilitation effectiveness model developed during this project used a predictor variable that is called the "percentage total catchment rehabilitated" in this paper.

The "total catchment" was calculated from the measured percentage complete values for the public and private networks, assuming that that 50% of the total network is public, and 50% private. For example, if 100% of the public network were rehabilitated, but only 50% of the private properties had passed final inspection, then the percentage of the total catchment rehabilitated would be 75% = 0.5 (1.0 + 0.75).

Merging individually measured public and private percentage complete values into one variable makes it easier to forecast the likely reductions for planning work; as only variable, rather than two variables, are required to describe the amount of rehabilitation undertaken within a mini-catchment. While calibrating the model the actual values were available for both public and private percent complete, but no significant improvement in the fit of the model was noted when these two measurements were included separately.

2 DEVELOPING AN UNDERSTANDING OF THE VARIABILITY IN REHABILITATION EFFECTIVENESS

2.1 DATA REQUIRED FOR THE ASSESSMENT

Last year NSCC presented a paper at the 2008 NZWWA (Water New Zealand) Annual Conference describing the statistical analysis used to revise the design flow section of their wastewater network design standards. Key to the statistical analysis undertaken for this project was the development of a city-wide database that brought together the following sources of data for every mini-catchment and CARE-catchment that has been flow gauged and modelled in the city:

- The hydraulic modelling outputs that describe the hydrology of the catchment: RDII% , peak wet weather flow (PWWF), etc;
- The catchment characteristics: population, area, pipe (length, age, material, etc),
- The database includes over 200 individually flow gauged and modelled catchments from across North Shore City.

For the rehabilitation effectiveness study, this database was further built on by adding relevant rehabilitation parameters:

- The rehabilitation parameters: which pipes and houses were rehabilitated, which private properties have rehabilitation work outstanding, etc. (for all 32 mini-catchments that had been rehabilitated).
- The measured reduction in RDII% and PWWF (for the 14 mini-catchments with measured post-rehabilitation results).

2.2 IDENTIFICATION OF VARIABLES THAT ARE CORRELATED TO THE EFFECTIVENESS OF REHABILITATION

Once the city-wide database was updated with rehabilitation data, the correlation of a number of different potential predictor variables was tested by looking for statistically significant correlations to the measured reduction in the I/I. A non-parametric statistical test, called the Spearman Rank Correlation test was used for this assessment. Six or so potential predictor variables were identified at this step. The correlations of these six variables varied from “very strong” to “very weak”.

Listed from the strongest to the weakest correlation; the top six correlations to reductions in RDII% and PWWF were:

1. Pre-rehabilitation RDII% (very strong);
2. Total percentage of the catchment rehabilitation (public + private) (very strong);
3. Percentage of the private network that has passed initial inspection, or subsequent follow-up inspections (Very Strong);
4. Percentage of the public network that was rehabilitated (Very Strong);
5. Pre-rehabilitation PWWF (Strong);
6. Number of private properties with major (likely direct) sources of inflow outstanding at the time of the post-rehabilitation flow gauging (Very Weak).

2.3 MODEL DEVELOPMENT

2.3.1 INTRODUCTION

Multivariate equations can be difficult to work with, as variables can either mask or increase the apparent correlation of other variables. The true correlation of some of the variables identified in the step above may have been hidden by other variables. Because of this, even the variables with “very weak” correlations from the top six correlations identified in the previous step were brought forward into the development of the models.

The basic principle of producing a mathematical model to describe a measured relationship is to produce an equation that uses as few predictor variables as possible, while producing the best fit to the measured data.

The R-squared value is probably the most commonly used means measure the fit of a model to data. The R-squared value describes the amount of the variability in the y-axis that is described by the model. Adding variables to the model will almost always result in a higher R-squared; but can worsen the predictive ability of the model. In other words, adding variables becomes a curve fitting exercise, as opposed to a modelling exercise.

The Predicted R-square value describes the ability of the model to predict *new* values. In contrast, the more commonly used R-square describes ability of the model to predict the values used to calibrate the model. The predicted R-square value is therefore a much more important measure of the usefulness of a model.

The goal of the model-build process was therefore to optimize the predictive R-squared.

2.3.2 MODEL DEVELOPMENT METHODOLOGY

After exploring several different software packages, the decision was made to fit the model manually by developing a model in Excel. By fitting the model in Excel, greater control could be applied to the development of the model.

The number of variables included in the model was trialed using both a forward-selection and backward elimination approach. As variables were added (forward-selection) or removed (backward elimination) the value that each variable contributed to the fit of the model to the measured data was evaluated. In the case of forward-selection, variables were only added if they added value to the model; in the case of backward elimination, variables were removed from the model if they did not add any real value to the fit of the model to the data. In additional to trialing numerous combinations of variables, the form of the equations (i.e. linear Vs. quadratic) was also changed. The goal during this process was to improve the fit of the model to the data.

For each of the trial solutions described above, Excel’s Solver was used to adjust the coefficients of the equation to try to fit each model to the measured data. Boundary conditions were used to ensure that the solver could only derive sensible and valid solutions.

The boundary conditions applied were chosen to have as little influence on the final fit of the model as possible; such that their main influence was to ensure a valid answer. Examples of the boundary conditions used include:

- That the percentage reduction cannot be greater than 100%;
- That the percentage reduction must not decrease as the percentage work increases;
- That the percentage reduction should be a positive number;
- For a constant amount of rehabilitation work the post rehabilitation RDII% must not decrease as the initial RDII% increases;
- The model should pass through the origin, i.e.:
    - If no rehabilitation is carried out then the percentage reduction must equal zero;
    - If the initial leakiness (or the initial peak flow) is zero then the percentage reduction must equal zero.

Many of the combinations of model form and variables failed to meet these simple boundary conditions, or met the boundary conditions but did not come close to providing a respectable fit to the measured I/I reduction results. This helped to narrow down the number of equations.

2.3.3 THE RELATIONSHIP BETWEEN THE MOST AND LEAST LEAKY MINI-CATCHMENTS

Within a CARE-catchment there will always be some mini-catchments that are leakier than average; and some mini-catchments that are less leaky than average. Because NSCC's policy is to rehabilitate the mini-catchments in the order of leakiness, starting with the leakiest mini-catchments first; until such time as the Project CARE rehabilitation target is reached; the relationship between the most leaky mini-catchment and the least-leaky mini-catchment within a CARE catchment needed to be understood.

There are typically between 8 – 12 mini-catchments within a CARE-catchment. The relationship between the most-leaky and the least-leaky mini-catchments was developed by:

1. Ranking each mini-catchment within a CARE catchment in the order from most to least leaky. This exercise was undertaken citywide, for all 216 mini-catchments for which results are currently available.

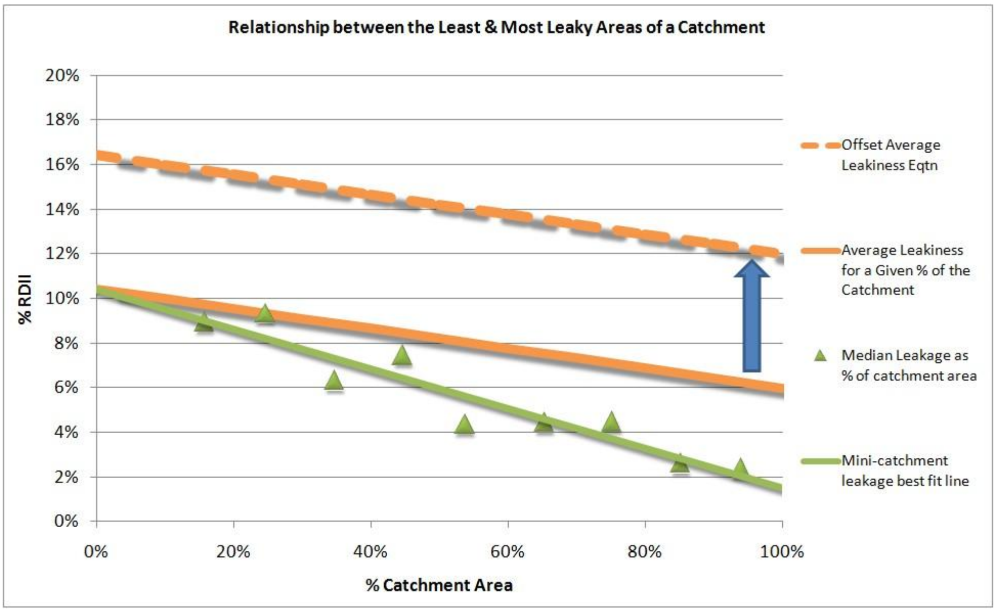
2. The ranked mini-catchment RDII leakage values were then pro-rated into 10% intervals between 0% and 100% of the CARE-catchment area, with 0% of the CARE-catchment being allocated the most leaky mini-catchment and 100% being allocated the least leaky mini-catchment.

3. Twenty-three CARE-catchments have been modelled to date, and so, there were 23 data-points in each 10% interval after this process was complete. The median leakage for each interval was then calculated. The median values are plotted in Figure 2, as the green dots.

4. A line of best-fit was determined for the median leakage rates (the continuous green line, Figure 2). This line of best fit was then used to calculate the average leakage in a CARE-catchment for any given percentage of the CARE-catchment (when working from the most to least leaky areas of the CARE-catchment). The average leakage is plotted in Figure 2 as the continuous orange line.

If one assumes that the ratio between the most-to-least leaky mini-catchments holds approximately true for all CARE-catchments (large or small; leaky or watertight) in the city; then the average leakage line can be offset to the measured RDII% for any CARE-catchment in the city. By offsetting the line, it is possible to estimate how leaky the mini-catchments within the CARE-catchment will be, even if the mini-catchments have not yet been measured. An example is provided in Figure 2.

Figure 2: Most to Least Leaky Relationship within a Catchment



Example: The RDII% of a CARE-catchment was measured to be 12% at 100% of the CARE-catchment area. By offsetting average leakiness line to the measured 12% RDII at 100% of the catchment (the discontinuous orange line) we can now estimate that the average leakage of mini-catchments in our example CARE-catchment: the worst (in terms of leakage) 20% of this catchment is estimated to have an RDII% of just under 16% RDII, and the worst 60% of the CARE-catchment will have a leakage of just under 14% RDII.

The mathematical equation that described the offset average leakage line is:

$$\text{Offset average leakiness} = \text{Effective RDII\%} = -0.0445x + 0.4445 + \text{RDII (at 100\% of the catchment area)} \quad (4)$$

The final models use Equation 4 to offset the Initial RDII when rehabilitating less than 100% of the catchment area. A better fit to the measured mini-catchment rehabilitation effectiveness was noted when Equation 4 was included in the modelling. Based on this, it was decided that it was possible to use the same equations for predicting the effectiveness of I/I for both mini-catchments and CARE-catchments.

2.3.4 DETERMINING THE FINAL MODEL FORM AND PREDICTIVE VARIABLES

After following through literally hundreds of combinations of alternate model form and predictive variables for both the RDII and Peak Flow Reduction models; a handful of the models remained. These models all met the boundary conditions and visually had a reasonable fit to the measured data as well as with reasonable R-squared values.

The final models were evaluated by calculating the predictive R-squared value of the model. The model with the highest predicted R-squared and lowest standard error of prediction was selected for the project.

Example: The measured rehabilitation effectiveness showed a strong correlation to the pre-rehabilitation PWWF, and it improved the R-squared fit of the models to the measured reductions. However, the ability of the rehabilitation effectiveness models to predict new data was found to be worse when the pre-rehabilitation PWWF was included as a predictive variable in the model. For this reason, the pre-rehabilitation PWWF was not included in the final models.

3 SEWER REHABILITATION EFFECTIVENESS MODELS

3.1 OVERVIEW

Two rehabilitation effectiveness models were developed:

- A model to predict the likely reduction in RDII % (the percentage of the total rainfall falling in the catchment that enters the wastewater sewer); and,

- A model to predict the likely reduction in peak wet weather flow (L/sec/ha).

3.2 VARIABLES THAT CAN BE USED TO PREDICT THE EFFECTIVENESS OF THE REHABILITATION

During the model build process (Section 2.3) it was identified that just two variables could be used to provide a reasonable prediction of the reduction in RDII% and PWWF. The two variables were:

- The percentage of the total (public + private) network rehabilitated;

- The initial leakiness of the catchment (measured in RDII%);

The relationship between the most leaky and least leaky areas within a catchment is taken into account within the model; and is also described using the same variables: initial RDII% and the percentage complete.

3.3 PERCENTAGE COMPLETE AS A PREDICTOR VARIABLE

NSCC's rehabilitation policy was to rehabilitate 100% of a mini-catchment. It had been assumed by NSCC until quite recently that the rehabilitation teams were getting very close to this 100% figure. A review of NSCC's databases showed however, that this was not the case. The statistics on the percentage complete to date are:

- The average percent complete in a mini-catchment for the public network is 58%, the maximum 90%.
- The average percent complete in a mini-catchment for the private network is 69%, the maximum 96%.
- The average percent complete for the total network (public + private) in a mini-catchment is 64%, the maximum 83%;

(Note: these statistics include all 32 mini-catchments that have been rehabilitated, not just the 14 mini-catchments for which measured effectiveness is available).

These figures suggest that despite the rehabilitation team's best efforts, it may not be possible to rehabilitate 100% of a mini-catchment. It was recommended to NSCC that the planning engineer now include an assumption about the percentage of each mini-catchment that can be rehabilitated within their calculations, while determining the number of mini-catchments that need to be rehabilitated to reach the WNSIP I/I reduction target for the CARE-catchment.

3.4 INITIAL RDII% AS A PREDICTOR VARIABLE

The initial (pre-rehabilitation) RDII% was the strongest determinant of the effectiveness of the rehabilitation. It was noted that the law-of-diminishing returns starts to take a significant effect at around 15% RDII, for both the RDII% reduction and the PWWF reduction models. This observation can be seen in Figures 3 and 4, in that the percentage reduction drops off more steeply below 15% RDII.

3.5 RDII PERCENTAGE REDUCTION MODEL

The RDII% percentage reduction model was expressed by the equation:

$$\begin{aligned}\text{RDII \% Reduction} &= Initial\ RDII\ factor \times \ Percentage\ Complete \\ &= (0.257Ln(-0.0445x + 0.0445 + RDII_{Pre}) + 0.988) \times x^{1.055}\end{aligned} \tag{5}$$

Where: x is the Percentage Complete (the percentage of the total catchment (pubic + private networks) that has been rehabilitated)

The solution space of the RDII reduction effectiveness equation and fit of the model to the measured RDII reduction is depicted in Figure 3 and Figure 5 on the following page.

The components that make up the RDII% percentage reduction model are:

- The *Initial RDII factor* is a logarithmic equation that describes how the effectiveness of the rehabilitation changes as the RDII% changes.

$$Initial\ RDII\ Factor = a.\ Ln\ (Effective\ RDII\%) + b \tag{6}$$

- The *Effective RDII%* is the effective leakage of the area that is rehabilitated within a CARE-catchment or mini-catchment, as described in detail in Section 2.3.3.

  $$\text{Effective RDII\%} = -0.0445x + 0.4445 + RDII_{Pre\text{-}rehabiliation} \tag{7}$$

  Where:

  - x is the Percentage Complete (the percentage of the total catchment that has been rehabilitated)
  - $RDII_{Pre\text{-}rehabiliation}$ is the measured RDII for the catchment (CARE or mini).

- The *Percentage Complete* is described using a power equation; however the coefficient, c in the equation below drops out in the final model (Equation 5):

  $$\text{Percentage Complete} = c \cdot x^{d} \tag{8}$$

3.6 PEAK WET WEATHER FLOW PERCENTAGE REDUCTION MODEL

The PWWF model was the same as the RDII% model, just with different coefficients:

$$\begin{aligned}\text{Peak Flow \% Reduction} &= Initial\ RDII\ factor \times\ Percentage\ Complete \\ &= (0.303 Ln(-0.0445x + 0.0445 + RDII_{Pre}) + 1.163) \times x^{0.761}\end{aligned} \tag{9}$$

Where: x is the Percentage Complete (the percentage of the total catchment that has been rehabilitated)

The solution space of the PWWF reduction effectiveness equation and fit of the model to the measured PWWF reduction is depicted in Figure 4 and Figure 6 on the following page. Because the same components of the equation make up the PWWF percentage reduction equation, they have not been repeated here.

Figure 3: RDII% Percentage Reduction Model Solution-Space

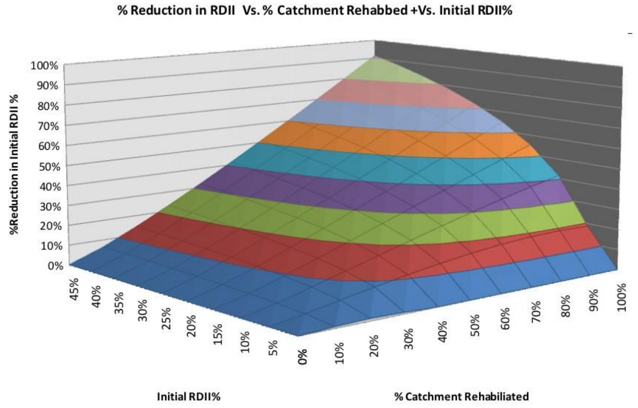


Figure 3 depicts the 3D-model solution space of the RDII% percentage reduction model. The relationship between the initial RDII% and the percentage of the catchment that is rehabilitated can be seen.

Figure 5: Measured Percentage Reduction in RDII% Vs. The Modelled Percentage Reduction in RDII%

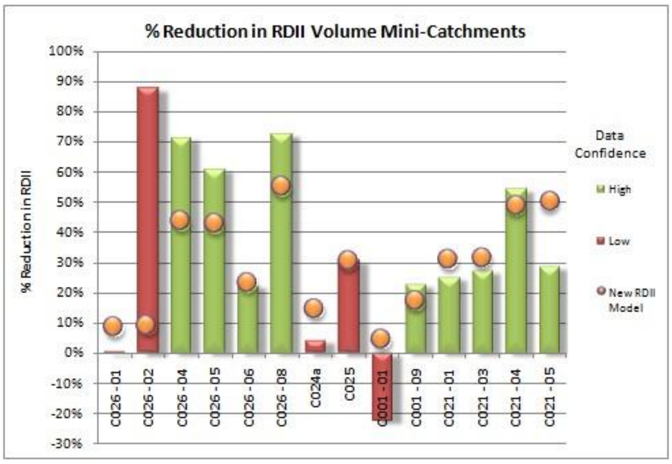


Figure 5 depicts the measured <u>percentage</u> reduction in RDII% vs. the fit of the model to the data.

Each column represents a mini-catchment that has been rehabilitated, flow gauged and hydraulically modelled; and from this, the I/I reduction effectiveness measured. The confidence in the measured results is indicated by the colour of the columns.

The RDII% rehabilitation effectiveness model (Equation 5) is plotted on the chart by the orange circles. The model was fitted to the mini-catchments with "good" confidence in the measured results.

The model can be seen to be under-predicting the mini-catchments in CARE-catchment C026, denoted by the C026 in first-half of the mini-catchment's ID.

Figure 4: PWWF Percentage Reduction Model Solution-Space

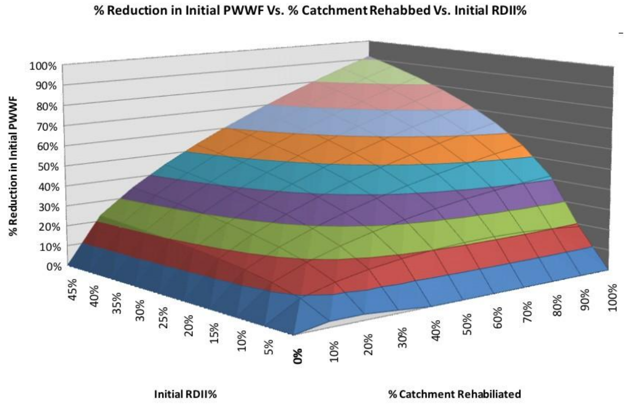


Figure 4 depicts the 3D-model solution space of the PWWF percentage reduction model. The relationship between the initial RDII% and the percentage of the catchment that is rehabilitated can be seen.

The PWWF model indicates that there are large reductions to be achieved from rehabilitating the first 20% of a mini-catchment. In contrast, the RDII reductions are more linear, increasing steadily as the percentage complete increases.

Figure 6: Measured Percentage Reduction in PWWF Vs. The Modelled Percentage Reduction in PWWF

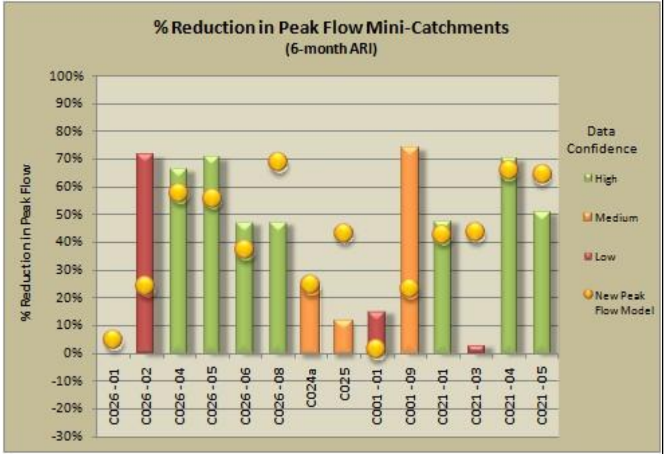


Figure 6 depicts the measured <u>percentage</u> reduction in PWWF vs. the fit of the model to the data.

Each column represents the 14 mini-catchments with measured I/I reduction effectiveness results. The confidence in the measured results is indicated by the colour of the columns.

The percentage reduction in PWWF as calculated by the PWWF model (Equation 9) is plotted on the chart by the orange circles. The model was fitted to the green coloured mini-catchments.

4 UNDERSTANDING THE MODEL PREDICTION CONFIDENCE

4.1 ABILITY TO PREDICT THE VARIABILITY

Two models to predict the effectiveness of sewer rehabilitation were developed. One model predicted the percentage reduction in the RDII% (the volume of rainfall) and the other, the percentage reduction in the peak wet weather flow (PWWF).

Because the models were fitted to a relatively small number of measurements (Section 3); the confidence intervals of the model predictions will be relatively wide, and therefore need to be considered when using the I/I reduction effectiveness model's outputs.

4.1.1 THE RDII REDUCTION MODEL PREDICTION CONFIDENCE

The RDII reduction model had:

- An R-squared of 0.75;
    - In other words, the RDII reduction effectiveness model was replicating 75% of the variability in the measured RDII reduction data that it was calibrated to;
- A Predicted R-squared of 0.59.
    - In other words, the RDII reduction effectiveness model was able to predict 59% of the variability in the new data;
- Standard Error of Prediction of 0.16
    - In other words, we have 68% confidence (the first standard deviation) that the actual reduction in RDII will lie within ±0.16 (i.e. ±16%) of the predicted value.

4.1.2 THE PWWF REDUCTION MODEL PREDICTION CONFIDENCE

The 6-month ARI peak wet weather flow (PWWF) reduction model had:

- An R-squared of 0.81;
    - In other words, the PWWF reduction effectiveness model was replicating 75% of the variability in the measured RDII reduction data that it was calibrated to;
- A predicted R-squared of 0.76.
    - In other words, the RDII reduction effectiveness model was able to predict 76% of the variability in the new data;
- Standard Error of Prediction of 0.125
    - In other words, we have 68% confidence (the first standard deviation) that the actual reduction in PWWF will lie within ±0.125% (i.e. ±12.5%) of the predicted value.

4.1.3 MODEL ACCURACY DISCUSSION

Clearly, the measures of model accuracy outlined in Section 4.2.1 indicate that the RDII and PWWF reduction models are, by no means "accurate". Nor would, with only 11 measurements to base the models on; your pragmatic engineer expect great accuracy.

The important point to stress is it is not the accuracy of the models which matters, but rather it is the understanding of the confidence intervals of the models that is important. When the confidence intervals are understood, the engineer can make informed decisions on the relative risks associated with undertaking a rehabilitation project.

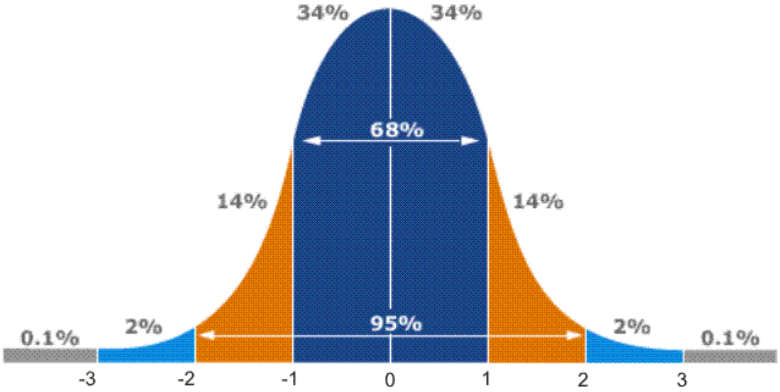
4.2 ONE-SIDED PROBABILITY CURVE

Business men and women spend their lives worried about success. Engineers on the other hand, typically spend their lives more concerned about failure, than success. But the glass half-empty engineer is usually a happy engineer, because very few people will complain if the widget that he/she designed lasts longer, or performs better than promised. On, the other hand people get upset if a product breaks down prematurely, or does not perform as well as it was supposed to.

The operation of a wastewater network is usually measured by its mean time between failure. NSCC's wastewater network is required to overflow due to rainfall no more than 2-times per year, on average. If a rehabilitation project is commissioned and the reduction in I/I is better than forecast, then there will be additional capacity in the network for future generations and / or potential other follow-on cost savings for the community. However, if the rehabilitation project does not reduce the I/I by the anticipated amount, there may be cost-implications to bring the network up to standard using other means and/or a failure to comply with resource consents; as well as implications for the environment and thereby the community.

As such, the model prediction confidence intervals can be taken to be one-sided. This means that the engineer can be approximately (see the paragraph below) 84% confident that the actual reduction will be better than the predicted reduction from only one standard-deviation away from the model's predicted reduction (100% - 0.1% – 2% - 14% = 84%, Figure 7). Within two-standard deviations of the modelled reduction, it is possible to be (around) 97.5% confident of bettering the forecast reduction.

Figure 7: A Standard-Normal Probability Curve



These confidence intervals assume that the data is normally distributed. We do not have enough data to be able to confirm that the data or the model predictions are normally distributed; however, even if they are not normally distributed, the overall effect on the confidence intervals is likely to be small in comparison to the relatively large error margins already attached to the model's predictions. Given the lack of sufficient data to confirm normality; the advantages in terms of simplifying the understanding and usability of the results; and lastly, the likely small effect (in relative terms) that a non-normal distribution would have on the model confidence intervals, we have for the purposes of this project, assumed the data to be normally distributed.

4.3 CALCULATION OF THE PREDICTION CONFIDENCE INTERVALS OF THE MODEL

The PRESS (PREdiction Sum of Squares) statistic is the sum of square of the deleted residuals:

$$PRESS = \sum_{i=1}^{n} \left(y_{(observed)i} - y_{(predicted)i} \right) \tag{10}$$

The standard error of the prediction is the square root of the PRESS statistic divided by the degrees of freedom:

$$Standard\ Error\ of\ Prediction = \sqrt{\frac{PRESS}{n-2}} \tag{11}$$

The Predicted R-squared is calculated by:

$$R^2(pred) = 1 - \left(\frac{PRESS}{SStotal} \right) \times 100 \tag{12}$$

The sum of squares total is calculated by:

$$SS_{tot} = \sum_{i} (y_i - \bar{y})^2 \tag{13}$$

Where: y(bar) is the average of the observed values.

4.4 WHAT CONFIDENCE CAN WE HAVE THAT THE PROPOSED REHABILITATION WORKS WILL REDUCE INFLOW AND INFILTRATION TO OUR PERFORMANCE TARGET?

The RDII and PWWF reduction models track through the middle of the measured reductions in RDII and PWWF, in other words; the models predict the most-likely reduction in RDII and PWWF, and the actual measured reductions are evenly displaced either-side of the model. As such, the actual reduction will be more than the predicted reduction 50% of the time, and less than the predicted reduction 50% of the time.

As described in the previous section, the engineer is likely to only be concerned about the actual reduction being less than the predicted reduction. Therefore, the engineer can be 50% confident that the actual reduction will be better than the predicted equation.

By subtracting off the standard error of prediction from the modelled reduction, the engineer can be 84% confident that the actual reduction will be better than the calculated reduction.

For example: The RDII model has predicted a reduction of 50% in RDII%, the standard error of prediction for the RDII model is 16%. Therefore the engineer can be around 84% confident that the actual reduction due to the rehabilitation works will be better than 34% (50-16%).

5 PRACTICAL APPLICATION OF THE SEWER REHABILITATION EFFECTIVENESS MODEL

5.1 WASTEWATER NETWORK COST-OPTIMIZATION

NSCC required cost-benefit tables to be developed as inputs into their cost-optimization model, as a part of their Project CARE 2006 review of the wastewater network strategic improvement program, WNSIP. The RDII% and PWWF reduction effectiveness models were used to calculate the percentage of the CARE-catchment that required rehabilitation in order to achieve a target reduction in RDII and PWWF.

By multiplying the percentage of the CARE-catchment requiring rehabilitation by the unit-rate cost of rehabilitation, NSCC's cost-optimization model could determine the cost of reducing the initial RDII or PWWF to a lower rate of leakage. Repeating this process for the first standard error of prediction enabled an assessment of the cost-sensitivity of rehabilitation options to be assessed. Table 2 on the following page provides an example.

Depending on the outcomes of the 2006 WNSIP cost re-optimization, many more mini-catchments may yet be rehabilitated. The cost of the city-wide WNSIP program to achieve the same level of service across the city will be estimated by using the 50% confidence interval outputs. The cost-sensitivity analysis is used by NSCC's planning engineers on a mini-catchment by mini-catchment basis, to ensure that the most-robust options are selected through the cost-optimization process.

5.2 PREDICTING MINIMUM RDII% AND PWWF THRESHOLDS FOR REHABILITATION

Because the effectiveness of rehabilitation is determined by the initial RDII% for both the RDII% and PWWF models; at some point the likelihood of achieving a significant reduction in the RDII% or PWWF will become too small to consider commissioning the project. The following table (Table 1) depicts a projection of where the models indicate the minimum threshold to achieve the nominal reduction in RDII of a net 1% decrease in RDII%; and for PWWF, a nominal net 1.0 L/sec/ha decrease in PWWF is likely to be.

Table 1: Rule-of-Thumb Rehabilitation Thresholds

To achieve a 1% decrease in the Pre-Rehabilitation RDII			To achieve a 1 L/sec/ha decrease in the Pre-Rehabilitation PWWF		
Percent total complete (public and private) in the catchment	With 50% confidence of bettering a 1% reduction	With 84% Confidence of bettering a 1% reduction.	Percent total complete (public and private) in the catchment	With 50% Confidence of bettering a 1 L/sec/ha reduction.	With 84% Confidence of bettering a 1 L/sec/ha reduction.
	(RDII %)	(RDII %)		(L/sec/ha)	(L/sec/ha)
65%	5% --> 4%	10% --> 9%	65%	2.6 --> 1.6	3.6 --> 2.6
80%	4% --> 3%	8% --> 7%	80%	2.4 --> 1.4	3.2 --> 2.2
90%	4% --> 3%	7% --> 6%	90%	2.2 --> 1.2	2.9 --> 1.9

Assuming NSCC continues to rehabilitate their wastewater network using the same methods; then Table 1, above can provide NSCC's wastewater engineers with a rough guide of the minimum pre-rehabilitation RDII% required to achieve a nominal net reduction in the RDII% of 1%; and / or a net reduction in the PWWF of 1 L/sec/ha. The engineer can assess the project risk against the confidence intervals indicated on the table.

Table 2: Example of the Cost-Benefit Data produced for NSCC's Cost-Optimization Model

		Most Likely Reduction						Most Likely Reduction			
		Percentage of the Total Catchment (Public + Private) requiring rehabilitation						Unit Rate Cost of Reduction for the CARE-catchment			
		Pre Rehabilitation RDII%						Pre Rehabilitation RDII%			
		8%	9%	10%	12%	Unit Rate Cost	$500/m	8%	9%	10%	12%
Target Post-Rehabilitation RDII%	4%	-	-	-	-	Target Post-Rehabilitation RDII%	4%	$ -	$ -	$ -	$ -
	5%	100%	100%	-	-		5%	$ 500	$ 500	$ -	$ -
	6%	67%	87%	100%	100%		6%	$ 335	$ 437	$ 500	$ 500
	7%	32%	55%	72%	93%		7%	$ 158	$ 273	$ 358	$ 466
	8%	-	27%	46%	73%		8%	$ -	$ 133	$ 231	$ 363
	9%	-	-	23%	53%		9%	$ -	$ -	$ 115	$ 267
	10%	-	-	-	35%		10%	$ -	$ -	$ -	$ 177
	11%	-	-	-	18%		11%	$ -	$ -	$ -	$ 90
	12%	-	-	-	-		12%	$ -	$ -	$ -	$ -
		With 84% Confidence of Exceeding						With 84% Confidence of Exceeding			
		Percentage of the Total Catchment (Public + Private) requiring rehabilitation						Unit Rate Cost of Reduction for the CARE-catchment			
		Pre Rehabilitation RDII%						Pre Rehabilitation RDII%			
		8%	9%	10%	12%	Unit Rate Cost	$500/m	8%	9%	10%	12%
Target Post-Rehabilitation RDII%	4%	-	-	-	-	Target Post-Rehabilitation RDII%	4%	$ -	$ -	$ -	$ -
	5%	-	-	-	-		5%	$ -	$ -	$ -	$ -
	6%	-	-	-	-		6%	$ -	$ -	$ -	$ -
	7%	100%	-	-	-		7%	$ 500	$ -	$ -	$ -
	8%	-	100%	100%	-		8%	$ -	$ 500	$ 500	$ -
	9%	-	-	89%	100%		9%	$ -	$ -	$ 444	$ 500
	10%	-	-	-	91%		10%	$ -	$ -	$ -	$ 457
	11%	-	-	-	52%		11%	$ -	$ -	$ -	$ 260
	12%	-	-	-	-		12%	$ -	$ -	$ -	$ -

Note: Unit rate cost of rehabilitation are illustrative only and do not represent the actual costs of rehabilitation to NSCC.

Example: 9% RDII reduced to 7%: The RDII% model (Eq 5) shows that the most-likely percentage of the CARE-catchment that will require rehabilitation to achieve the 9% to 7% RDII reduction is 55% of the total catchment (public + private). The cost of this rehabilitation will be an average of $273/m for every meter of pipe in the CARE-catchment. Assuming there is there is 30,000m of pipe in that catchment, then cost will be $8.19m (30,000m x $273/m). In the sensitivity model run, a reduction from 9% to 7% RDII is not possible. Instead only a reduction from 9% to 8% is possible, at a cost of $15m. This cost-benefit information will be used by the cost-optimization software to determine the most cost-optimal solution for the citywide network.

5.3 RULE-OF-THUMB ESTIMATIONS

The model equations for predicting the RDII% reduction and PWWF reduction (Equations 5 and 9) are fairly complicated. To assist NSCC's planning engineers to make high-level decisions when accurate calculations are not required; simple linear "rule-of-thumb" equations were prepared, as well as some charts to help quickly calculate the potential reductions.

The rule of thumb calculations assume that the percentage complete of the rehabilitation will be equal to the average percent complete from the rehabilitation teams to date. The average percent complete for the total catchment (public + private) to date is 64% (rounded in these calculations to 65% complete). By locking-in the percentage of the catchment complete at a set number, the only variable becomes the pre-rehabilitation (initial) RDII%.

The rule-of-thumb equations for RDII were:

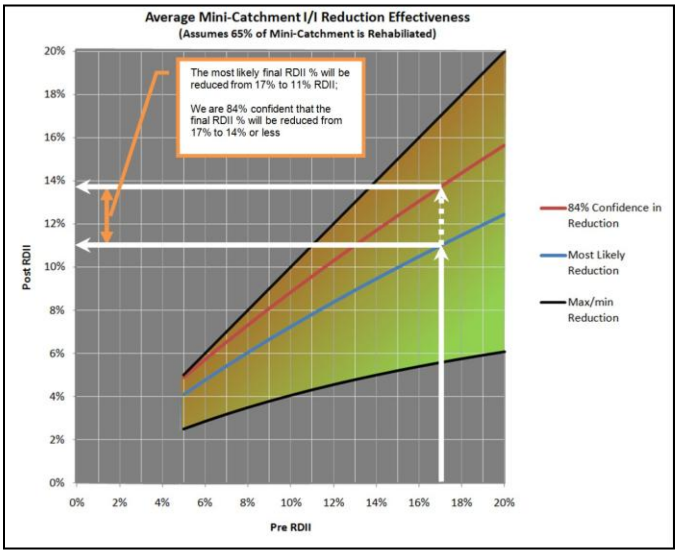
$$\begin{gathered} \mathrm{RDII}_{post}\ (84\%\ \text{Confidence}) = 0.71\ \mathrm{RDII}_{pre} + 0.02 \\ \mathrm{RDII}_{post}\ (\text{Most Likely Reduction}) = 0.55\ \mathrm{RDII}_{pre} + 0.02 \\ \text{Where: the } \mathrm{RDII}_{pre} \text{ is entered as a numerical value, i.e. 25\% is entered as 0.25.} \end{gathered} \tag{14}$$

The rule-of-thumb equations for PWWF reduction were:

$$\begin{gathered} \mathrm{PWWF}_{post}\ (84\%\ \text{Confidence}) = 0.45\ \mathrm{PWWF}_{pre} + 0.88 \\ \mathrm{PWWF}_{post}\ (\text{Most Likely Reduction}) = 0.31\ \mathrm{PWWF}_{pre} + 0.88 \end{gathered} \tag{15}$$

Where: the PWWF is entered in L/sec/ha.

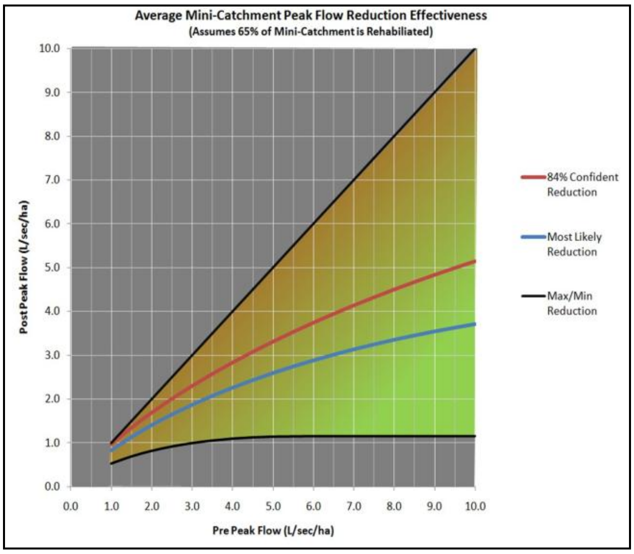
Figure 8: Rule-of-thumb Guide for quick RDII Reduction Assessment



The most likely final RDII % will be reduced from 17% to 11% RDII;

We are 84% confident that the final RDII % will be reduced from 17% to 14% or less

Figure 9: Rule-of-thumb Guide for quick PWWF Reduction Assessment



6 CONCLUSIONS

Because NSCC has used the same consistent approach to catchment rehabilitation for the last 10 years, NSCC's I/I effectiveness database was valuable for the purpose of developing an understanding of the causes of variation in a common approach to network rehabilitation. Had different methods of civil works or differing criteria by which the pipes were selected for rehabilitation been used; this study would have been considerably more difficult, if not impossible.

The effectiveness of the rehabilitation in I/I has been described by two models, one predicting the percentage reduction in the RDII% (essentially, the reduction in the rainfall volume in the sewer); and the other predicting the percentage reduction in the Peak Wet Weather Flow (PWWF). Between 60 and 75% of the variability in the effectiveness of sewer rehabilitation can be described by the two models via RDII% and PWWF as measures of the rehabilitation effectiveness.

The models use the *initial RDII%* and the *percentage of the catchment that was rehabilitated* as input factors. Other variables with strong correlations to the rehabilitation effectiveness were identified, but were not included in the models developed during this study, because the predictive ability of the models got worse with their addition.

Although the predictive ability of the models is not strong, by understanding the confidence intervals in the prediction ability of the I/I reduction effectiveness models, an engineer can develop an understanding of the variability in the effectiveness not described by the model, and factor this uncertainty into their design considerations.

The I/I reduction effectiveness measurements for additional mini-catchments will become available in 2009/10, and NSCC will refine the model when the data becomes available. It is expected that the confidence intervals in the models will improve with the additional data.

These two models have improved NSCC's understanding of the cost-benefits of controlling I/I through sewer rehabilitation; the ability to forecast target reductions in I/I; and have improved NSCC's knowledge of where the cut-off point in the leakiness of the wastewater network, below which potential benefits from sewer rehabilitation may be too marginal to warrant commissioning the work.

NOMENCLATURE

I/I, Inflow and Infiltration; NSCC, North Shore City Council; PWWF, Peak Wet Weather Flow (does not include the dry weather component for the purposes of this paper); RDII, Rainfall Dependant Inflow and Infiltration; RDII%, the percentage of the rainfall that falls in the catchment that gets into the wastewater sewer; WNSIP, wastewater network strategic improvement program.