Cost-effective and Reliable Inflow-Infiltration Reduction -

Have They Got It Right Down-Under?

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ABSTRACT

Up until 2010, due to extreme drought conditions in much of Eastern Australia arising from a predominantly El Nino weather cycle in the Pacific Ocean over the preceding decade, Inflow and Infiltration (I/I) management practices in Australia had not progressed or been implemented to any great extent further from the initial implementation work done in this field, mainly in Sydney in the 1990s. However, over this same period, due mainly to very different climatic conditions, there has been a significant amount of work done throughout New Zealand in I/I management.

With the onset of the wetter, predominantly La Nina patterns and the associated end of the drought in the 2008-2010 period, the management of wet weather flows in wastewater systems is now receiving more focus than at any time in the past 15 years in both Australia and New Zealand.

The Water Services Association of Australia (WSAA) is an industry membership organization that represents the 25 largest water companies/authorities in Australia and New Zealand. To respond to the evolving market need of its member organizations, WSAA recently engaged GHD, in association with local consulting partner Urban Water Solutions (UWS) to develop a Best Practice Guideline Document on I/I Management.

The initial part of this project aimed at determining the range of current I/I management practices in use across Australia. These practices and the resulting I/I reduction outcomes were compared and benchmarked with known and researched practices in New Zealand, USA and South East Asia.

Using the practices implemented in the identified examples of successful project outcomes, a Good Practice I/I Management Guideline Document for Australian and New Zealand water utilities was developed. This document is now become the industry guideline document for I/I management programs across Australia and New Zealand.

Comparison with various practices in I/I reduction and management in the USA carried out in the study indicated a range of processes were being used in different jurisdictions in the USA and a broad range of outcomes were being achieved. Given the initial drivers for the WSAA project, this suggests that the findings of the WSAA work are potentially also very relevant in the USA and Canada.

What the WSAA work found was that from the significant number of projects whose outcomes have now been analysed, there is now a robust knowledge base upon which to make far more
reliable and informed predictive estimates of I/I reduction levels achieved from different levels of system rehabilitation. The work in New Zealand has evolved to a point where a predictive model of the likely level of I/I reduction that can be achieved from existing levels for different extents of system rehabilitation now exists.

This is considered to represent a significant advancement worldwide in the planning of wastewater system improvement and management programmes.

Of greatest value to the wastewater systems industry is that the work gives wastewater planners and managers a far more robust basis upon which to undertake I/I reduction programmes through system rehabilitation with the expectation of certain outcomes for a given financial investment.

Some useful analysis and calculation tools to consistently support this methodology and also guidance on realistic targets and likely outcomes provide particular added value.

Hence its contents can be used to more reliably plan works of this type and their associated capital budgets, reducing the risk of failure that has plagued such programs in the past. This outcome therefore removes many of the perceived risks associated with the implementation of I/I management programmes in the past.

This paper will be of interest to the wide range of delegates challenged by the issue of infiltration and inflow in the effective management of their wastewater systems.

**KEYWORDS**

Inflow/Infiltration Reduction, Predictive Model, Rehabilitation, Cost-effectiveness

**INTRODUCTION**

Undertaken in two distinct stages, at its outset, the project had as its objectives the following:

- To deliver a comparative review and report on the infiltration and inflow management practices within participating Australian Water Utilities with a view to achieving the following:
- Establishment of a common understanding of current I/I performance and management processes across the participating WSAA organisations;
- Benchmarking these practices with those in use in New Zealand, the USA and any other jurisdictions;
- Resulting from the above, development of Best Practice Guidelines / Methodology document for I/I Management.
- Determination of how I/I can be realistically reduced using various rehab techniques and associated costs.
- A definition of how other wastewater system improvements can be integrated with I/I Management Solutions.
METHODOLOGY

Understanding Current Status in Australia

To better understand the extent and nature of current I/I practices in Australia, as part of this exercise, a survey questionnaire was sent out to all WSAA-participant organizations to develop an understanding of current and intended approaches and practices related to I/I management.

Fourteen WSAA participant organizations responded to the questionnaire. Key results of the survey are as follows:

1. Drivers for undertaking an I/I Management Program were identified as follows:
   - To achieve regulatory and/or licensing compliance;
   - To better manage or mitigate business risk associated with operation of the wastewater system;
   - To be more environmentally sustainable;
   - To assist with the development of capital works programmes;
   - To better manage and address operational problems, including overflows, at the wastewater treatment plant;
   - To reduce the location and frequency of overflows within the wastewater collection system; and
   - To address problems with treatment plant operation or effluent reuse potential created either by seawater or saline groundwater intrusion.
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3. Only 3 of the 14 respondents confirmed they currently had an I/I Management programme in place.

4. I/I Reduction programmes are seen by respondents as less reliable a solution to wastewater system capacity deficiencies and overflows than system conveyance and detention storage solutions.

5. System target wastewater overflow containment standards are set mainly by regulators but in some cases by the regulators in conjunction with the water company/authority.

6. Storm water interactions and saline intrusion are seen as significant issues for a number of the survey respondents when dealing with I/I.

7. Governance arrangements and wholesaler-retailer interactions are not seen as important considerations in I/I management.

8. There is a good understanding of the role that private house laterals play in being a potential source of I/I into a system.
9. No survey respondent has developed a process for addressing sources of I/I coming from private house laterals.

10. There is significant appetite amongst survey respondents for a Good Practice Guideline Document such as this one.

11. There is some appetite for common I/I KPI calculations tools that could be provided by WSAA to its member organisations.

**Current Status Elsewhere**

Research carried out by the project team indicated that I/I reduction was currently commonly being used as an effective wastewater system management tool in New Zealand, the USA and in Singapore.

The predominant nature of combined stormwater/wastewater pipe systems in Europe and the United Kingdom means that I/I reduction is not as relevant to wastewater system managers there as it is in Australia.

Guideline documents for I/I management have been produced in New Zealand in 1996 and in the USA, most notably the WEF publication “Existing Sewer Evaluation & Rehabilitation “ (MOP FD-6, 3rd Edition 2009) and also WERF’s “Reducing Peak Wet Weather Flows through I/I Reduction” (2003.)

The research identified that I/I management is a common management tool, with widespread implementation for wastewater system managers across the USA.

**INFLOW & INFILTRATION KEY PERFORMANCE INDICATORS (KPIS)**

Historically, I/I analysis projects carried out in Australia, New Zealand and the USA have been done using a range of parameters that quantify the various sources of I/I.

These sources are commonly understood as Groundwater Infiltration (GWI) or base flow; and Rainfall dependent inflow and infiltration (RDI/I).

RDI has historically been analyzed using two parameters that are based on the need to target its sources so as to reduce it— one that is an indication of the total volume of RDI and one that is indicative of relatively easily removable direct stormwater inflow.

Taking the learnings of previous projects completed, moving forward, it was recommended in the WSAA project that I/I be analyzed using four simple parameters, each calculated on a flow monitor or pump station catchment basis.
**For Dry Weather (Groundwater) Infiltration**

A population-based flow factor, which is the ratio of the measured average dry weather flow to the estimated population.

\[
GWI_1 = \frac{ADWF_{measured}}{Population_{theoretical}} \text{ where the unit is l/person/day}
\]

As guideline values, when the ratio’s value is below 140l/p/d, it is indicative of exfiltration. When the value is greater than 220 l/p/d, then significant groundwater infiltration is likely to be occurring.

As a potential cross-check if desired or if available, a water consumption-based flow factor, being the ratio of the measured average dry weather flow to the metered water consumption (where available).

\[
GWI_2 = \frac{ADWF_{measured}}{Water\ Consumption_{measured}}
\]

The normal expected range is 0.7 to 0.9.

When the value is below 0.5, it is indicative of exfiltration. When the value is greater than 1.2, then significant groundwater infiltration is likely to be occurring. The relationship between water consumption and wastewater generation was investigated in detail in a study by Melbourne Water\(^1\).

**For RDII Volume**

A percentage of total ingress parameter, measured on an individual flow monitor or pump station catchment basis, which is the measure of the percentage of actual rainfall falling on a catchment that ends up in the wastewater system.

\[
RDII_1 = \frac{Volume\ of\ RDII\ _{measured}}{Rainfall\ Volume_{measured}}
\]

\[
= \frac{(Recorded\ Wet\ Weather\ Volume\ -\ Average\ dry\ weather\ volume)\ /(Measured\ rainfall\ depth\ x\ catchment\ area)}
\]

Typical values for an older system in good condition are in the range 2-5%. Values of greater than 20% have been encountered in some Australian and overseas projects, indicating very high levels of wet weather response.

**For Peak Wet Weather Flows**

A wet weather flow peaking factor, which represents the extent of Storm Water Inflow (SWI) is the ratio of the peak flow recorded during a specific rainfall event to the measured average dry weather flow preceding that event.

\[
SWI_1 = \frac{Measured\ PWWF}{Average\ Dry\ Weather\ Flow}.
\]

This parameter can be measured at any flow monitoring point.
Historical design practice was to set this number at 5.0. Studies have encountered values as high as 30, indicating a significant number of direct inflow sources in the associated catchments.

**Threshold Trigger Values**

Whether pursuing an I/I reduction program is justified will depend on the performance and operational problems that are being addressed in the system. In addition, a full multi-criteria analysis on the viability of an I/I management program in relation to other options as outlined in Section 4 may be warranted.

It is useful however to have some idea of threshold or trigger values of the various I/I KPIs so as to know whether pursuing an I/I reduction program through system rehabilitation is likely to be prudent.

Research\(^7,8,14,22\) carried out as part of this project has identified that when measurable RDII\(_I\) parameter is less than 8-10%, the success of rehabilitation programs aimed at reducing it is much harder to quantify and therefore the associated works are much harder to justify.

A threshold value of the RDII\(_I\) parameter of 8% was therefore recommended in the WSAA Study.

Unless there are other on-off reasons such as a localized overflow that would benefit from such a program, where the RDII\(_I\) parameter is less than 8%, consideration of system-wide rehabilitation as an improvement measure to reduce system wet weather volumes is not recommended.

Similar threshold values were included in the Guideline document for the GWI and SWI parameters as follows: Groundwater Infiltration - GWI – 250 l/p/day or as an alternate, where GWI is estimated as 20% of ADWF; and Stormwater Inflow (SWI) – 8.

**GOOD PRACTICE I/I REDUCTION METHODOLOGY**

The research carried out during this project\(^5,6,7,8,9,10,22,23\) has identified that the most successful results have been achieved where a common five-step methodology has been adopted. On the basis of replicating these outcomes, the common methodology is defined as the Good Practice I/I Reduction Methodology. These 5 stages are summarized in Figure 1.

![Figure 1. – Summary Flow Chart of Good Practice I/I Reduction](image-url)
Calculations of the I/I Reduction Effectiveness

In relation to Stage 5, it is felt that the methodologies and techniques had evolved significantly since the publication of the Manual.

One example is how the levels of I/I reduction achieved have been calculated. Three methods are outlined in the WSAA Report as follows –

1. Linear Regression (R% vs Rainfall Volume) Technique
2. Linear Regression – Control/Target Technique
3. Calibrated Model Technique

The research indicates that Methods 1 and 2 as described above are in common use in the USA. Examples of use in the USA of Method 3 could not be found.

Methods 1 and 2 are explained by Figures 2 and 3 below.

**Method 1 - Linear Regression (R% vs Rainfall Volume) Technique**

This technique has historically been used (mainly in the USA but also formerly in a number of Australian studies pre2000) to calculate the reduction in RDII volumes resulting from the rehabilitation works and is the simplest and cheapest way of calculating RDII reductions.

The RDII volume amount is plotted against Rainfall Volume for each of the pre-rehabilitation cases and also the post rehabilitation cases. As shown in Figure 2, a line of best fit is fitted for each of the pre and post rehabilitation data sets. A linear regression analysis is used to determine the relative reduction shown by these two lines of best fit.

![Figure 2 – Linear Regression (RDII Volume vs. Rainfall Volume) Technique for Calculating I/I Reduction Effectiveness](image)
**Linear Regression – Control/Target Technique**

This method was also used in some pre-2000 Australian studies and is commonly referred to in a research-identified range of US projects.

It involves the calculation of the reduction of I/I KPIs in rehabilitated catchments (the “Target” catchments) relative to the performance outcomes of the same KPIs in adjacent like wastewater catchments where no rehabilitation works have been carried out. (the “Control” catchments). In this way, this method attempts to cater for the variability posed by antecedent soil moisture and its effects on wastewater hydrology during the pre and post rehabilitation gauging periods.

Figure 3 shows how this calculation is carried out.

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![Figure 3 – Linear Regression (Control vs. Target) Technique for Calculating I/I Reduction Effectiveness](image)

**Calibrated Model Technique**

Since approximately 2000 in most New Zealand studies, calibrated hydrologic and hydrologic models for each of the pre and post-rehabilitation scenarios have been developed as the basis for calculating I/I reduction levels.

These models are then each run to predict system behaviour and overflow volumes and performance over a long time series of rainfall data, typically 10 years, to simulate the performance of the system against a wide range of actual rain events.

Resultant RDII volumes are then calculated for a range of events within the typical design spectrum of the time series, e.g. all events between a 2 month and a 2 year containment standard.

Care needs to be taken in this process in the definition of the commencement and conclusion of a particular flow event generated by the range of rainfall events within the time series.

The difference in RDII volumes between the pre and post rehabilitation time series is then calculated and a reduction figure is derived.

Similarly, changes in response to either a range or certain peak flow events can also be calculated using the outputs of this process.
This process is considered the most robust and accurate. Analysis using this method is now comprehensive. This method has the obvious added advantage of then being able to apply the results back into a hydraulic model of the investigated system so as to test or verify the level of reduction in system overflows that were possibly the reason for undertaking the rehabilitation works in the first place.

The selection of the most appropriate method is a function of the following all of which require consideration in the method selection process:

- Degree of desired rigour and accuracy;
- Cost;
- Required timeframes for production of results;
- Technical capability that is available to complete the analysis, either in-house or outsourced; and
- The existence or otherwise of a fully calibrated hydrologic and hydraulic models.

There are no known studies where the calculation methods have been compared.

**I/I REDUCTION COST EFFECTIVENESS ASSESSMENT**

Calculating the cost-benefit ratio of the I/I reduction, either at planning stage or post-implementation is a key process that should be followed on each I/I management project.

The costs of the actual rehabilitation works can be fairly readily defined. At the planning stage, this requires assuming certain levels of rehabilitation works and developing cost estimates for these works.

The benefits of carrying out these works are somewhat more complex to define. The cost benefits of doing the rehabilitation works comprise the following:

1. The reduced volumes that would otherwise be transported through the system. There are a range of operations and maintenance costs associated with these, the majority being pump station power costs. With knowledge of current pumping costs, the savings in these costs can be readily estimated.
2. The reduced volumes that are treated at the WWTP. With knowledge of treatment costs per ML of wastewater, these savings in costs can be fairly readily estimated.
3. The reduced extent of infrastructure upgrades (e.g. pump station or pipe capacity upgrades or storage volumes) that would have otherwise had to have completed and invested in to meet a specific target level of service. It is possible that with an I/I reduction programme in place, these costs are no longer required and hence this is a cost saving.
4. The capital reserved for inevitable asset renewal that would no longer have to be invested because of the rehabilitation works.
5. Where appropriate, the reduction in fines or other financial penalties for excessive overflows imposed by the Regulator.
6. Other non-tangibles such as the reduction in water company/authority reputational damage image etc could be valued and included in the assessment.
All of these savings, be they “one-offs” or on-going, need to be estimated on a net-present value basis over the life of the rehabilitation works. It is suggested that the design life of 30 years is adopted for this approach. The various sources of savings then need to be summed and compared against the net present value of the costs of the rehabilitation works to determine the cost-benefit ratio. i.e. is the investment in the rehabilitation program justified on economic grounds.

**HOUSE LATERAL INFLOW AND INFILTRATION**

The WSAA Study Group survey carried out as part of this project indicated the ownership and responsibility of house laterals and hence responsibility for their repair, is many and varied throughout the WSAA membership. Survey responses indicated that the ownership boundary is fairly evenly split between:

- the first inspection opening (I/O)
- the property boundary
- the junction on the main sewer

Most of the more recent projects 1,2,7,8,9, 10,14,22,25 acknowledge and document the contributions made to total I/I volumes by house laterals. These sources indicate that up to half of the total volume, comprising both infiltration and direct inflow, is contributed by house lateral sources.

Research carried out in this project has identified four particular cases where large scale lateral repair programs have been undertaken, namely

1. the East Bay Municipal District project, (the subject of another paper at this conference)
2. the UK Study,
3. the North Shore City Council (Auckland, New Zealand) project.
4. The Hillsborough case study (Auckland, New Zealand)

The historical problem with chasing out this RDII is that in all jurisdictions studied, the ownership of the house lateral by the property owner and hence the responsibility for rectifying the problem has resulted in difficulties in getting laterals repaired.

Hence removal of RDII sources arising from faults in the laterals has been problematic. The absence of legal levers, political sensitivities and the responsibility for private drainage frequently falling under the remit of the local government agency, as opposed to the water company or authority, results in enforcement of defect notices as a further complicating factors.

The North Shore case study is considered to represent the most advanced catchment-wide program aimed at lateral repair in Australasia. This program has worked within the paradigm of the conventional ownership arrangement of private ownership from the property boundary. It has shown the challenges that even with dedicated resources applied to lateral repair, it has taken 2 years to get 75% of identified house lateral defects repaired.

When earthenware and concrete pipes have been used, it is generally recognised in most studies referred to above that a significant source of house lateral I/I is at the actual junction of the lateral with the sewer. The heavy pipes drop vertically over time, shear off the joint and create a major source of entry for infiltration.
Tree root intrusion in shallower house laterals is also considered to be a major source of house lateral I/I.

Although not studied in detail or proven, recent drought conditions in most parts of Australia over the last 10 years is thought to have probably made this more of an issue as tree roots “search” for otherwise unavailable sources of water.

**Complexities of House Lateral I/I**

Thinking regarding ownership and responsibility for repair have generally been aligned and so the argument of why a public utility should pay for the repair of a privately owned lateral occurs. A similar argument occurs when one questions why would a private person have to pay for the repair of a lateral it owns when a portion of this might be out in a street or road.

Repair of private laterals is further complicated when the following is considered: Who is responsible for the portion of lateral that connects multiple properties to the public sewer? – eg apartment blocks or strata titled units, particularly in areas where a large portion of tenanted properties exist and owners are non-resident, often in locations well remote from the property, even overseas.

Given all of the above, few agencies have actively pursued large scale lateral repair programs.

The research carried out in this project identified the EBMUD project as the most comprehensive procedural, legal and financial arrangement that has been developed and implemented to address the difficulties related to a system-wide lateral rehabilitation program.

The UK case has addressed the main problem area of the EBMUD program, with the water company assuming ownership of the shared sections of laterals and has also dealt with any inconsistencies with regard to the ownership boundary of the lateral.

It was proposed that if WSAA member agencies wish to seriously address the reduction of I/I coming from private properties, then they consider the implementation of the key aspects of the EBMUD, UK and North Shore CC programs that have been the subject of this investigation.

These key relevant points are:

- Funding, resourcing and maintenance of an inflow source detection program for the removal of these defects, including the necessary database management associated with this task is a significant investment in a water agency’s human and capital resources
- A change in the boundary of the lateral ownership where part of the lateral is shared so that the water agency owns the lateral up to the point where it is no longer shared.
- That the ownership boundary in all locations be adopted as the property boundary.
- Legislative change will be required to address these matters and these requirements will vary significantly between Australian states and will be different again in New Zealand.
• Adoption of a multi-criteria trigger point plan for lateral testing and repair (if required) as per EBMUD experience with property sale being at least one of the trigger points with consideration also for major renovations as a trigger.
• As the EBMUD experience highlights, developing policy and protocols for dealing with exemptions and time extensions will be required early in the evolution of such processes.
• In cases where a more targeted program of lateral repair is warranted to reduce I/I in certain concentrated areas, develop a lateral replacement policy informed by an economic business case analysis that considers each and all of the following as options for the funding of the lateral replacement:
  o The water authority carrying out and paying for the repair of the on-property portion of the lateral.
  o The water authority carrying out the repair on the property owners behalf and charging them for this work by either of 3 methods—
    ▪ a separate charge; or
    ▪ a “soft-loan” incentives by the water company-authority to the property owner, reimbursable to the water -authority by separate payment of an ongoing levy on their water-wastewater bill or local government rates.
    ▪ where owners are unable/unwilling to pay, place a lien/caveat upon the property for the cost of the works, accruing interest at an agreed rate recoverable upon sale of the property.
  o The property owner carry out the identified repairs and fund it themselves either directly or by the soft-loan mechanism outlined above. Not only does it create an extra burden on ratepayers who may not be adequately skilled to deal with it, this option would require significant monitoring and investment of resources by the water company-authority to ensure compliance. It is hence considered the least-favored option.

PREDICTING I/I REDUCTION

A significant number of projects in these jurisdictions have now been analyzed to the point that there is a robust knowledge base upon which to now make more reliable predictive estimates of I/I reduction levels achieved from different levels of system rehabilitation.

This is considered to represent a significant advancement in the planning of wastewater system improvement and management programs.

Extents of public sewer rehabilitation vs I/I Reduction Achieved- Guideline Values

Of particular interest is one conclusion that unless at least 40% of the total piped system within a catchment is rehabilitated, there is no guarantee of reducing RDII at all.
It is also clear from this result that complete rehabilitation of the catchment is likely to achieve the maximum I/I reduction outcomes.

This data was summarised in this report as shown in Figure 4.

<table>
<thead>
<tr>
<th>% of Total Public System Rehabilitated</th>
<th>Maximum Reduction in RDII (%)</th>
<th>Reduction in GWI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>60</td>
<td>+/-80</td>
</tr>
<tr>
<td>80</td>
<td>40</td>
<td>+/-70</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>+/-50</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>+/-30</td>
</tr>
</tbody>
</table>

**Figure 4 – Reduction for Different Extents of Public Sewer Rehabilitation**

**Extents of Rehabilitation vs I/I Reduction Achieved- Guideline Values**

Of the I/I reduction results obtained through the research exercise undertaken in this project that have been deemed as reliable, the levels of I/I reduction achieved have been evaluated to assess what levels of I/I volume reduction can be achieved from what extents of rehabilitation.

Rehabilitation works have been categorized into one of three classes as follows:

1. **Level 1** – Removal of all inflow defects identified through a program of house-to-house inspections, smoke testing and manhole inspections;
2. **Level 2** – Level 1 works in addition to complete sealing of all the public sewers within a catchment and
3. **Level 3** – Level 2 works in addition to sealing all the private property laterals up to the house.

Clearly and as expected there is significant variation in the results achieved. A comprehensive review carried out in New Zealand by GHD in 2003 for North Shore City Council\(^1\) through research, the RDII volume reduction results of over 50 projects carried out in Australia, SE Asia, NZ and the USA at that point in time. Whilst it is acknowledged that these projects may have used vastly different techniques to calculate levels of I/I reduction achieved through these projects, the RDII reduction levels were plotted against the extent of rehabilitation works carried out.

The conclusions that can be drawn from the research\(^2,3,4,23\) is that with a well advised, managed and controlled program of I/I reduction works the rates of I/I volume reduction as shown in Figure 5 can be obtained.
### Table: Levels of I/I Reduction Achievable for Different Levels of Rehabilitation

<table>
<thead>
<tr>
<th>Rehabilitation Level</th>
<th>Reduction in RDII (%)</th>
<th>Reduction in Peak Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-15</td>
<td>0-25</td>
</tr>
<tr>
<td>2</td>
<td>15-50</td>
<td>30-40</td>
</tr>
<tr>
<td>3</td>
<td>40-80</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Predictive RDI/I Reduction Model**

The most advanced research that could be located in the WSAA Study identified that North Shore City Council (now part of Watercare Services Limited) has rehabilitated 32 catchments over the last 10 years. Results have been analyzed for more than 14 of these catchments.

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. Additional I/I reduction effectiveness measurements for additional mini-catchments will become available over time. Watercare 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.

The models were developed by testing the predictive ability of the models, as opposed to the fit of the models to the existing data. This ensured that the models developed had the best ability to predict the likely reduction in catchments for which reduction results are not yet available.

During this process 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; and
- The initial leakiness of the catchment (measured in RDII%);

An equation that provides an estimate of the leakiness throughout a catchment was also developed, using the leakiness measured at the bottom of the catchment (by a flow gauge) as an input.

Based on the sample of catchments analysed, the following predictive model equations have been developed.
RDII Percentage Reduction

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

\[
\text{RDII} \% \text{ Reduction} = \text{Initial RDII factor} \times \text{Percentage Complete}
\]

\[
= (0.257\ln(-0.0445x + 0.0445 + \text{RDII}_{Pr}) + 0.988) \times x^{1.055}
\]

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

The three dimensional model can be represented graphically as the following –

The model calibration suggests that:

- an exponential increase in the reduction in RDII occurs:
  - until approximately 70% of the public sewer is rehabilitated. Beyond 70% the model calibration suggests that the law of diminishing returns kicks-in with little additional reduction in RDII.
  - as the percentage of private properties increase. When approximately 60% of the private properties had been rehabilitated, the model calibration tapers off quickly, however, the study also found that the maximum number of properties within a catchment with defective drainage is typically 60-70%.
- Up to 45% of the RDII reduction can come from the public network while the remaining 55% can come from the private network.
- The potential to reduce the RDII starts to drop off at an increasing rate when the pre-rehabilitation RDII drops below 10% RDII

Peak Flow Reduction (%)

The PWWF model was the same as the RDII% model, just with different coefficients:
Peak Flow % Reduction = Initial RDII factor × Percentage Complete

\[ = (0.303 \ln(-0.0445x + 0.0445 + \text{RDII}_{\text{pre}}) + 1.163) \times x^{0.761} \]

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

The three dimensional model can be represented graphically by the following –

The model calibration suggests that:

- an exponential increase in the reduction in Peak Wet Weather Flow occurs until approximately 70% of the public sewer is rehabilitated. Beyond 70% the model calibration suggests that the law of diminishing returns kicks-in with little additional reduction in Peak Wet Weather Flow.

- An approximately linear increase in the reduction in peak flow until approximately 60% of the private properties had been rehabilitated (those expected to have defective drainage).

- Up to 35% of the Peak Wet Weather Flow reduction can come from the public network while the remaining 65% can come from the private network

Other variables with strong correlations to the rehabilitation effectiveness were identified, but were not included in the models developed during this study.

**Groundwater Infiltration Reduction**

It is therefore concluded that whilst reduction in RDII can be now more reliably predicted based on results obtained from previous studies, reductions in GWI are far more uncertain. Where GWI exists it is considered prudent to estimate likely reductions in GWI as being approximately half those of RDII.
Levels of reduction in GWI are much harder to predict. Many of the studies referenced\textsuperscript{5,8,9} have actually shown an increase in ADWF after system rehabilitation. This is considered mainly due to the possible exfiltration conditions that could have existed prior to the rehabilitation.

**CONCLUSIONS**

The project has used the outcomes of research and a range of case studies to define what is now regarded as good practice for the Australian and New Zealand water industries and this is now documented in WSAA’s Good Practice Guideline document.

Features of this document include:

1. Definition and adoption of a consistent set of I/I key performance indicators.
2. A five-step process, which if followed rigorously, will result in reduction outcomes consistent with the most successful programmes completed in these jurisdictions.
3. Advice on expectations of guideline I/I reduction levels achievable if the methodology is followed correctly and a predictive model for these reduction levels.
4. A suite of calculation tools and techniques that will enable consistent calculation and analysis of I/I in wastewater systems and its removal.
5. Discussion of the contentious issues associated with the responsibilities for removal of I/I entering the system through privately-owned house laterals.
6. Advice regarding potential risks and failure points in implementing a successful I/I reduction programme.

Most importantly, based on research carried out as part of this project, it is apparent that much of the findings of this project and content of the WSAA Good Practice Guidelines Document for Wastewater Inflow and Infiltration Management is also relevant for wastewater managers and operators across the USA and Canada.

**ACKNOWLEDGEMENTS**

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