INFLOW AND INFILTRATION ASSESSMENTS – EASY TO GET IT WRONG

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ABSTRACT

As wastewater networks age, managing stormwater inflow and groundwater infiltration is likely to become increasingly important in controlling wet weather overflows and in servicing growth. In theory there should no rainfall ingress or groundwater entering a separated wastewater network, but in practice significant volumes do occur.

An Inflow and Infiltration (I/I) assessment recently undertaken for Christchurch City Council was based on two methods: using flow gauge results and using a hydraulic model. This provided a rare opportunity to compare these assessment methods and results. If the I/I assessment undertaken for Christchurch City Council was based only on wastewater network modelling results, a number of catchments would have been prioritised without identifying confidence issues in some of the modelled results.

This paper will address a range of typical problems that are common when undertaking inflow and infiltration assessments and will demonstrate that undertaking these assessments is not easy and the consequential risks are significant.

KEYWORDS

Inflow and Infiltration, I/I, sewer rehabilitation, wastewater, modelling.

1. INTRODUCTION

1.1. BACKGROUND

Wastewater network operators are often concerned about inflow and infiltration (I/I) issues. A common theme is that they know there is a significant response to rainfall in their separated networks, but often do not know how big the problem is, how to carry out carry out a reliable assessment and how to identify the most cost effective solutions to combat I/I. In addition there is often insufficient time and/or budget to carry out a thorough I/I assessment, and there are significant risks if it is not done properly.

The "Infiltration & Inflow Control Manual Version 2" (I/I manual) was published in 2015 by WaterNZ, which provides direction about inflow and infiltration.

This paper will not duplicate what has been produced in the I/I manual but will provide some guidance on some of the issues and risks when undertaking I/I assessments and how to get best value for money.

This paper will in part draw on recent experience of an Inflow and Infiltration Assessment carried out for Christchurch City Council. This project confirmed and highlighted a number of issues and related risks. The Christchurch project was unique in that an I/I assessment was carried out based on wastewater network modelling results as well as based on flow gauging results. This provided an opportunity to compare the outcomes of both assessments and the methods used.

1.2. EFFECTS OF INFLOW AND INFILTRATION

Water entering in a separate wastewater network can be classified into three sources:

- Dry Weather Flow (DWF) is a combination of domestic, commercial and industrial wastewater flows.
- Rainfall Derived Inflow and Infiltration (RDII), rainfall which enters the wastewater network from a variety of sources. This is normally expressed as the percentage of rainfall entering the wastewater network (RDII%).
- Groundwater Infiltration (GWI), water entering the network from the groundwater table.

There are many effects from inflow and infiltration, and these are described extensively in the I/I manual. The most common issues resulting from excessive I/I are:

- Wet weather overflows resulting in pollution, not meeting Levels of Services and/or not meeting resource consent conditions
- Reduced capacity to accommodate future demand
- Increased operation costs
- Reduced treatment efficiency
- Exfiltrating wastewater out of the leaky system during dry weather and causing groundwater pollution
- Significant costs to reduce I/I
- Negative exposure of water authority.

In practice most gravity wastewater networks leak and receive some amount of RDII and GWI; these wet weather inflows generally dominate sewer capacity and for a significant enough storm (and particularly under wet antecedent conditions) a sewer can be overwhelmed by this water, causing an overflow to the environment. Understanding the RDII response is critical to assessing the frequency at which the sewer will be overwhelmed and hence defining sewer network capacity. It is this frequency upon which a containment standard authorising overflows to the environment is often based.

RDII is a complex phenomenon that is difficult and expensive to measure, represent and source, as amongst many other factors it can be both a point and diffuse source, enter both private and public assets and is highly dependent on antecedent conditions. RDII characteristics are often unique to a given catchment and are not fixed in time e.g. deterioration of the network over time results in increasing leakiness. To quantify and reliably estimate RDII requires extensive data collection and planning resources, which allows the capacity of the wastewater network to be assessed.

Measuring and representing RDII is crucial to assessing wastewater network capacity and its exceedance, to determine whether it containment standards are being met, to develop solutions to mitigate the effect of the RDII flows and/or allow capacity for growth.

2. TYPICAL PROBLEMS

This section describes some of the issues that we have encountered during many years of inflow and infiltration analyses, along with suggestions about how to minimise the risks. This includes pre and post sewer rehabilitation leakage assessments to determine the actual reductions achieved and the costs. It is important to undertake assessments before and after sewer rehabilitation (see further section 2.15) to understand what was actually achieved and to improve assessment, design and construction processes. It is our experience that consistent high quality gauging and assessment methods are required to enable post rehabilitation assessments.

The following section discusses issues by topic generally following the sequence from catchment selection to capturing flow data to processing to analysing to making recommendation.

2.1. CATCHMENT SIZES

Inflow and infiltration is never spread equally across a network. Often it is just a small percentage of the network that contributes disproportionately to I/I related problems. Sewer rehabilitation to reduce I/I is expensive and should therefore be targeted at those areas where the benefits outweigh the costs.

Network wide hydraulic analyses are generally used to set flow or I/I reduction objectives in order to meet existing and future performance objectives. For example, wet weather overflow frequencies or additional capacity to accommodate increased demand can be achieved by upsizing the pipe network or building storage. These types of upgrades can be averted by reducing I/I rates meeting a reduction target. Setting an I/I reduction target is important as well as checking after implementation whether or not this target was met.

Large catchments can mask the true extent of I/I problems and potential reduction rates because high rates of leakage within the network can be 'averaged out'.

Figure 1: examples of averaging out RDII results

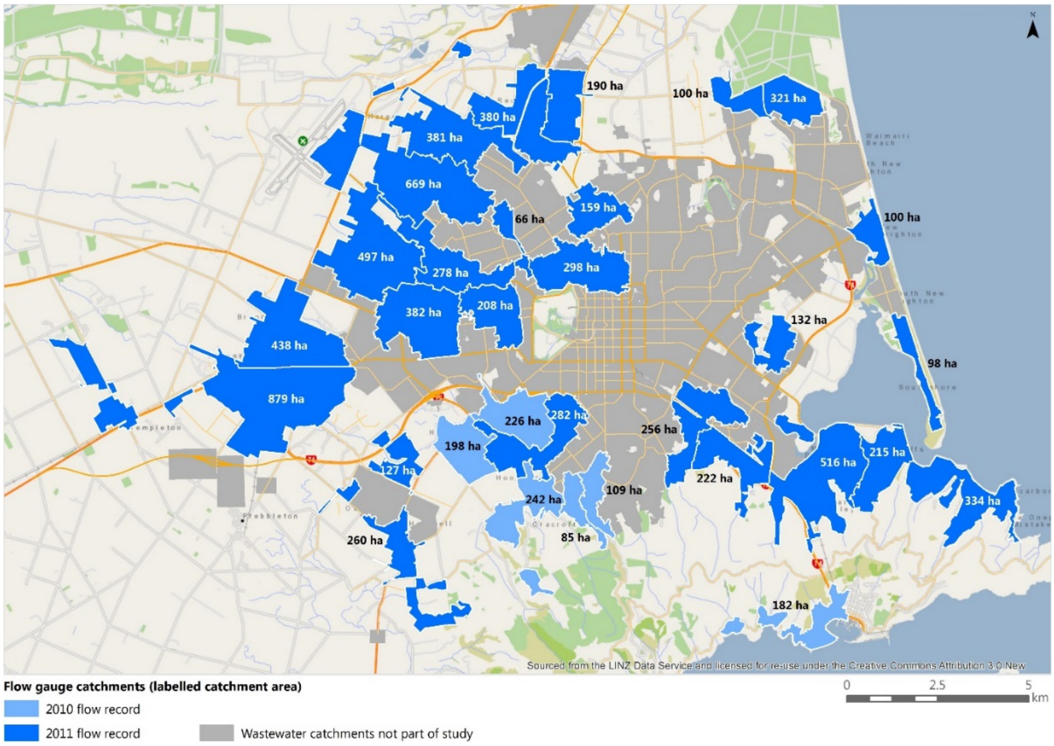
example: catchment A		
sub catch ment	RDII [%]	area [ha]
A1	8%	8
A2	19%	8
A3	7%	18
A4	3%	20
A5	10%	14
A6	22%	10
A7	6%	15
Total	9%	93

example: catchment B		
sub catch ment	RDII [%]	area [ha]
B1	7%	9
B2	21%	15
B3	8%	8
B4	15%	9
B5	28%	22
B6	8%	9
B7	20%	18
Total	18%	90

When a large catchment shows a relatively high leakage rate not all sub catchments contribute to this problem. Figure 1 shows two fictitious examples. Catchment A shows a total RDII% of 9% which is relatively low, but two of the sub catchments (A2 and A6) have very high RDII rates and may be cost effective to rehabilitate. This assumes that catchments with an RDII% of more than 15% can be cost effectively rehabilitated (discussed further in Section 2.18).

For catchment B the total RDII% is 18% which is very high but three out of seven sub catchments have a relatively low leakage rate (<10%). So without assessing the leakage rates at this small scale the (financial) risk would have been that catchments B1, B3 and B6 would have been rehabilitated with little benefit. Because the costs of sewer rehabilitation are significant it always pays to measure the leakage at a high resolution before final decisions are made for sewer rehabilitation. Focusing on the leakiest parts of the catchments will achieve the highest return on investment (see also section 2.18).

Figure 2: Location of catchments used in the Christchurch study



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Large catchments can be used however to identify priority areas where more detailed I/I studies should be carried out.

The location of the catchments included in the Christchurch assessment are shown in Figure 2. The catchments flow gauged in 2010 are shown in light blue and those gauged in 2011 in dark blue.

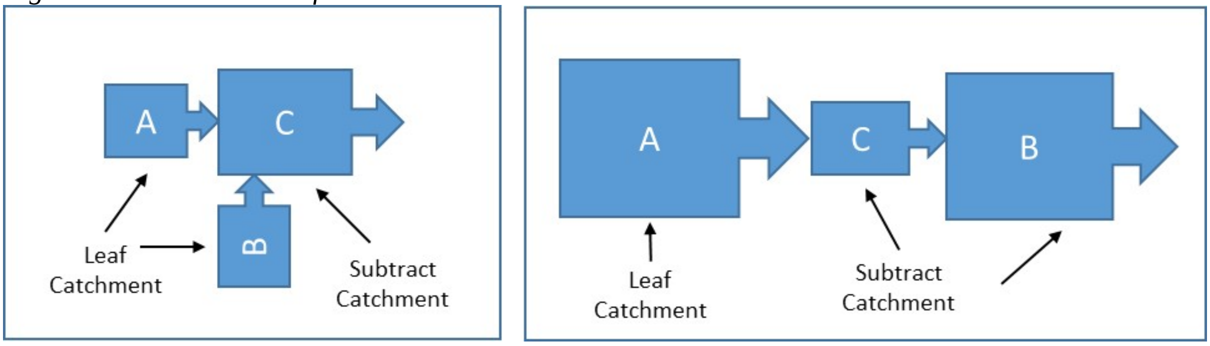
In this example the catchment sizes investigated varied from 66 to 880 ha with the median at about 240 ha, as the purpose of the flow gauging was to calibrate the wastewater network model. However, these catchment sizes are too large for a reliable and accurate representation of the I/I performance indicators. In our experience, a desirable and practical size for flow gauge catchments that could be used to commission I/I renewal works is 5-25 ha (maybe up to 40 ha).

Potential savings from targeting renewals works with catchments down to a size of 5-25ha, can be illustrated by considering a catchment area of 200 ha with approximately 120 m public sewer per ha (both based on the Christchurch project). At approximately $500 per meter to rehabilitate sewers (overall costs public and private), if only the detailed flow gauging identified that 50% needed of the catchment needed rehabilitation (instead of the full catchment), about half of the cost would be saved (about $6 million).

2.2. POTENTIAL PROBLEMS WHEN USING SUBTRACT CATCHMENTS

A subtract flow gauge catchment is a gauged catchment that also receives flows from gauged upstream catchments. When calculating flows from these subtract catchments (excluding upstream catchments) the quality of the data becomes dependent on the quality of both the downstream and upstream flow data.

Figure 3: subtract and leaf catchments



As the size of the subtract catchments becomes relatively smaller compared to upstream catchments as illustrated in the right hand plot of Figure 3, the flow measurement uncertainty becomes an increasingly significant portion of the net flow from the subtract catchment. It is not uncommon for the measurement uncertainty to be 50% or more of the net flow from the subtract catchment. It is important to be aware of the measurement uncertainty when reviewing results from subtract catchments, in order to avoid making decisions based upon poor data. In respect of subtract catchments, we recommend:

1. Subtract catchments are avoided where possible.
2. Quality requirements in gauging specifications are high.
3. The reliability of the outcomes is considered during assessments and subsequent recommendations.
4. Outcomes are presented as net catchments as well as gross catchments (total area and flows upstream of a gauge).
5. If the upstream catchment is large, the limits of flow measurement accuracy can easily become a very significant portion of the total flow from a small downstream catchment. Flow monitors need to be located with this in mind, so as to avoid wasted money and effort.

2.3. GAUGE LOCATIONS

When choosing sites for locating flow gauges the following considerations need to be taken into account:

- Desired size of catchments.
- Avoiding subtract catchments where practicable.
- Accessibility including health and safety related to access for installation and periodic site visits.
- Outside the influence of pump stations. Both downstream of a pumping station outlet as well as upstream where the flows are influenced by stop/start behavior.
- Avoiding additional relatively large upstream catchments (as explained in section 0).
- Clear of locations where likely backflow occurs from downstream parts of the network.

2.4. THE IMPORTANCE OF SOIL MOISTURE LEVELS

In stormwater analysis, the relationship between rainfall annual recurrence interval (ARI) versus runoff ARI is assumed to be 1 to 1, i.e. the 2-year rain storm results in the 2-year runoff peak flow and volume. For RDII and consequential wet weather overflows, this is not the case due to the influence of soil moisture (antecedent conditions).

Our experience has shown that it is common that a large storm event in summer produces little response (RDII) in the sewer. The reason for the lack of response is that the low soil moisture enables much of the rainfall to be absorbed, with the result that little of the rainfall enters the sewer. By contrast, the same event occurring in winter, when soil moisture levels are high, would produce a large response in the sewer. For example, a 6-month rain storm in summer after a long dry period may result in no sewer capacity issues, while a 1-month rain storm in winter after a prolonged wet period may result in numerous sewer capacity issues. If correctly calibrated, a hydraulic model enables the two scenarios described above to be accurately replicated within the hydrological model.

Understanding the different responses of the sewer to different soil moisture conditions is an important part of assessing the I/I of a catchment. For example, if the I/I results are based on a flow gauging study undertaken in summer, it is possible that the conclusion would be that the catchments have low levels of rainfall-induced I/I. Similarly, a flow gauging study carried out only in winter could possibly overstate the average response of the catchment to the storm, when considered over a year.

When calculating I/I for Christchurch, 15.9 years of historic rainfall data was run through the 2011 wastewater network model. Assuming that this model is properly calibrated, this long-term analysis allows for a more statistically robust assessment of I/I, by ensuring that the analysis comprises several years of differing environmental conditions when determining the long-term average leakiness of the network. However, the modelling results are dependent on the reliability of the calibration.

2.5. WHAT EVENTS SHOULD BE USED?

I/I is dependent on rain event characteristics as well as on antecedent (soil moisture) conditions, catchment characteristics and many other factors.

Small storms are of little interest for the following reasons:

- The antecedent conditions (soil moisture) have a relatively greater influence on the wet weather response in the sewer, causing a large scatter of I/I results and greatly decreasing the confidence in any I/I values calculated from small events.
- Small rainfall events often have a larger spatial variation. It is difficult to decide whether the rain gauge results are representative, and therefore able to be used for the assessment.
- Model calibrations to small events are difficult and usually poorly match measured flow data.

Figure 4: scatter of RDII% results against rainfall event ARI

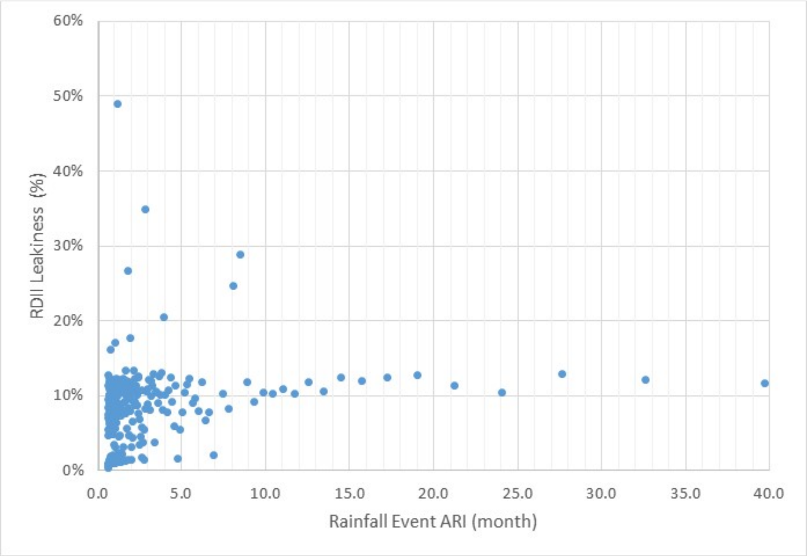


Figure 4 shows an example of RDII versus rainfall ARI in a Christchurch catchment using the 15.9 year time series of rainfall data. The scatter during the smaller storms is large. During the bigger events the RDII converges.

Larger storms are also of limited interest. The reasons are:

- It is unlikely that large storms would be captured during a short gauging period.
- During very large storms the hydraulic response will change e.g. because of limited entry capacity into a network. For example, the network may already be surcharged, with the hydraulic grade line higher than the surrounding groundwater table. In this situation the measured flow would not take into account the potential I/I during a large event, because the stormwater cannot get into the sewer.
- Our experience has shown that unfortunately a common mistake is for hydraulic models to be calibrated to a large storm, where an overflow was occurring upstream of the flow gauge. Therefore, we recommend that for larger events the hydraulic modeller needs to check that there are no limitations in the hydraulic network which are preventing all of the flow reaching the flow gauge, before and during the hydraulic model calibration process. In this situation only the tail/recession of the storm in the days after the peak of the event will be useful for calibration purposes.

In the Christchurch example, of the eight rainfall events for the flow gauging I/I analysis (four events for two sets of gauge locations), seven storms were in the range of return periods between one and five months, and one event had an 11 month return period.

2.6. GAUGING PERIOD

For I/I analyses gauging data should include some continuous dry weather periods to determine the dry weather flow hydrograph (see I/I manual, section 5.2) and a number of wet weather events to allow for the calculation of I/I parameters (ingress and peak flow). Weekly DWF patterns need to be incorporated in the assessments. In addition there is a need to cover a range of soil saturation levels in order to account for the differing response to various antecedent conditions, as explained in the previous section.

Because of the cost of flow gauging, there is a temptation to make the gauging period as short as possible. Often the flow monitoring period has proven to be too short for robust I/I analysis. It is common that during data processing some events cannot be used for a range of reasons, such as the quality of the gauge data or the way the system was operated during an event. Ultimately this can lead to sub optimal sewer rehabilitation solutions which can cost orders of magnitudes higher than additional flow gauging and I/I assessments.

To minimise this risk of getting incomplete data sets, some flow gauging specifications have included requirements on completeness: no data – no pay. Because of the aggressive physical environment that flow gauges are located in, it is to be expected that there will be data gaps. After many years of experience and with the current technology for data capture and wireless data transfer, we suggest it might be more cost effective to gauge for longer periods while reducing (expensive) site visits and accept (some) data gaps. If the gauging period is long enough there will be enough wet weather events to choose from later and the gauging period is more likely to catch a range of soil moisture levels.

Monitoring that captures flows when soil moisture levels are at their annual lowest, right through the time when soil moisture levels are at their highest is likely to provide the best range of conditions against which to calibrate a hydraulic model which can accurately replicate the I/I in the network. At critical points in the network it might be justified to install permanent flow gauges. If this is not possible we suggest at least three months for sub catchment gauges in the winter (May-November) with a minimum of three dry weather periods totalling at least 10 days and a minimum of five wet weather events with an ARI of between two months and two years. When using a limited period, it is important to check whether good quality data have been captured before the gauges are removed. The targeted mini-catchment flow gauges could be then supported by 6 to 12 months of gauging data in trunk sewers or at strategic locations, making sure that the catchments are representative of conditions in the target monitoring area, including factors such as soil type, similar groundwater levels, sewer material types and ages.

2.7. PUMP STATION FLOW DATA

The following section describes issues are encountered when using pump station data.

2.7.1. PUMP STATION FLOW DATA

To assess I/I using pump station data, incoming flows are required. However, pump station flow measurements are often only of outgoing flows. If the incoming flow rate exceeds the pump-out rate, the flow data flat-lines at the pump station capacity, which makes an accurate hydraulic model calibration difficult if not impossible. To overcome this problem at pump stations, incoming flows are derived from outgoing flows and storage/level relationships. Many difficulties can arise, which if not addressed, may result in the calculated inflow not being accurate enough.

2.7.2. INSTALLED OR NOMINAL CAPACITY IS UNRELIABLE

The nominal (design) capacities of pump stations are often not the actual capacities. Draw-down tests are required to confirm the actual capacity of the pumps during the assessment phase. Pump rates can change throughout a monitoring period due to ragging or partial blockages of pumps.

2.7.3. MAGNETIC FLOW DATA (METERED DATA)

Although magnetic flow data (metered data) connected to pump stations are more reliable than just using pump capacity, they are still outgoing flows, not incoming flows.

2.7.4. INACCURATE START AND STOP LEVELS AND WET WELL VOLUMES

It is important to confirm the start and stop levels of pumping stations. They have often been changed after installation and sometimes not well documented or verified. In some cases some of the storage between start and stop levels includes storage in the incoming pipes. Depending on the equipment installed, start and stop levels can change without warning throughout the monitoring period due to fat build-up or other reasons.

2.7.5. MANUAL OPERATION

The actual operation of the pump station is sometimes different to the assumed operation. This can occur by manual intervention by operators, which usually happens during the wet weather events of interest in I/I analysis. An example is the manual starting of a pump i.e. overriding the start level. Network operators need to be instructed during the gauging period to avoid ideally any manual overriding of automatic setting, and if any manual intervention is undertaken carefully record this. A detailed operational diary of any changes in the network and its operation is recommended.

2.7.6. AGGREGATED DATA

SCADA systems are generally not set up with the objective to capture and analyse flow data for I/I analyses. SCADA systems often aggregate data to large time intervals (e.g. every 15 minutes, every hourly or every day). This is because of the communication processes associated with SCADA systems, which were not necessarily developed for detailed data capture. For flow analyses pump start and stop times should to be logged to the second. Ideally, the equipment will log the wet-well level on the change of a pump state (i.e. off to on, or on to off), and at either a timed interval in between, or based upon a pre-set percentage change in level. The more resolution, the more reliable the data.

2.7.7. SUMMARY OF ISSUES WITH PUMP STATION DATA

Because of these issues, pump station data often turns out to be unusable at worst, or less accurate compared to in-pipe flow gauge data. Some of these issues can be prevented through good pre-planning. It is important to use as-built information, recently recorded draw down tests and monitor the wet-well levels throughout the monitoring period. In general pump station data can still be very helpful because pump station data records often provide a much longer record of network operation, which can assist in validating the model, and provide indicative assessments as long as the inaccuracies and related assessment outcomes are well understood.

2.8. IN-PIPE GAUGING DATA

When done well, in-pipe flow gauge data is usually much more accurate and reliable than pump station data. In-pipe flow monitors capture the actual incoming flows from a catchment. However, it is not easy to undertake good quality flow gauging, so it is important that gauging specifications are used to ensure good quality data is delivered.

The flow monitors should be calibrated as part of the contract and checked by an independent review. Surprisingly common mistakes that can have enormous effects on the reported flows include:

- Flow monitor not installed in the correct pipe.
- Pipe diameter not correctly used in flow calculations.
- HVQ (height, velocity, flow) gauges:
    - The flow can be determined using either the Continuity Equation (Flow=area x velocity) (preferred) or the well-known Manning’s equation.
    - If the velocity data is unavailable, the Manning’s equation can be used as a backup, as it is dependent on depth (and not velocity), provided the friction values are well understood at the site.
    - Two common failures are: 1) Mannings flow data that has been calculated incorrectly, and/or 2) the corollary; poor or non-existent continuity data ($Q=v*a$) being delivered when good Mannings data was available.
- For weir gauges, the weir equation being applied at times when the weir equation is invalid, due to the not forming correctly (e.g. due to backwater effects) or ragging of the weir.
- Flow monitor data being blindly trusted, and not supported or verified by manual measurements.

Given that incorrect flow monitor data could potentially trigger millions of dollars of capital expenditure, we recommend that water authorities employ a robust flow monitoring specification, use only experienced flow monitoring companies and arrange for an independent review of the installation and the data. We believe that it is important that the review is carried out during the monitoring period (i.e. to verify that the correct pipe is being monitored), and on submission of the final flow monitoring data (Henderson, (2012); Water NZ,).

Example of inconsistent gauge data when cross checking against other catchments is shown in Figure 5.

Figure 5: Example of inconsistent gauge data

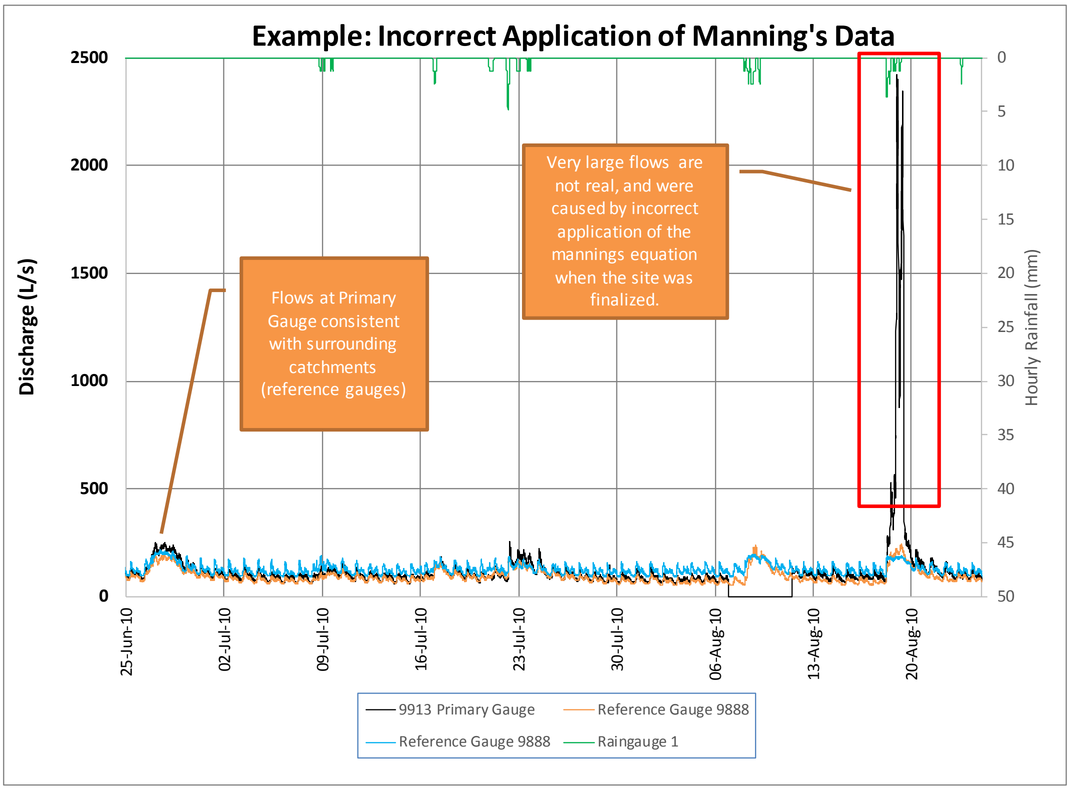


Figure 5 shows an example of inconsistent gauge data when cross checking against other catchments. This shows a high-level check of flow gauging identified erroneous data. The premise of the check was that catchments usually respond in a similar fashion, and anomalies are likely either an error, or a real event that needs to be understood. The black data series shows the gauge being checked. Adjacent catchments (in blue and orange) are plotted for reference, to help identify anomalous behaviour. Rainfall is shown in green. The behaviour of the all three catchments for first three storms is similar. The fourth storm in the record (20 August 2010) can be seen to have flows much larger than the reference gauges. Further investigation into the gauging records for this site revealed that the flows during the 20 August storm were calculated using the Manning’s equation (because velocity was temporarily unavailable for the storm, hence the continuity equation could not be used to calculate the flow) and that the Manning’s equation had been incorrectly applied, resulting in the final flow data being reported to be much larger than in reality.

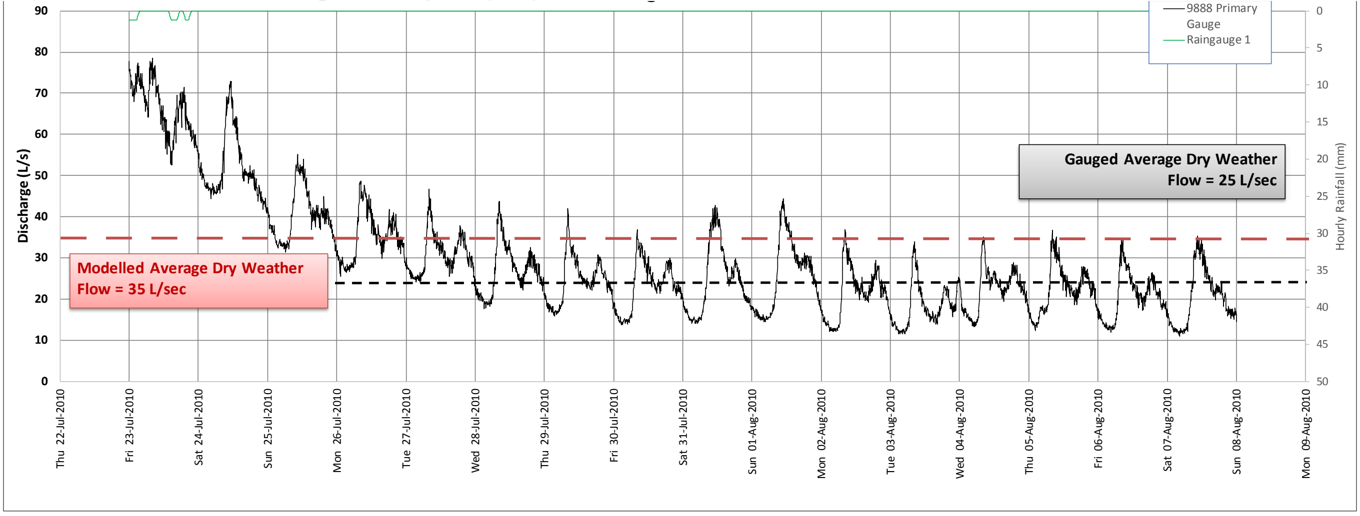
2.9. MODEL CALIBRATION

The reliability of I/I assessments is very dependent on the reliability of the model. A well calibrated model is indispensable. Calibrating models to mimic I/I has been proven a challenge but very good calibration results are possible using the appropriate models, good flow gauge data and skilled staff. Models are often built and calibrated with a purpose other than I/I assessment, such as an assessment of (trunk) sewer capacity during peak flows. For this purpose a satisfactory calibration during these peak wet weather flows is adequate to meet its purpose, and calibration during dry weather or smaller storms is less important.

For I/I assessments good calibration for both dry and wet weather is essential because the RDII calculation is the difference between the total wet weather flow and the dry weather flow. If the dry weather flow calculated using the model is too low, then the RDII will be too high and vice versa.

Figure 6 shows an example where a calibrated model was used for an I/I assessment. The black line shows the flow gauge results during a dry weather period. The diurnal pattern is clearly visible as well as the tail of a storm just preceding the dry weather period (rainfall plotted as green line at the top of the graph). The average daily dry weather flow of approximately 35 L/s, calculated from the model results, was super imposed on this graph (red line). It clearly shows that the model calculates a significantly higher dry weather flow compared to the 25 L/s that was measured. This suggests poor dry weather flow calibration at this site. This means that when the model over predicts the dry weather flows, the calculated RDII levels are under predicted.

Figure 6: model DWF compared to flow gauge data



It is important to verify the quality of the model calibration during both dry and wet weather flow.

2.10. MODEL RUNS

A well-built and calibrated model will represent the best understanding of the wastewater network and encapsulate a number of assumptions including:

- Existing asset arrangement
- Existing operational regimes
- Dry, wet and base flow – requires gauging data and calibration (including I/I)
- Future network configurations
- Future flows (due to growth, deterioration, impact of climate change etc.).

Based on these assumptions network performance issues can be identified and solutions to these issues can be developed. The power of model analysis is in the option analysis, where numerous network configuration and changes in loading assumptions can be made to develop a cost optimal solution. In particular comparison of leakage characteristics between sewer catchments, is most reliably done using a calibrated model where the impact the antecedent condition can be accounted for. This allows for identification of catchments suitable for I/I reduction, and the prioritisation improvement works.

Generally, to assess network and RDII performance a long term simulation (LTS) is undertaken, in the order of at least 10 years of rainfall record. This takes account of a range of antecedent impacts on network performance and allows a statistical approach to developing network performance (i.e. RDII responses and spill frequency responses. It is this frequency upon which a network discharge consent authorising overflows to the environment may be based. Conversely adopting a design storm approach to the assessing of performance is often overly conservative and can result in excessive capital works being committed, due to errors in applying antecedent conditions (and hence simulating the RDII response) and that rainfall ARI does not necessarily correspond to sewer flow ARI. In short, for separate sewer network a LTS approach using models is preferred, to assess performance and develop solutions due mainly to the influence of RDII network performance.

2.11. DIFFERENCE BETWEEN USING GAUGING VS MODELLED DATA

2.11.1. COMPARING THE METHODS

The I/I assessment project in Christchurch enabled us to compare I/I assessment outcomes using (raw) flow gauging results against wastewater network model outputs. The differences between the two methods are summarised in Table 1.

Table 1: Model based I/I assessment compared to Flow Gauge based I/I assessment

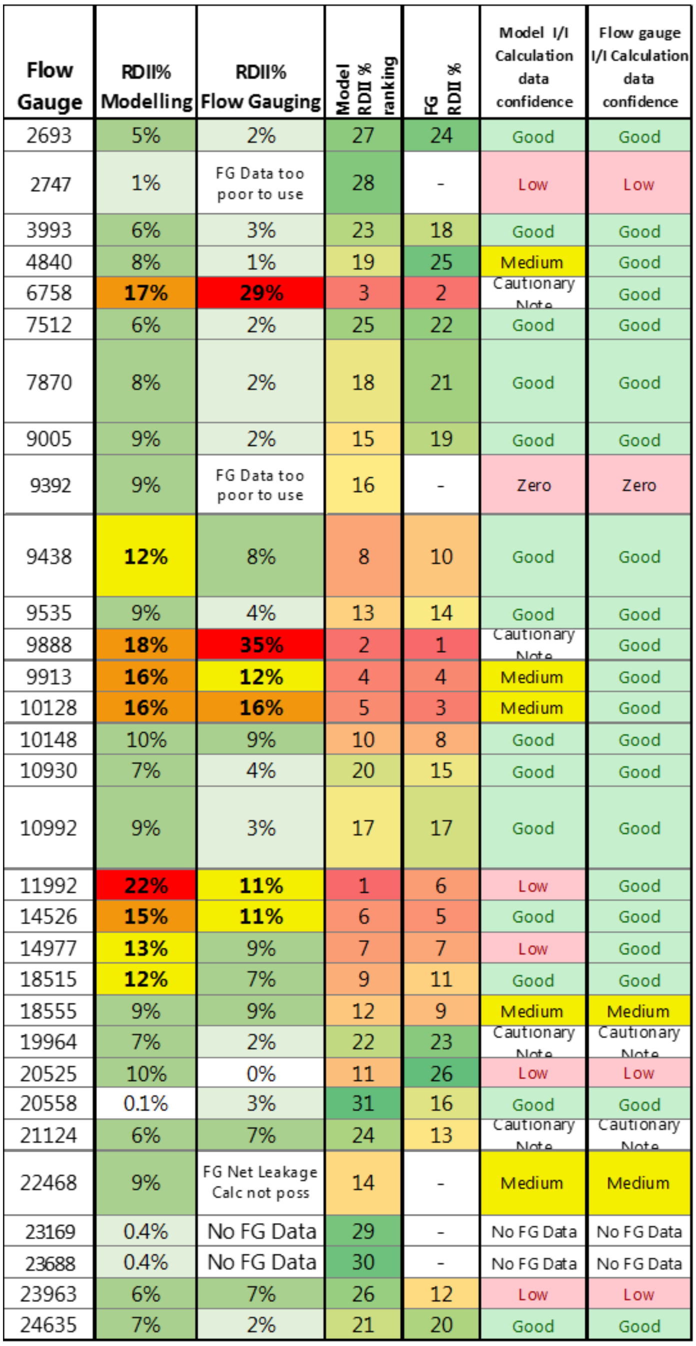
	Model based assessment	**Flow gauge based assessment**
Type of events	Simulated events	Real events
Accuracy of flow calculation	The hydraulic model is only as good as the data used to calibrate it. Therefore, the model is dependent on the quality of flow gauging data. Errors in sewer flow gauging data are common, and need auditing to confirm quality before these are being used for calibration purposes and flow gauge based assessments. Depending on calibration – note, a model can be calibrated for a different purpose (say design flows) and might not have a reliable calibration for I/I purposed (range 2 month – 2 year ARI events).	Depending the range of events and soil saturation levels used and Depending on the quality of flow gauging – needs auditing to confirm quality. As described above, reported rates of I/I can be biased by soil moisture levels occurring at the time that flow gauging was undertaken.
Range of events	Many events between 2 month and 2 year ARI	Limited number of events
Statistically robust?	Provided both the flow gauging data is accurate, and the calibration is accurate, then yes, the hydraulic model outputs are statistically robust.	No
Suitable for post rehabilitation assessment?	Yes; because the same rainfall series is used to compare pre and post rehabilitation flows. The use of a hydraulic model also enables any changes in the catchment to between the pre- and post-flow gauging studies be negated out; e.g. population growth, or differing soil moisture levels between the years that the flow gauging studies were undertaken (i.e. a wet year versus a dry year).	No
Conditional	Need a well calibrated model	Need range of suitable events

2.11.2. COMPARING THE RESULTS

Table 2 shows the outcomes of the RDII% assessments based on modelling results compared to those based on flow gauging results for Christchurch. It is clear that the two results do not have a direct relationship. However, this is expected for all the reasons explained above with antecedent conditions being the most important ones. Furthermore, the I/I rates calculated directly from flow gauge data are based on only four storms for any one gauge, whereas the model results are based on 15.9 years of recorded rainfall and evaporation data.

It is expected that the relative order of the catchments in the study should be similar regardless of the calculation methodology. Considering only the RDII of the catchments means that the effects of antecedent conditions on the quantum of I/I ingress determined from the flow gauging results become less significant. Where the ranking of the flow gauge RDII varies significantly from the hydraulic model results, this disagreement should be investigated and understood. While the difference may be real, our experience is that the difference is mostly due to limitations in the available data, or a mistake in the hydraulic model.

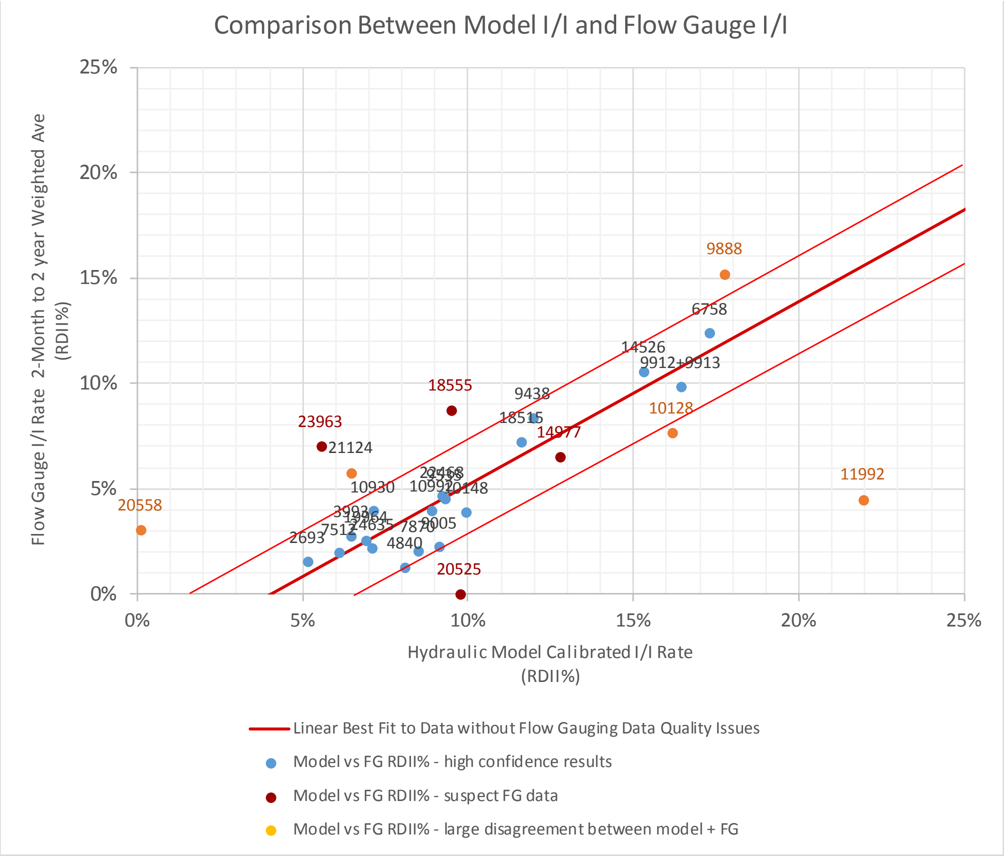
Table 2: RDII% outcomes compared between model based and flow gauge based assessments.



Flow Gauge	RDII% Modelling	RDII% Flow Gauging	Model RDII % ranking	FG RDII %	Model I/I Calculation data confidence	Flow gauge I/I Calculation data confidence
2693	5%	2%	27	24	Good	Good
2747	1%	FG Data too poor to use	28	-	Low	Low
3993	6%	3%	23	18	Good	Good
4840	8%	1%	19	25	Medium	Good
6758	**17%**	**29%**	3	2	Cautionary Note	Good
7512	6%	2%	25	22	Good	Good
7870	8%	2%	18	21	Good	Good
9005	9%	2%	15	19	Good	Good
9392	9%	FG Data too poor to use	16	-	Zero	Zero
9438	**12%**	8%	8	10	Good	Good
9535	9%	4%	13	14	Good	Good
9888	**18%**	**35%**	2	1	Cautionary Note	Good
9913	**16%**	**12%**	4	4	Medium	Good
10128	**16%**	**16%**	5	3	Medium	Good
10148	10%	9%	10	8	Good	Good
10930	7%	4%	20	15	Good	Good
10992	9%	3%	17	17	Good	Good
11992	**22%**	**11%**	1	6	Low	Good
14526	**15%**	**11%**	6	5	Good	Good
14977	**13%**	9%	7	7	Low	Good
18515	**12%**	7%	9	11	Good	Good
18555	9%	9%	12	9	Medium	Medium
19964	7%	2%	22	23	Cautionary Note	Cautionary Note
20525	10%	0%	11	26	Low	Low
20558	0.1%	3%	31	16	Good	Good
21124	6%	7%	24	13	Cautionary Note	Cautionary Note
22468	9%	FG Net Leakage Calc not poss	14	-	Medium	Medium
23169	0.4%	No FG Data	29	-	No FG Data	No FG Data
23688	0.4%	No FG Data	30	-	No FG Data	No FG Data
23963	6%	7%	26	12	Low	Low
24635	7%	2%	21	20	Good	Good

Figure 7 shows the same results in a graph. While some variance between flow gauge based I/I calculations and model based I/I calibrations is to be expected, a large difference in the rank of the results may indicate a problem with the model calibration, or some other issue, which needs to be better understood.

Figure 7: RDII results based on model results and flow gauging (compared)



2.11.3. DISCUSSION

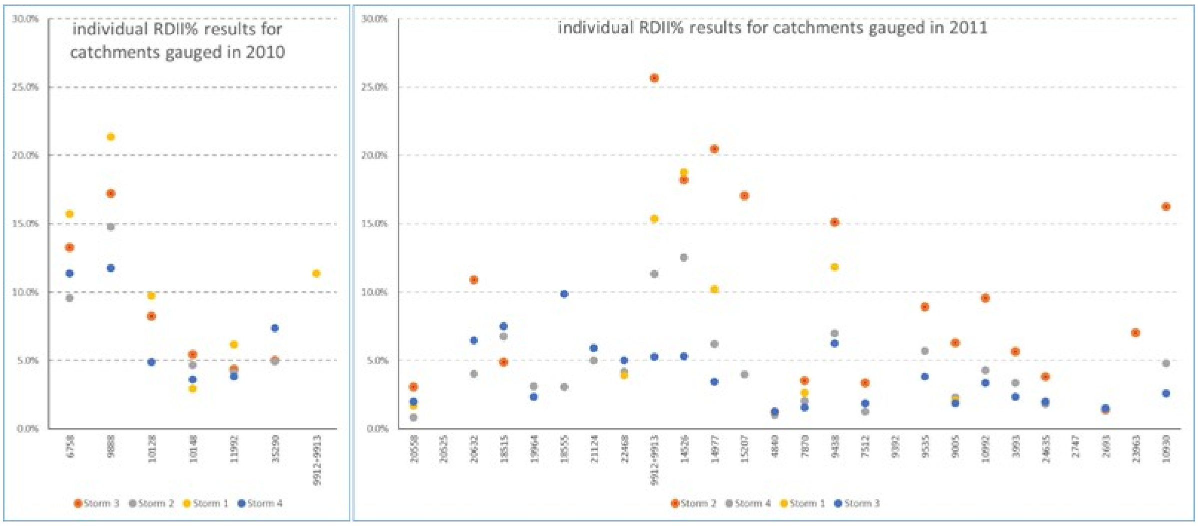
When calculating the rate of I/I leakage directly from flow gauge data, the results are entirely dependent on the prevailing short and long-term weather conditions. For example, is it a particularly dry or wet year? Experience has taught us that antecedent soil moisture levels have a significant effect of the calculated I/I values. Did small or large storm events occur during the monitoring period? As Figure 8shows, the calculated percentage of rainfall ingress increases for large storms. (Note that what isn't shown in Figure 8 is that the increase in wet-weather ingress will change to a decrease once the network starts to reach the limit of its ability to convey additional flows)

Because of the large effect that the storm size has on the rate of ingress, it should be expected that I/I values calculated using flow gauge data alone will vary significantly. For example, if, by chance, only small storms occurred during the flow-monitoring period the calculated leakage rate would be smaller (or under estimated), than a gauging period consisting mostly of large storms. We have chosen to weight the ingress rates calculated from individual storms based upon the storm size, to align, as best possible, the results that are produced by a long-term simulation run in a hydraulic model.

It is for these reasons, that I/I ingress rates are best calculated using a well-calibrated hydraulic model, as the biasing effects of dry and wet years can be reduced. For example, when calibrating the hydraulic model, the calibrations should done only after one year's rainfall is pre-run through the runoff/leakage model, in order to align the hydrological model with the prevailing long-term weather conditions that exist during the flow monitoring period.

When using I/I assessments based on only flow gauge results, the I/I parameters are typically averaged over the storms that have been used. Figure 8 shows the scatter of RDII% results across the events used for the Christchurch catchments. Not all of these events were always able to be used for the analyses because of flow gauge data quality. The scatter illustrated the randomness of I/I results when only using gauging results.

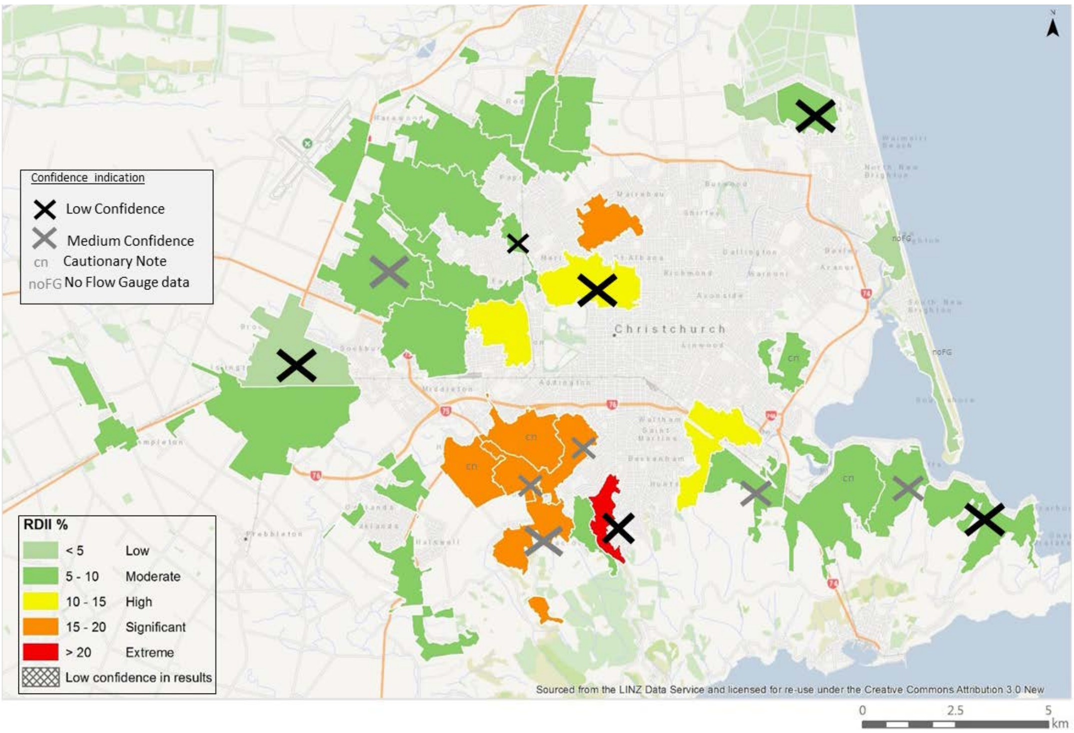
Figure 8: scatter of RDII results based on flow gauge data cause by the different events



2.12. BETTER UNDERSTANDING OF DATA CONFIDENCE

Using both the modelling and flow gauging methods for Christchurch provided an opportunity to compare gauging data against model data. We were able to look at dry weather flows and responses against rainfall (RDII). Although this has taken considerable effort, this has provided the opportunity to undertake an extensive data confidence assessment. A significant number of I/I assessment outcomes were assigned a medium to poor confidence, as shown in Figure 9. This was caused by many factors, such as the flow gauge data quality; highly variable industrial water use; and the quality of the dry and wet-weather calibration of the model. This does not imply that the results are not to be used, but that any further actions need to consider / investigate the reasons for the lower confidence

Figure 9: RDII results mapped also showing confidence levels



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Although we consider an I/I assessment based on modelling to provide a more reliable and robust outcome, hydraulic model outputs are entirely dependent on the model calibration. Had a validation of both the source flow gauging data; and the hydraulic model's calibration not been undertaken, the potentially erroneous hydraulic model outputs would not have been detected. In the example above, many of the catchments with significant to high RDII results have a low to medium data confidence. The obvious risk is that, in the absence of this data confidence assessment, significant investment might be spent in the wrong areas.

Having well calibrated models supported by flow gauge results capturing a wide range of dry and wet weather periods as explained above is ideal for carrying out reliable I/I assessments.

2.13. WET WEATHER PARAMETERS

In the Christchurch project we used the following wet weather parameters:

RDII%: the total volume of rainfall entering the wastewater network as a percentage of the total rainfall in the catchment.

RDII 2: the total volume of rainfall entering the wastewater network per length of public sewer.

The reason for the use of this second RDII parameter was that we observed during the project that the average sewer length per catchment (m/ha) varied considerably. This can be caused by a different network pattern, such as in commercial areas where there is likely to be a large street-grid, or where there are large reserve areas. The I/I into the network is more likely to originate from the direct surroundings of the pipe locations, so we also calculated the volume of RDII per length of piped network (m^3 RDII per m public sewer). For this reason it is arguably a better indicator for RDII, however there is no industry accepted grading available.

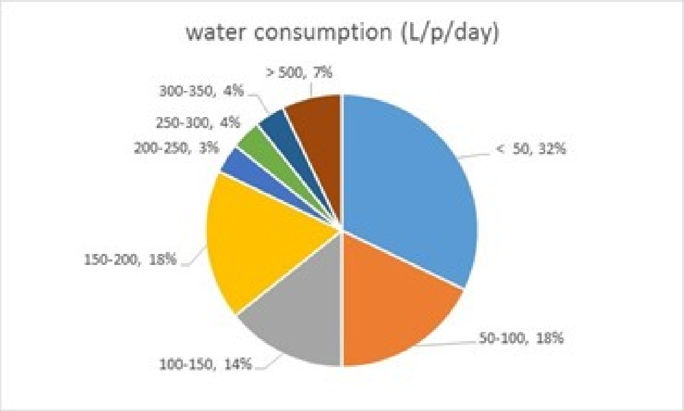
For this project it was decided not to include the consideration of peak flows, as the main purpose was to assist in predicting reductions of RDII volumes during a network optimisation project currently underway. Peak flows are not used in this process. In addition peak flow calculations are often more erratic, not often used in network analyses and more time consuming to calculate. They can be very useful in illustrating peak flows during storms to the wider public and are useful when looking at peaking factors.

2.14. DRY WEATHER PARAMETERS INCLUDING GROUND WATER INFILTRATION

2.14.1. WATER CONSUMPTION

To enable the groundwater infiltration (GWI) indicator to be calculated, the metered water consumption per catchment is required. This is most accurate if it is based upon water consumption metered for each individual property. Water consumption can vary widely for many different reasons within a city and between cities. It is not advised to use consumption rates from other cities because of different climatic circumstances, whether volumetric charges are applied and whether there is an active water demand strategy implemented. Figure 10 illustrates how much water

Figure 10: range of water consumption based on water meter readings



consumption can vary by property hence using a city wide average would show very different RDII results.

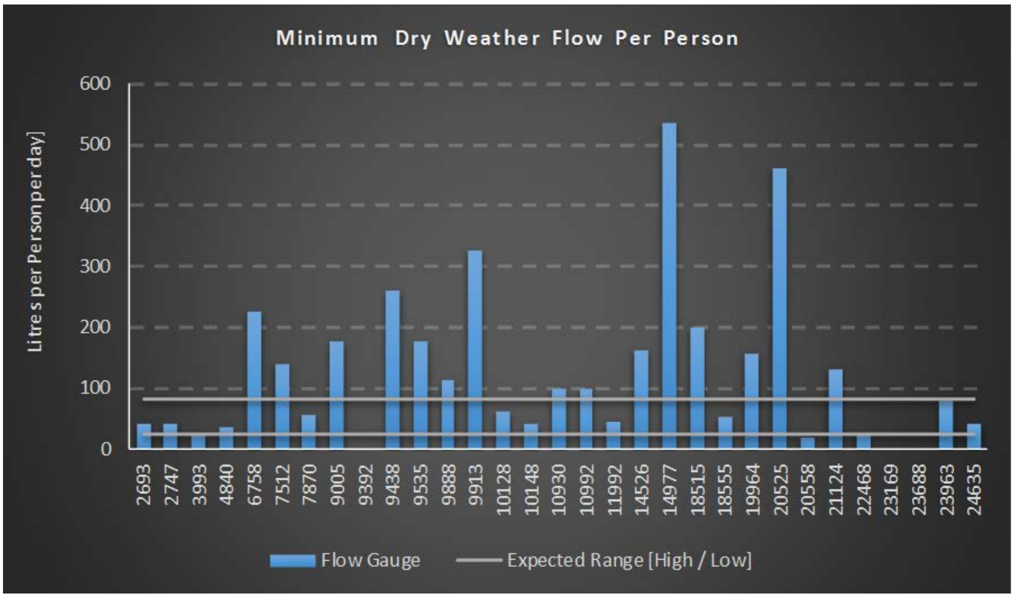
2.14.2. GROUND WATER INFILTRATION

In many ways, excessive groundwater is a greater problem than wet weather ingress (RDII), as it is happening constantly, not just when it rains. These flows take up sewer capacity that would otherwise cater for existing and future (growth) demand, and leaves less capacity to convey wet weather flows resulting in increased wet weather overflows. It is therefore beneficial to add an assessment of groundwater infiltration in the scope of any I/I assessment.

Minimum dry weather flow (DWF) typically occurs at around 4:00am when the water use from the resident and commercial population is at its lowest. At this time of day (with the exception of catchments where continuously operating wet industry users exist) the majority of the flow is likely to be from groundwater infiltration. There is no industry standard for this parameter. Based on an average water use of between 250 and 300 L/person/day, no more than at a rate equivalent to about 50 L/person/day would be expected, and this would be at the high end of the range. Including an assessment of ground water infiltration in to the scope of any I/I assessment can be very useful.

The minimum dry weather flow per person in Christchurch is shown in Figure 11. This shows a large number of catchments as having large to very large volumes observed in the middle of the night. Almost all of these are in residential areas with a small likelihood of commercial discharges, therefore implying large flow of groundwater entering these catchments. Further detailed, possibly more targeted investigations would need to be carried out to understand the reason for these large flows.

Figure 11: minimum dry weather flow per catchment



2.15. COMPARING I/I RESULTS

There are two reasons to compare I/I performance parameters:

1. To determine pre and post sewer rehabilitation I/I rates
2. To monitor change in I/I over time

An assessment of performance before and after sewer rehabilitation is important. The predictability of the achievable reduction of inflow and infiltration is less certain compared to other options for network capacity improvements, such as increased conveyance or storage. What is actually achieved needs to be considered when reviewing the scope of outstanding improvement works.

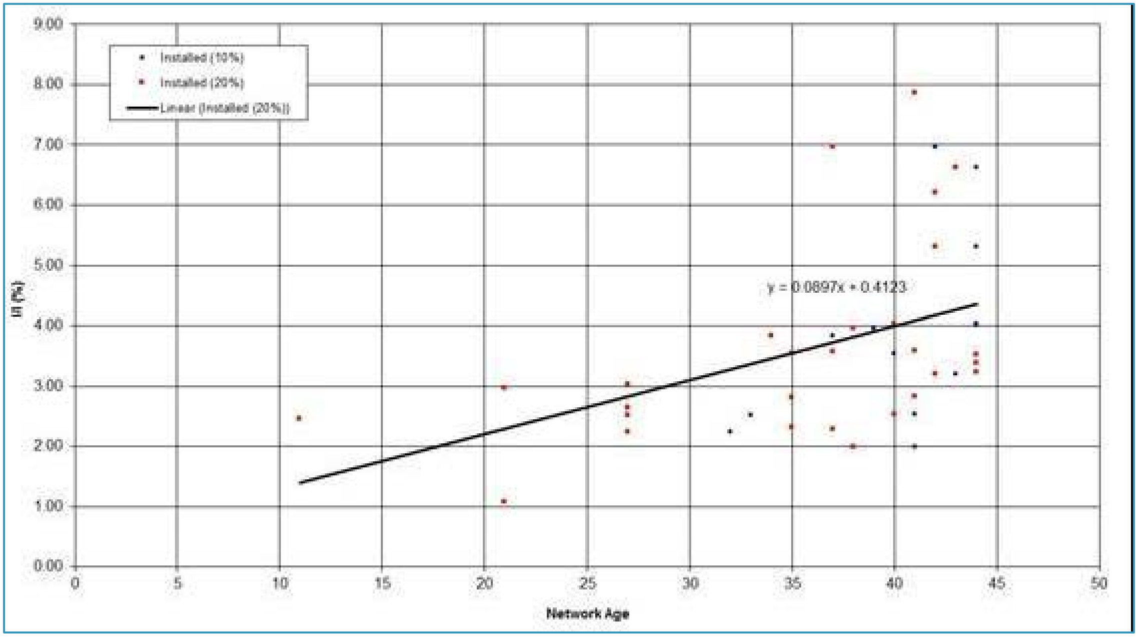
When comparing I/I performance before and after sewer rehabilitation, it is essential that the same events are used and this can only be achieved by applying long term series rainfall data to a well-calibrated wastewater network models. This comparison is not possible using flow gauge results, because a different set of storms and antecedent conditions will be captured and are therefore not comparable.

The only reliable way to compare these results is to use long term time series applied to models calibrated to the I/I results that are being compared. So two models are required. One calibrated to before and one calibrated to after rehabilitation flow gauge results. This is conditional on the models being well calibrated to support I/I assessment.

2.16. SYSTEM DETERIORATION AND RENEWAL PROGRAMMES

There is very little known about system deterioration rates. In general networks will get leakier as they get older. Many variables such as pipe material, workmanship and age will influence the I/I rates. Figure 12 shows the RDII rates calculated in North Shore City around 2007 as a function of network age. It shows that RDII increases with pipe age.

Figure 12: increasing leakiness over time



2.17. INTEGRATION OF RENEWAL PROGRAMMES

At some point every part of the network needs renewal or replacement. Depreciation is often used to fund renewal programmes. Typically renewal programmes are based on pipe condition and criticality. A large part of New Zealand is facing an increased renewal need as the networks get older. I/I is an additional consideration to get more benefits out of a renewal programme. Integration between I/I reduction works and other renewal programmes is recommended. Depending on the water network operator's financial system, part of an I/I reduction programme can be partly funded through the wastewater network renewal programme (often linked to depreciation).

2.18. COST EFFECTIVE IMPROVEMENTS IN INFLOW AND INFILTRATION

Although this is not in the scope of this paper, it is important to note that there is a limit to what I/I reduction can realistically achieve. An effectiveness assessment based on RDII and peak flow before and after sewer rehabilitation (RDII and peak flow) was completed for Watercare Ltd. (Shaw, 2011). While the lining of 100% of the public sewers, and repair of 100% of identified private property defects was targeted, these targets were never achieved for a range of reasons. The study showed that I/I reductions were most cost effective for catchments with very high RDII (>15%) and also showed that the benefits of sewer rehabilitation decrease rapidly when RDII is less than 10% before rehabilitation. Values higher than 10% are likely required to make the percentage reduction in I/I high enough to warrant the commissioning of renewal works. The outcomes of this study have been used in the I/I manual.

2.19. FALSE ECONOMY – COST OF GAUGING AND MODELLING VS COST OF SEWER REHAB

It is not cheap to undertake flow gauging, wastewater network model build and calibration, and an I/I assessment. Often these types of expenses are funded from operational budgets. It is our experience that I/I leakage rates vary widely across a network and focussing sewer rehabilitation on the catchments with the highest I/I is the most cost effective and also has more certain I/I reduction outcomes. Based on the example provided in section 2.1, flow gauging, model build and calibration and undertaking an I/I assessment when breaking this 200ha catchment up into 13 sub catchments would cost around 2% of the total cost for rehabilitation. Given the expense of comprehensive sewer rehabilitation, we believe this expense is worthwhile.

2.20. COUNCIL KNOWLEDGE AND NEED FOR CAPACITY BUILDING

We have tried to demonstrate that I/I management is complex and that there are significant risks. It is important that staff are aware of these risks and ensure the scope of any I/I assessment project is robust.

We suggest it is important that some basic knowledge about I/I assessment is acquired within the water network operator to ensure projects are well managed and outcomes understood.

3. SUMMARY AND CONCLUSIONS

An increasing number of water authorities are concerned about inflow and infiltration (I/I), but a common theme is that organisations realise there exists a significant response to rainfall in their separated networks, but often do not know how big the problem is, how to carry out carry out a reliable assessment and how to identify the most cost effective solutions to combat I/I. In addition there is often insufficient time and budget available to carry out these assessments.

With the publication of the Water NZ Inflow & Infiltration Control Manual, more guidance is available in I/I management. However, undertaking I/I assessments, whether based on flow gauge results or modelling outcomes, is more complex and has high associated risks that are not covered in the I/I manual.

As wastewater networks age, managing stormwater inflow and groundwater infiltration is likely to become increasingly important in controlling wet weather overflows and in servicing growth. In theory there should no rainfall ingress or groundwater entering a separated wastewater network, but in practice significant volumes do occur.

Inflow and infiltration (I/I) is never spread evenly across a network. Often just a small percentage of the network contributes disproportionately to I/I related problems. Sewer rehabilitation to reduce I/I is expensive and should therefore be targeted at those areas that will reduce I/I the most and are therefore the most cost effective. Using catchments that are too large, sometimes in an effort to save on flow gauging and modelling expenses, will average out I/I results and consequently not enable the network operator to target the parts of the network with the highest I/I.

Understanding the different responses of the wastewater network to different soil moisture conditions is an important part of assessing I/I. Storms that trigger an overflow event in a wet period might not trigger a response in a middle of summer, as the dry soil absorbs more of the rainfall. Using a well-calibrated hydraulic model with a long term series rainfall record enables assessments based on a representative range of soil moisture conditions and hence a more accurate behaviour of the network performance and ultimately ensuring efficient capital expenditure.

The reliability of I/I assessments based on modelling outcomes is dependent on the calibration of the model. Models are often built and calibrated with a different purpose such as an assessment of (trunk) sewer capacity during peak flows. Models used for I/I assessments also have to be well calibrated for dry weather flow, otherwise errors result in the calculation of Rainfall Dependent Inflow and infiltration (RDII). A well calibrated model using a range of dry and wet weather events including soil moisture conditions based on high quality gauging is essential.

Undertaking I/I assessments based only on flow gauge data are unlikely to cover the range of storms and soil moisture conditions needed to provide a reliable I/I assessment, and are therefore less statistically robust than an I/I assessment using long term rainfall data and a wastewater network model. However, good quality flow gauge results are essential to calibrate the model and are very useful to undertake data confidence assessments of the I/I results based from a hydraulic model.

An inflow and infiltration assessment recently undertaken for Christchurch City Council was based on two methods: using flow gauge results and using a hydraulic model. This provided the opportunity to compare assessment methods and results. If the I/I assessment undertaken for Christchurch City Council was based only on wastewater network modelling results, a number of catchments would have been prioritised without identifying possible issues with some of those results.

High groundwater infiltration was identified in some areas of Christchurch using flow gauge data. This is of concern because these flows occur constantly. Groundwater inflow takes up capacity that would otherwise cater for existing and future (growth) demand and leaves less capacity available to convey wet weather flows, resulting in increased wet weather overflows. It may be beneficial to target areas with high groundwater infiltration rather than areas with high RDII.

Using a well-calibrated wastewater network model with a long term rainfall data record is the best method for undertaking an I/I analysis. If this is combined with a robust assessment of flow gauge data, the confidence in the assessment is improved. While an assessment using this degree of scrutiny may appear expensive, the cost savings that can be achieved in sewer rehabilitation, by targeting this where it will reduce the most I/I in the most cost effective way, far outweigh the analytical costs.

It is important that I/I assessment work is well scoped. Council staff need to be aware of the potential risks associated with I/I assessments. Sewer flow data should be reviewed to ensure it is of high quality. There should be close scrutiny of the calibration of the hydraulic model used. Lastly, the calculations of the rate of I/I should take into account differing antecedent conditions.

So just accepting flow gauge data as provided and/or hydraulic models perceived to be adequate might lead to incorrect recommendation that would possibly involve many millions of dollars of investments.

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