INNOVATIVE TECHNIQUES FOR TARGETED INFILTRATION AND INFLOW INVESTIGATIONS

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ABSTRACT

Traditional methods of infiltration and inflow (I/I) assessment are based on catchment flow monitoring and analysis against standard I/I parameters. Such studies provide the basis for I/I remediation programmes that are often targeted at the catchment level which may contain kilometres of pipe. An opportunity was identified to provide much more value to the I/I investigations in the township of Levin.

Horowhenua District Council (HDC) had experienced major operational and environmental issues resulting from excessive wet weather flows and elevated base flows during winter. During the course of investigations groundwater infiltration (GWI) was identified as the main contributing factor and the problems were isolated to the catchments in the north. The extent of GWI in the identified area was such that over 140,000m^3 of was entering annually which represented over 90% of the total I/I.

Locating the source of GWI became the primary focus and groundwater (GW) submergence analysis and night flow isolation studies were carried out that allowed sourced of GWI to be identified in lengths of 100-600m. The key outcome was isolating 89% of the total I/I from the northern catchments to 1806m of pipe representing less than 2% of the total Levin Network. GWI from this small length of pipe was responsible for 9% of the annual flow to the treatment plant. The source of historical extreme GWI could also be determined using the submergence analysis tool and taking into account other contributing factors such as pipe material and age. The combination of methods allowed a prioritised I/I rehabilitation plan to be developed so that future remedial works could be applied in a targeted cost effective way.

KEYWORDS

Groundwater infiltration, inflow, source detection, night flow isolation, groundwater submergence, sewer remediation

1 INTRODUCTION

This paper details the approach used to isolate and quantify I/I issues in the township of Levin. The key areas of focus are the innovative monitoring methods used to isolate I/I sources on a detailed level and how the resulting data can be used to develop a targeted I/I remediation plan.

Observations of the problem by HDC were of excessive wet weather flow volumes to the wastewater treatment plant (WWTP) with daily wet flow (WWF) rates often exceeding 10,000 m^3/day from an average daily flow (ADWF) in dry weather of approximately 4,000 m^3/day. During the winter months these volumes were known to increase significantly, up to 30,000m^3/day was recorded during a rain event in August 2008. The excessive flow entering the network was leading to operational issues at the WWTP and there were also environmental concerns about overflows at pump stations and other parts of the system. Groundwater infiltration (GWI) was thought to be a contributing factor to the problems due to the existence of known defects in parts of the aging sewer network and the widely reported high GW levels in the region.

Addressing such I/I issues through remediation and sewer renewal is good practice and helps to ensure levels of service are met, however, due to the cost of rehabilitation works this process is often very costly if applied at the catchment level. The aim of this study was to reduce these costs by providing a remediation plan that goes beyond the catchment level, instead focusing on specific pipe lengths and manholes within problem catchments. To achieve this traditional monitoring and I/I analysis was supplemented by other innovative monitoring techniques that provided considerably more detail on the location of I/I. Additionally the detailed data allowed the potential flow reductions to be accurately measured. Each phase of investigation was planned in response to the results of continuous I/I analysis that was made possible through the use of telemetered monitors and online I/I analysis.

The viability of this approach has been further verified by recent studies that suggest that addressing a significant I/I problem may actually lead to significant cost savings on major network projects such as WWTPs, disposal fields and storage. However, the benefit of flow reduction is often heavily reliant how much of the network is required to be rehabilitated to achieve the desired reduction. The potential for such savings can only be examined through accurate investigations.

2 SUMMARY OF THE FLOW MONITORING PHASE

The flow monitoring phase was critical in determining the nature of the I/I in Levin and provided the basis for subsequent investigations. The information in the following section provides the necessary background data to understand why some catchments became the focus of further investigations and why certain techniques were used.

2.1 MONITORING NETWORK CONFIGURATIONS

The flow monitoring phase of investigations from September 2011 to May 2012 followed a similar methodology to that of a traditional I/I monitoring program with the approximately 100km of piped network divided into major catchments and analysed against standard I/I indicators. The initial gauge network was put in place to quantify the contribution of I/I from these major catchments. Gauge locations were reconfigured after 3 months in response initial results which showed that the major I/I issues were confined to the northern catchments 860 and 1720. As a result, further gauges were installed upstream of catchment 1720 creating catchments 1790, 801 and 333. Catchments 78506, 1866 and 717 were also included after significant direct inflows were observed in catchments 782 and 614. A long term network was established from May 2012 with gauges retained at 860, 93 and 801. The key change to note is the moving of 1720 upstream to 93 to make the catchments more equal in size. Figure 1 shows the Levin wastewater network gauge catchments prior to May 2012. Table 1 gives the physical details of each catchment.

Figure 1: Levin Flow Gauge Catchments

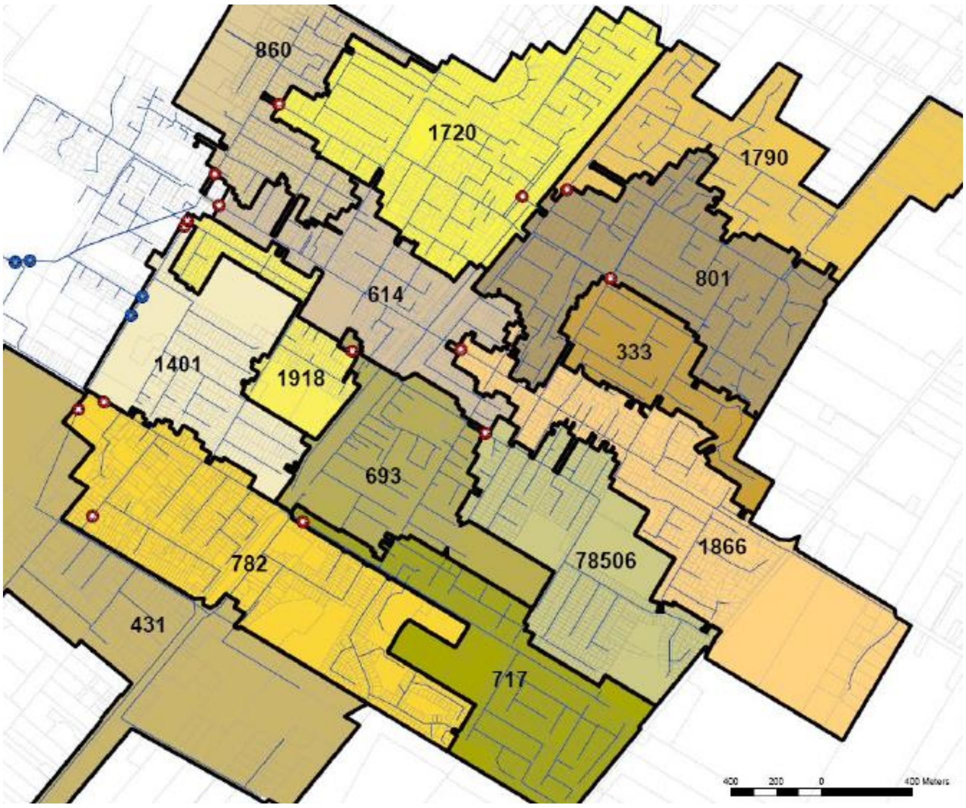


Table 1: Levin Flow Gauge Catchment Details

Flow Gauge (sub-catchment)	Population	Area (ha)	Pipe length (m)	% of piped network	Upstream landuse
1992 (flow diversion)	NA	NA	NA	NA	Industrial/Residential
431	276	262.47	8731	9.0%	Industrial/Residential
782	1508	101.58	8383	8.6%	Residential/Commercial
717	1478	66.40	8162	8.4%	Residential
1401	702	56.43	4000	4.1%	Residential and A&P
1918	374	26.78	2742	2.8%	Residential/Commercial
693	951	57.13	7261	7.5%	Residential/Commercial
78506	1034	69.75	5893	6.1%	Residential
614	700	56.28	5945	6.1%	Residential/Commercial
1866	1436	101.2	6984	7.2%	Residential
860	848	52.61	4983	5.1%	Residential/Commercial
1720	1649	98.84	12065	12.4%	Residential/Commercial
801	1867	85.42	11553	11.9%	Residential/Commercial
1790	948	76.73	6470	6.7%	Residential
333	833	33.22	3860	4.0%	Residential
Total	**14604**	**1344.1**	**97032**		

2.2 I/I ANALYSIS AND RESULTS

2.2.1 WET WEATHER INDICATORS OF I/I

The key difference between the Levin I/I analysis and a traditional study was the use of telemetered monitoring and online I/I analysis tools to continuously analyse rain events and plan additional phases of investigation. This type of dynamic monitoring worked well as the need for additional gauges was identified quickly and could be acted upon.

At the completion of the two phases of flow monitoring it was found that up to 87% of the total wet weather I/I volume was contributed by the catchments upstream of 860 which represented only 39% of the total catchment. The significance of this lies more in the fact that 61% of the catchment (61 km) could be ruled out of requiring immediate rehabilitation. The addition of gauges upstream of 1720 eliminated catchments 333 and 1790 as being significant contributors ruling out a further 10 km of pipe. The source of the wet weather I/I issue was therefore isolated to catchments 860,1720 and 801 containing 28.6 km of pipe.

Table 2 below shows the I/I severity (leakage rate) of the catchments in Levin over the duration of the study. I/I severity is a standard indicator that normalises I/I volume to the length of pipe and rainfall depth and is expressed in the unit Litres of I/I per metre of network per mm of rainfall (L/m/mm). Figures exceeding 3-4 L/m/mm are generally indicative of an I/I issue. Please note that catchments referred to as “total” include the flow from the entire upstream network. “Net” catchments exclude upstream catchments.

The figures presented clearly show the isolation of I/I in the catchments upstream of 860.

Table 2: I/I Severity

Gauge Catchment	Event 1	Event 2	Event 3	Event 4	Event 5
431	2.15	2.33	2.08	1.64	*MD*
782 (net)	*NI*	*NI*	*NI*	0.41	0.78
782 (total)	0.63	0.58	0.22	0.05	0.16
717	*NI*	*NI*	*NI*	0.12	0.08
1401	*MD*	0.57	0.73	0.23	0.81
1918 (net)	-	-	-	-	-
1918 (total)	1.08	1.89	0.73	0.49	0.82
693	1.56	2.09	0.20	0.37	0.13
614 (net)	-	-	-	-	-
614 (total)	0.17	1.10	0.18	*Neg.*	0.15
78506	*NI*	*NI*	*NI*	0.16	0.28
1866	*NI*	*NI*	*NI*	0.05	0.32
860 (net)	1.89	0.50	1.31	3.32	*MD*
860 (total)	0.99	6.79	4.73	3.27	*MD*
1720 (net)	*NI*	*NI*	*NI*	3.70	1.93
1720 (total)	0.73	9.23	5.26	3.01	2.70
801 (net)	*NI*	*NI*	*NI*	3.35	1.23
801 (total)	*NI*	*NI*	*NI*	2.35	0.87
1790	*NI*	*NI*	*NI*	1.21	0.60
333	*NI*	*NI*	*NI*	0.16	0.23

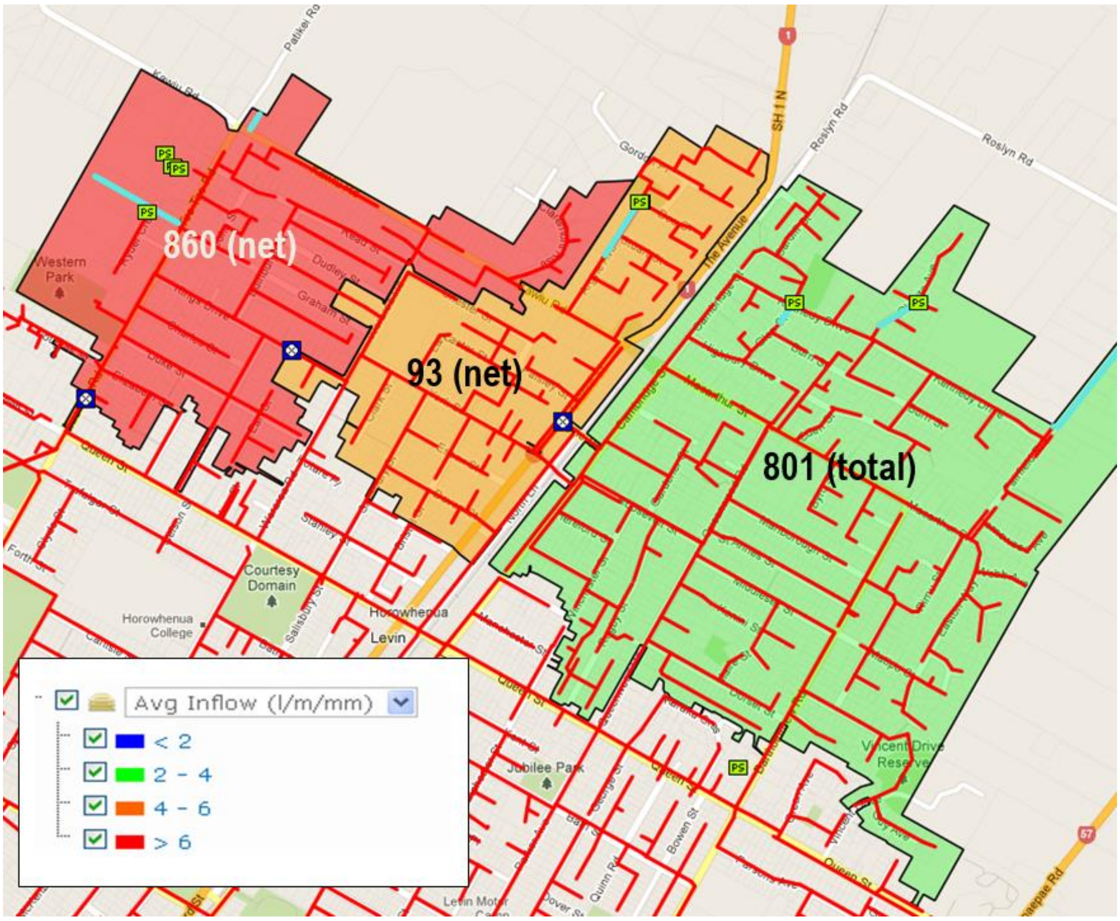
NI: Gauge not installed
MD: Missing data during event

Further analysis of the long term network data after May 2012 in table 3 below perhaps gives a more accurate impression of the I/I in catchments 860 and 93. The enhanced accuracy is due to the more equal catchment size resulting in the reduction of error associated with subtracting upstream flows. The results are also shown in the thematic map in figure 2.

Table 3: Long Term Gauge I/I Severity

Long term gauge catchment	**Event 1**		**Event 2**		**Event 3**	
	I/I severity (L/m/mm)	**I/I inference**	**I/I severity (L/m/mm)**	**I/I inference**	**I/I severity (L/m/mm)**	**I/I inference**
860 (net)	9.6	Very high	17.0	Very high	12.4	Very high
93 (net)	3.0	Moderate	7.2	Very high	1.1	Low
801 (total)	2.2	Moderate	4.5	High	2.5	Moderate
860 (total)	3.5	Moderate	7.7	Very high	3.4	Moderate

Figure 2: Thematic Map of I/I Severity



2.2.2 DRY WEATHER INDICATORS OF GWI

As suspected the majority of the I/I volume was entering as GWI which remained elevated for up to one month after rainfall. Due to the length of the monitoring period the seasonal effects of GWI could be analysed in detail to determine the actual effect of GWI year round.

Table 4 demonstrates how GWI in the catchments upstream of 860 cause dry weather flows (DWF) to increase by 38% during periods of high GW (loosely associated with winter) which in turn causes the total dry weather flow in Levin to increase by 19%. Linked to this are the wastewater production rates (WWP) which are presented in tables 4 and 5. WWP is a measure of the influence of GWI on dry weather flow rates and is based on widely accepted per capita domestic water use rates. It is calculated by dividing the daily flow volume by the population. A WWP of 180-220 L/p/day is regarded as normal. Less than this implied wastewater is exfiltrating. Greater than this implies that groundwater is entering or industrial discharges are contributing to the daily flow such as in catchment 431. Hence, it is only an accurate measure in residential catchments.

The WWP figures show that catchment 860 (total) has generally normal GWI during low GW but significantly increase during high GW. The additional breakdown of 860 (total) in table 5 shows that GWI is in fact highly variable within the sub-catchments with 860 (net) showing significant GWI year round while WWP in 93 (net) only marginally exceeds what is considered normal. 801 (net) increases but remains within normal bounds. The key factor to note is the extent to which these figures increase rather than the indicators themselves as this is what suggests that defects exist in the network that are allowing GW to enter.

Table 4: Levin Catchments DWF Characteristics

Base gauge	**Catchment ADWF Characteristics**							
	Low GW			**High GW**			**Difference**	
	m^3/day	**% of total**	**WWP**	**m^3/day**	**% of total**	**WWP**	**Increase**	**% Increase**
860	1418	39%	231	1953	46%	318	535	38%
614	510	14%	161	532	12%	168	22	4%
1918	267	7%	202	269	6%	203	2	1%
1401	153	4%	219	156	4%	222	2	1%
782	427	12%	143	495	12%	165	68	16%
431	827	23%	2998	882	21%	3197	55	7%
Totals	**3604**			**4287**			**683**	**19%**

Table 5: DWF Characteristics in the 860 (total) Sub-catchments

Long term gauge/sub-catchment of 860 (total)	**Low GW**		**High GW**		**% seasonal increase in DWF**
	DWF (m^3/day)	**WWP (L/p/d)**	**DWF (m^3/day)**	**WWP (L/p/d)**	
860 (net)	490	369	869	654	77%
93 (net)	190	163	272	233	43%
801 (total)	673	185	797	218	18%
860 (total)	**1418**	**231**	**1953**	**318**	**38%**

2.2.3 KEY FINDINGS FROM THE FLOW MONITORING

The most critical finding of the flow monitoring phase was the isolation of the major I/I problems to the catchment 860 (total). No other catchment exhibited the magnitude of wet weather response or seasonal dry weather flow increase. It was estimated that 60,000-70,000m^3 of I/I was entering the catchment during periods of high GW in the form of wet weather inflows and elevated base flows from GWI. This represented 30% of the total flow from the catchment during these periods. All other catchments in Levin were deemed to be free of the type of I/I problems that would lead to the issues experienced by HDC. The possible exception being some direct inflows that caused high peak flows but low relative volumes in catchments 614 (net), 693 (net) and 1918 (net) in particular.

The data showed that up to 87% of the total wet weather I/I volume during specific rain events was contributed by this 860 (total). The addition of extra gauges narrowed this to the sub-catchments 860 (net), 93 (net) and 801 (net) which comprise a total pipe length of 28.6 km. 860 (net) having particularly high I/I severity year round, with the others showing more seasonal variation. GWI was identified as the main contributing factor to the excessive volume which was demonstrated by the data from periods of high GW where large rain events caused flow rates to remain elevated for periods of up to one month. These event recessions were responsible for up to 70% of the total event I/I volume. The extent of the observed GWI is such that it may be a factor in the initial response to rainfall also.

Dry weather data also confirmed the GWI issues with a 535m^3/day increase in dry weather flow observed from low to high GW. The effect on the total flow from Levin was an increase of 16%. More detailed gauging allowed this issue to be isolated to the 860 (net) catchment which showed high rates of GWI year round. This type of year round infiltration is not often noticed as it generally does not cause operational issues however, it has the potential to contribute large volumes of flow annually that must be treated and disposed at a cost to HDC. Adding this year round GWI volume to the observed flow increases during high GW indicates that HDC may be treating significant volume of additional flow.

3 METHODOLOGY FOR ACHIEVEING DETAILED ISOLATION

GWI was the primary focus of the next phase of investigations due to the evidence gathered by flow monitoring. It was proposed that the GWI issues were caused by high local GW that was the product of consistent rainfall in the wider region and the local geology. It is the resulting submergence of old and defective pipes and manholes leads to GWI. This hypothesis provided the basis for selecting source detection methods that would provide the necessary data to prioritise rehabilitation on a detailed level.

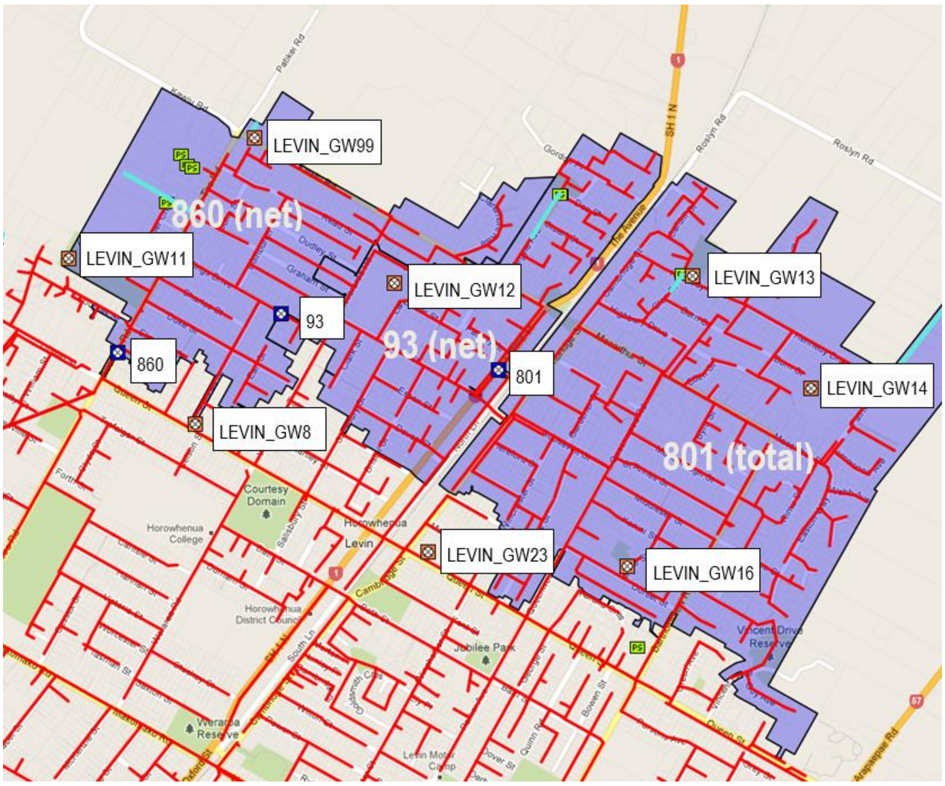
3.1 DEFINING AND MEASURING GWI

For the purposes of this paper GWI is defined as the component of dry weather flow that enters from saturated surrounding soils through defects in network infrastructure. GWI can be seen in dry weather as elevated base flows or following wet weather in extended periods of elevated flow. It is difficult to separate the portion of flow that is GWI from the total wastewater flow without monitoring inputs from individual households. It is also difficult (if not impossible) to define when direct wet weather inflow stops and GWI begins following rainfall. Achieving this was not the intention of this paper so for simplicity the severity of GWI is assumed to be directly linked to night flow which can be easily measured. Night flow includes a constant wastewater component form normal residential water use as well as GWI. For this study it is defined as the minimum hourly flow rate recorded between 01:00am and 05:00am during dry weather (more than 24hrs after rainfall). As the wastewater component is assumed to be constant any changes in night flow are therefore deemed to be the result of GWI. The residential nature and stable population in the target catchments reduce the influence of other factors that can influence night flow, reinforcing the viability of using night flow as an alternative GWI indicator.

3.2 LONG TERM FLOW AND GROUNDWATER MONITORING

Following the short term flow monitoring studies a long term gauge network was established on 8th May 2012 in the 860 (total) catchment at manholes 860, 93 and 801. The gauge locations reconfigured to improve accuracy in monitoring the sub-catchments by making them more even in size. The purpose of maintaining the long term monitoring was to continue gathering flow and rainfall data for the 860 (total) catchment to establish long term and seasonal trends and to monitor the success of any remedial works. A network of GW monitoring bores was included to gain an understanding of the relationship between GW level and I/I that had been proposed through the flow monitoring phase. Figure 3 shows the locations of all flow and GW monitors used for the investigations.

Figure 3: Long Term Flow and GW Monitoring Locations



3.3 NIGHT FLOW ISOLATION

The I/I report indicated that GWI was the most significant component of I/I in Levin. As such locating and quantifying GWI sources was considered to be the most important component of this study. This was achieved by taking measurements of night flow of using a technique called night flow isolation. The results of this work were the primary trigger for determining rehabilitation priority as they represented a quantifiable flow contribution which is perhaps the most meaningful pipe condition assessment available. The only limitation being the study represents a "snapshot" in time, hence the need to undertake the study during maximum GW submergence.

Night flow isolation is a method of isolating GWI sources on a micro level. It is done by measuring an instantaneous flow rate in specific lengths of pipe (approximately 100-600m intervals) within a larger catchment. A portable weir is used to measure the flow between 01:00-05:00 (night flow) to reduce the influence of domestic and commercial flows.

Figure 4: Portable Weir Installed in the Levin Trunk Sewer

Night flow isolation was carried out in sub-catchments 860 (net), 93 (net), 801 (net) and 1790 (net) when the long term gauges showed that base flows were increasing and that GW was high. A further study was done on the trunk sewer along Tiro Tiro Rd, Kings Dr and York St. In each sub-catchment GWI was measured at 9-12 locations that effectively isolated discrete pipe lengths.

It is difficult to appreciate flow rates measured in such small lengths of pipe such as those measured using this technique. To bring meaning to the results the flow rate was normalised to pipe length and a rating system was developed as set out in table 6 below.

Table 6: Night Flow Rate Severity Rating

Night flow rate (m^3/km/day)	**860 (total) Equivalent WWP (L/p/d)**	**GWI inference**
< 8	< 203	Low
8-15	203-247	Acceptable
15-25	247-310	High
25-45	310-437	Very High
> 45	> 437	Severe

The rationale for the ratings is based on WWP. Long term flow monitoring has shown the daily dry weather flow rate in catchment 860 (total) during low GW is 1418m^3/day equating to 231 L/p/d for the 6145 inhabitants. This WWP implies it is a relatively normal catchment with minor GWI. The specified ranges in the rating system are based on the WWP that would result at the base gauge 860 (total) if all pipes in the catchment were flowing at the measured night flow rate. The resulting theoretical increase or decrease in night flow does not affect the wastewater component but is treated a change in GWI which in turn changes the daily volume and WWP. This method provided a better understanding of the wider effects of a measured night flow rate and referenced it back to the more familiar WWP indicator.

3.4 GROUNDWATER MONITORING AND NETWORK SUBMERGENCE

Monitoring equipment was installed in 8 GW monitoring bores along with the long term flow monitoring network. They were placed throughout the target catchments to investigate the relationship between flow and groundwater level that was proposed in the I/I assessment. Investigating this relationship was critical to the investigations due to the assumption that GWI could only occur where the network was submerged and where defects were present.

The submergence analysis and night flow isolation were complementary in that the results of one study could be used to verify the other. If submergence was high then the results of the night flow would presumably be affected (depending on the existence of defects). If night flow was high then submergence must be an issue. This relationship provided certainty over the validity of each method.

Monitoring over and past the winter period was critical as HDC had advised that GW peaked during this time and it is thought that this peak was leading to increased network submergence hence the excessive flows observed. The key outcome of this investigation was to determine criticality based on the severity and frequency of pipe submergence. This was achieved through the development of an online tool that was designed to determine network submergence at any point in time using manhole invert levels and a calculated groundwater level at each manhole. The submergence data was limited to an estimated GW level at each manhole based on an interpolated GW level from the nearby bores. Bore monitors were placed to attain the best possible resolution however GW level is influenced by many local factors that cannot all be taken into account. For the purposes of identifying general areas susceptible to GW submergence, this tool proved to be very effective.

The key benefit of assessing GW submergence is the ability to continually review it through long term GW monitoring. Night flow isolation in comparison provides more a more accurate condition assessment but is limited to a single point in time. As HDC have kept a very good record of GW level in Levin that goes back some years, historical events could be therefore analysed to determine the network submergence. Because of this the historical extreme event recorded in August 2008 (that caused 30,000m^3/day to enter the WWTP) was able to be analysed to assist in locating the source of flow during extreme GW events.

3.5 PIPE AGE AND MATERIAL ASSESSMENT

This part of the assessment was seen as the least important as I/I contribution can only be speculated based on pipe material and age. In the absence of other data this kind of assessment provides a starting point for logically estimating where I/I will be coming from. This assessment was made much more meaningful by presenting it alongside GW submergence which is a key factor in determining if old pipes will contribute GWI.

In general the older the pipe the more likely it is to have defects that will contribute to I/I. However, if a thorough approach is to be taken pipe material must also be considered as pipe materials age differently and the associated construction methods may also influence the occurrence of defects. For this study earthenware (EW), reinforced concrete (RC) and asbestos cement (AC) pipes have been deemed as being more susceptible to infiltration. One reason for this is that pipes made of these materials will generally be old (greater than 40 years) as they were commonly used in this era but were replaced by superior materials such as PVC (polyvinyl chloride) and PE (polyethylene). The exception being RC which is still used today however, it is more susceptible to deterioration over time. It has been included due to its extensive use historically in Levin. Another reason for the choice of these materials is the installation of EW, RC and AC pipes involves laying relatively short lengths of pipes with seals at the joins that deteriorate over time. Such pipes were often installed incorrectly and are susceptible to offsetting under strain of ground movements seasonally or during construction.

The results of this assessment were indeed combined with the submergence analysis to form one probability based analysis. The probability of GWI being an issue was determined by the existence of the factors that contribute to GWI, namely GW submergence and pipe defects (estimated by pipe material and age).

3.6 DETERMINING REHABILITATION PRIORITY

Pipe lengths were assigned priority based on measured or potential I/I contribution. Excessive I/I contribution is seen as being directly linked to pipe defects which are in need of rehabilitation. It is important to note that pipe lengths identified through night flow isolation also include private connections and manholes. The criteria are set out below:

Priority 1 pipes: are those measured to be contributing to the excessive GWI observed in catchment 860 (total). These pipes were identified through the night flow isolation studies which were carried out on a dry day when GW was high and therefore represent the pipes causing the bulk of the background GWI problem. These pipes are also most likely to be contributing even more GWI during rainfall. Criteria are as follows:

- All pipe lengths where the measured GWI rate (night flow) is categorised as very high or severe.

Priority 2 pipes: are those where measured GWI is high or likely to increase during higher GW due to material and age. The pipes identified as priority 2 cover those most likely to be responsible for the remainder of the excessive flow seen during the peak August 2008 event. Criteria are as follows:

- All areas where the measured GWI rate (night flow) is categorised as high.
- Areas where the submergence analysis shows susceptibility GW submergence in the historical maximum GW scenario and the pipe material is earthenware, concrete or asbestos cement.

Priority 3 pipes: are those where submergence is not likely however, pipe material and age suggest they may require rehabilitation or replacement. Other pipes in this category are newer or pipes made of superior materials that are susceptible to submergence.

- All pipes over 40 years old not susceptible to submergence in the historical maximum GW scenario.
- All newer and superior material pipes susceptible to submergence in the historical maximum GW scenario.

Low Priority

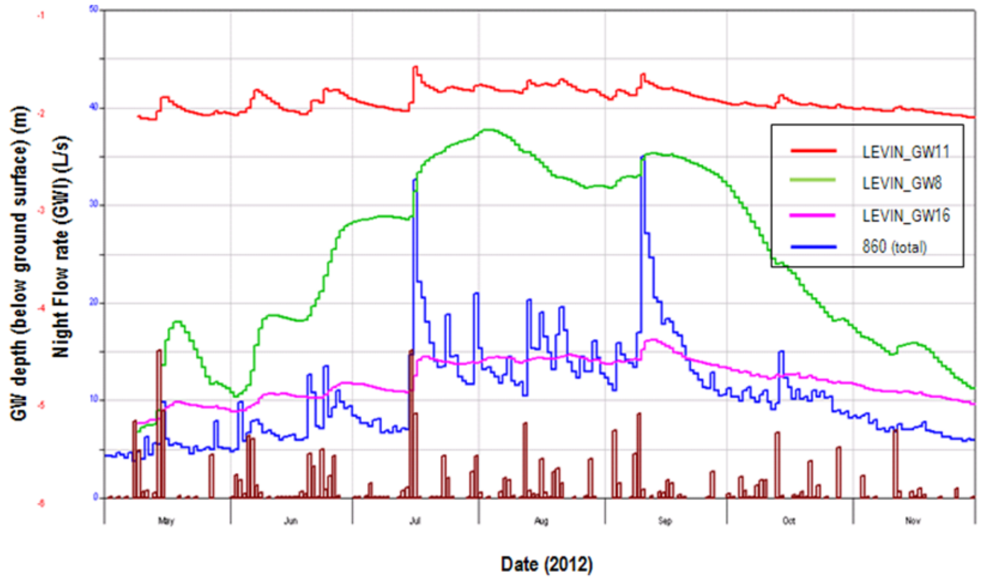
- Newer superior material pipes with no submergence

4 RESULTS AND DISCUSSION

4.1 LONG TERM GW AND FLOW TRENDS

Figure 5 below shows the effect of elevated GW level on night flow (level displayed in depth below surface). Note the increase in night flow from mid July through to October which coincides with an increase in GW level of between 0.4m and 3m (depending on bore location). This seasonal increase in flow was quantified in the long term flow monitoring results where dry weather flows were reported to increase from 1418m^3/day when GW was low to 1953m^3/day when GW was high. The total daily increase of 535m^3/day can wholly be attributed to the increase in night flow of from 5.6L/s to 12.1L/s. The wet weather recovery is also clearly affected by the persistent elevated GW level with night flow rates of over 25L/s recorded days after rainfall when direct inflows are not a factor. With the relationship between GW level and GWI established, night flow isolation studies were commenced to determine exactly where the GWI was coming from.

Figure 5: Graph Showing the effect of GW Level on Night Flow in 860 (total)



4.2 THE EFFECT OF GEOLOGY

It is important to view the GW level data in terms of how it will affect GWI entering the wastewater network. To do this the geology of the surrounding area must be taken into account. Without getting into too much detail, the most important factor to consider is the capacity of a soil to allow GW flow. This characteristic is chiefly affected by the elevation difference over the distance of an aquifer and the hydraulic conductivity (ability to transmit water) of the material.

Although the soil strata was not directly investigated, the bore logs from the new bore installations allowed the key layers to be approximated. The upper layers below the topsoil from 0-2m below surface are primarily alluvium, clay initially transitioning to a more silty material. Most significant to this study is the unconsolidated sand and alluvium that begins to appear in the clay and silt at approximately 2.0-3.0m below surface. This becomes clean sand at depths between 5.5-6.5m. Sand is very efficient at transmitting GW flow meaning any pipes with defects laid in this material are highly susceptible to GWI if submerged. In the transition zone from silt to sand (approximately 2-3m) high GWI rates are also likely. Although GW flow is an important factor to consider, the pipe condition will ultimately influence the actual rate of GWI of a submerged pipe in any layer of soil as defects must first exist for GWI to enter. This is factor addressed in the night flow isolation results where actual GWI rates are measured.

Figure 6: Soil strata and GW depth

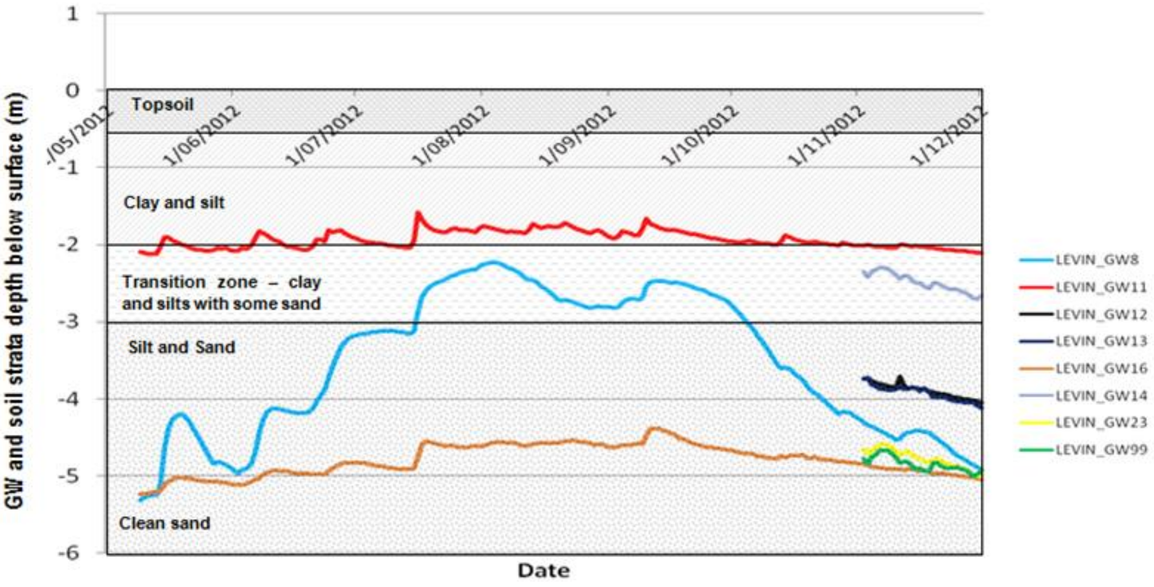


Figure 6 shows GW depth below surface and soil strata levels to give an indication of the conditions that combine to cause GWI in certain areas at different times of year. The graph would suggest that any defective pipes laid below 2m near GW11 would be susceptible to significant GWI year round. GW14 shows a similar trend with perhaps more seasonal variation. Near GW8 pipes are most at risk of GWI from August to October with high seasonal GW. GW levels in the areas near GW23, GW16 and GW99 are generally below where pipes are laid and are therefore less susceptible to GWI. Levels at GW13 and GW12 may be seasonally high, more data is required to confirm this.

4.3 NIGHT FLOW ISOLATION

Night flow isolation studies were carried out in the sub-catchments 860 (net), 93 (net) and 801 (total) over 3 nights in late August – early September 2012 when GW levels represented high winter conditions. A further study was carried out on the trunk sewer in November 2012 when GW levels had receded to summer low GW conditions. During all studies flow was measured at the base gauge 860 to so that relative contributions could be calculated. Table 7 below summarises the findings of the studies on a sub-catchment basis.

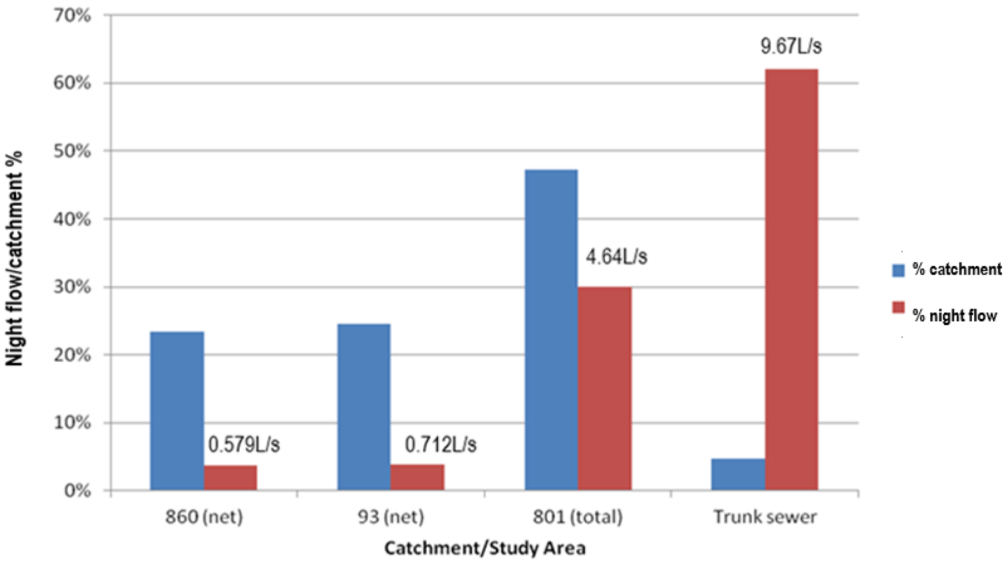
Table 7: Sub-catchment Night Flow Isolation Summary

	Catchment / study area	**Total pipe length (m)**	**Avg flow rate at base gauge 860 (L/s)**	**Total night flow measured (L/s)**	**Normalised night flow rate (m^3/km/day)**
Sub-catchment study	860 (net)	8904	13.75	0.579	5.62
	93 (net)	9385	16.89	0.712	6.55
	801 (total)	20903	16.06	4.639	19.2
	Un-gauged trunk	1806	15.6	9.67	462
	Total sub-catchments	**39192**	**15.6**	**5.93**	**13.1**
Trunk sewer study	Trunk sewer	2847 (1806m trunk only)	6.43	2.986	143
	Total sub-catchments	37125	6.43	3.230	7.52

During high GW conditions when the sub-catchment studies were undertaken, 5.93L/s of night flow was accounted for. This represented only 38% of the total 15.6L/s (on average) measured at the base gauge 860 (total) yet the total pipe length in the sub-catchments represents 95% of the contributing pipe length. By elimination it can almost certainly be assumed that the remaining 9.67L/s (62%) of night flow is coming from the remaining un-gauged portion of the catchment. This area, referred to as “the trunk” from here on, represented 5% of pipe total pipe length in 860 (total) and includes 1806m of trunk sewer over 300mm in diameter. In the trunk study GW levels were significantly lower and the sub-catchment contribution went down to 3.23L/s (52%) with the trunk contributing 3.0L/s (48%). Many sections of the trunk showed severe GWI despite the low GW conditions.

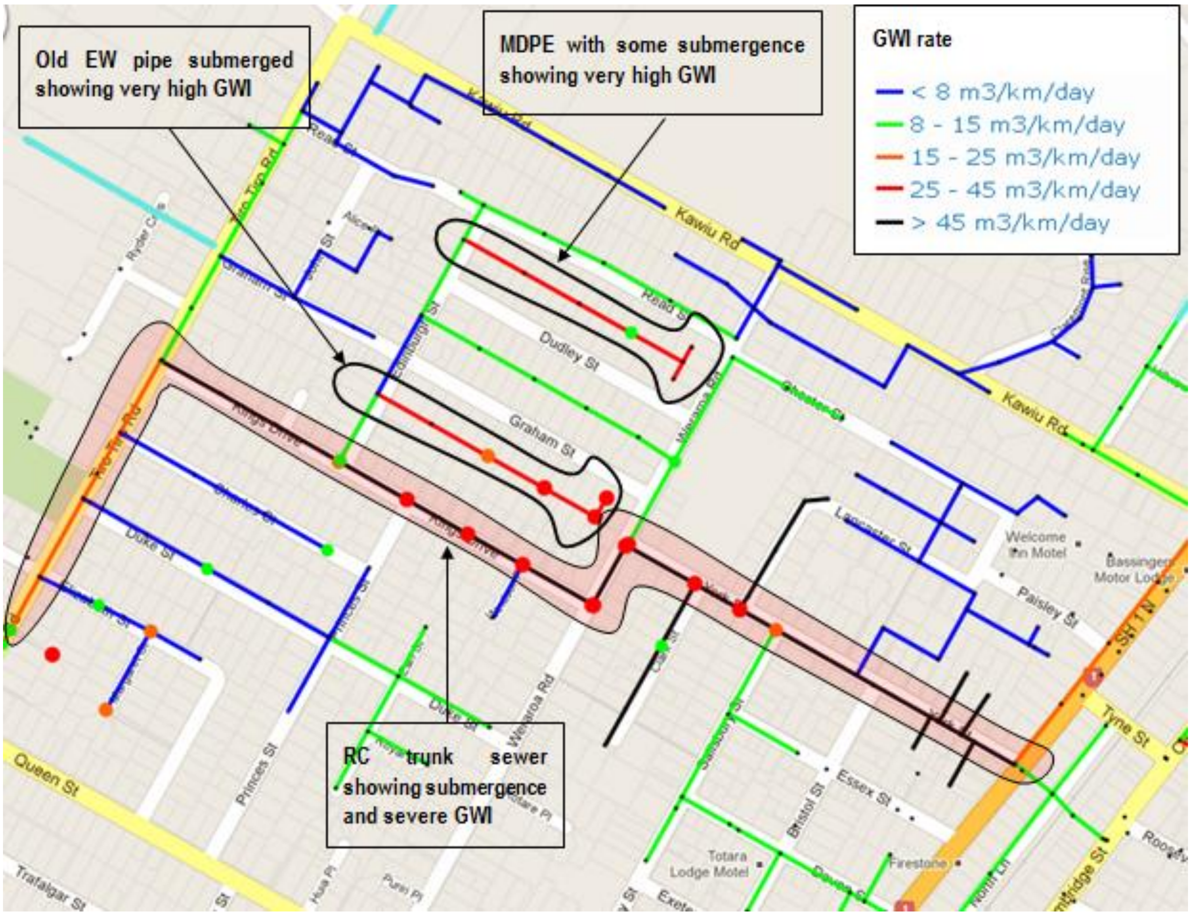
The findings of the study were conclusive. The trunk sewer representing a very small amount of the total network was responsible for the vast majority of GWI in Levin. Incidentally the poor timing of the trunk study (when GW was low) lead to the discovery of the pipes that were causing high flows year round in parts of the 860 (net) catchment. Figure 7 below graphically represents the disproportionate contribution night flow from the trunk sewer when GW was high.

Figure 7: Night Flow Contributions by Study Area



The following figures 8 and 9 are maps showing night flow rates of every measured pipe length within the 860 (total) catchment. Pipes have been colour coded according to the rating system outlined in section 3.3. Also included are the submerged manholes indicated by highlighted dots. The maps clearly show the sections of trunk sewer responsible for the GWI issues.

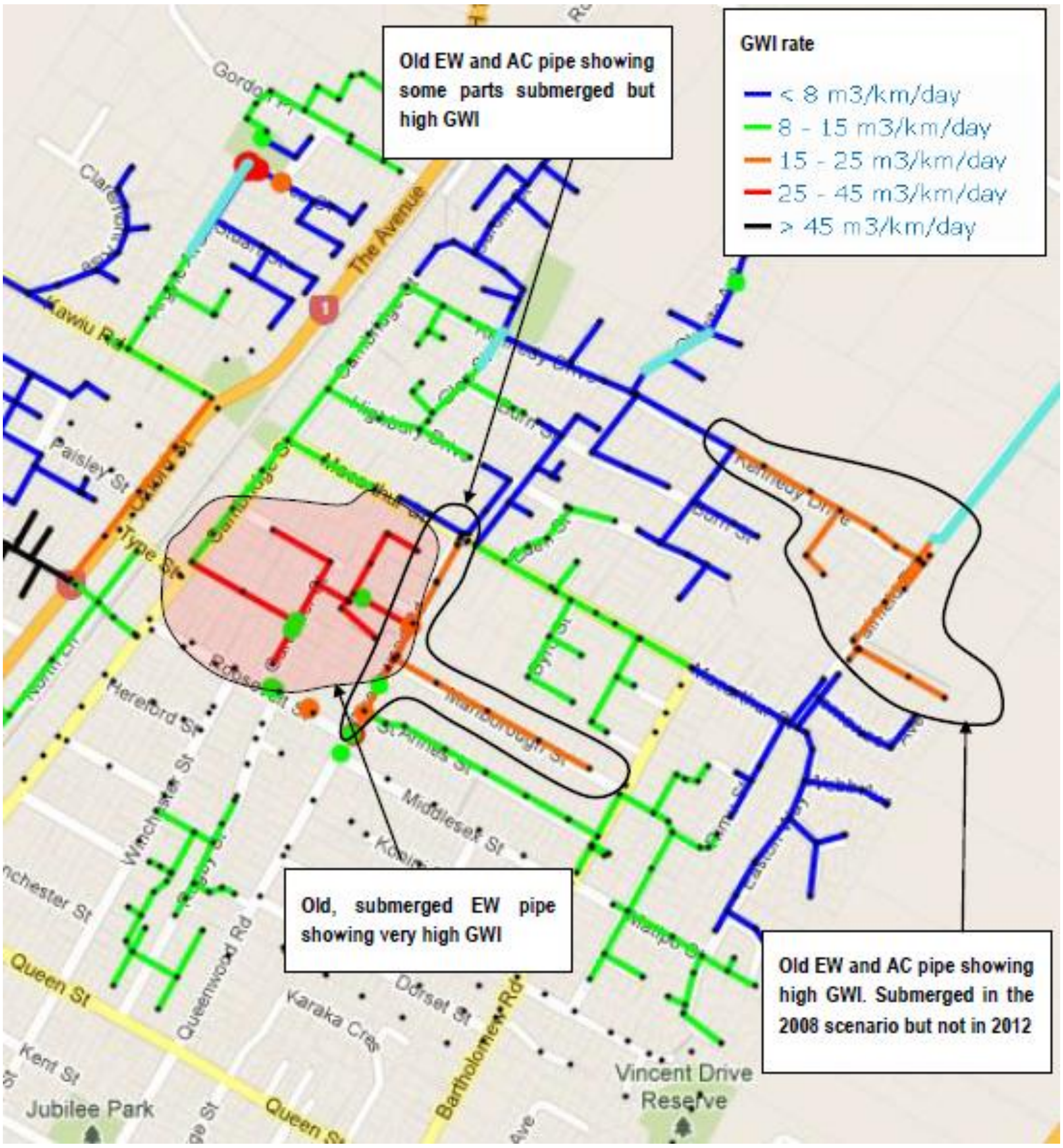
Figure 8: Map 1 of Night Flow Isolation Results


Old EW pipe submerged showing very high GWI

MDPE with some submergence showing very high GWI

RC trunk sewer showing submergence and severe GWI

Figure 9: Map 2 of Night Flow Isolation Results



Old EW and AC pipe showing some parts submerged but high GWI

Old, submerged EW pipe showing very high GWI

Old EW and AC pipe showing high GWI. Submerged in the 2008 scenario but not in 2012

4.4 SUBMERGENCE, MATERIAL AND AGE ANALYSIS

Figures 10 and 11 depict the manhole submergence during September 2012 (at the time night flow isolation was carried out) and the August 2008 event. The extreme nature of the August 2008 GW level is evident with a significant increase in network submergence. To relate this data to GWI it should be noted that the increase in GWI in 2012 reported in section 4.1 and figure 5 occurred as a direct result of the relatively isolated area of submergence depicted in figure 10. Note the identified submerged areas are very similar to the areas with high night flow rates.

The pipes that were found to be submerged in the August 2008 scenario will become priority 2 or 3 pipes depending on material.

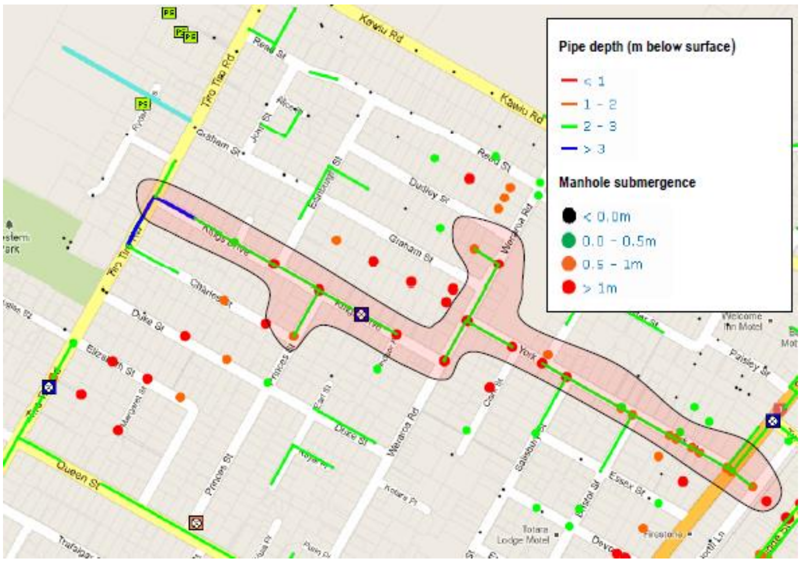
Figure 10: GW Submergence September 212

Figure 11: GW Submergence August 2008

4.4.1 SUMBERGENCE AND SOIL TYPE (PIPE DEPTH)

The figure below shows an example of an area identified as susceptible to GWI due to soil type (estimated by pipe depth). The trunk sewer along York St and Kings Drive is clearly the most susceptible as the majority is laid below 2m, nearer the sandy soils, and was submerged by over 1m in some places during high GW. Other parts show submergence but pipe depths were shallower (in clay soils) which may explain the lower measured night flow. It is important to note the actual GWI contribution is heavily dependent on pipe condition.

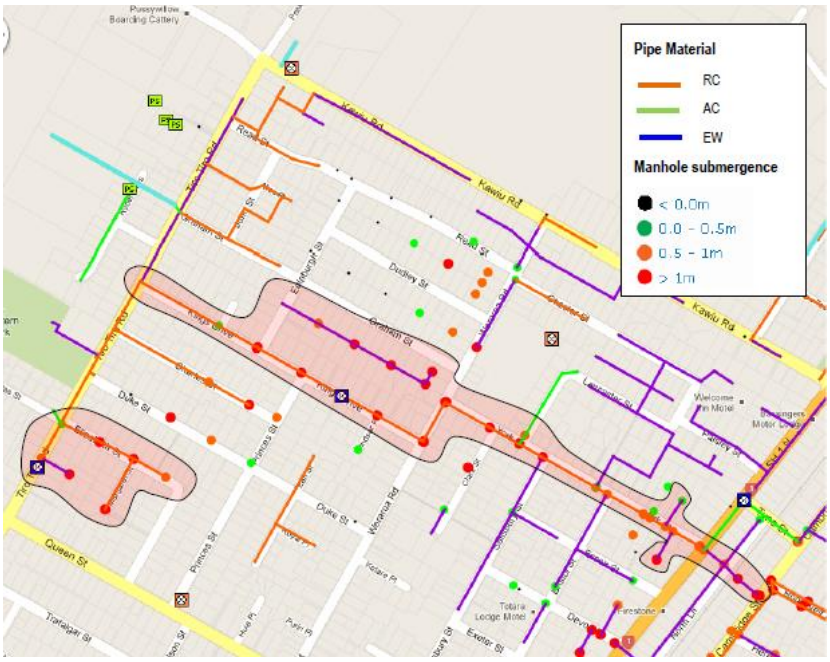
Figure 12: Network Submergence and Pipe Depth



4.4.2 SUBMERGENCE, PIPE MATERIAL AND AGE

The figure below shows an example of an area identified as susceptible to GWI due GW submergence, pipe material and pipe age. All susceptible pipe materials identified in this example are over 40 years old. Again the trunk sewer along York St and Kings Drive is clearly the most susceptible to GWI.

Figure 13: Network Submergence and Pipe Material

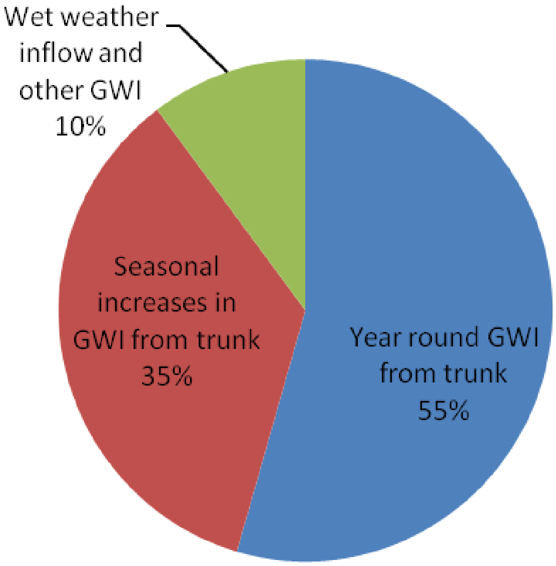


4.5 GWI VOLUME CONTRIBUTIONS

The long term monitoring showed base night flow (minimum dry weather flow rate) was approximately 5.6L/s in dry weather during low GW and approximately 12.1L/s during high GW. Using the percentage contributions from the night flow isolation (62% at high GW and 48% at low GW) the trunk can GWI can be estimated at 2.69L/s during low GW and 7.50L/s during high GW. Under normal conditions there should be nearly no GWI in a pipe of this length. Therefore it can be concluded that the 2.69 L/s during low GW and the 7.5 L/s during high GW is directly attributed to GWI that should not be there. The contributions from the remainder of the sub-catchments would appear to be slightly high during high GW due to pockets of defective pipe that were identified during night flow isolation. The figures from the trunk study suggest that GWI is not an issue in the sub-catchments during low GW.

The annual GWI contribution from the 1806m of defective trunk can be estimated for 2012 as follows using the above reasoning. The total comprises 85,000m^3 of year round GWI from the 2.69L/s found at low GW. During periods of high GW the increase to 7.5L/s for approximately 3 months contributes a further 55,000m^3. The total of approximately 140,000m^3 equates to 89% of the total 156,000m^3 of wet weather I/I and GWI in 860 (total). The total includes the 85,000m^3 of Year round GWI as well as 71,000m^3 of total additional flow during high GW as calculated for 2012. The remaining 16,000m^3 is wet weather inflows and increases in GWI in small areas of the sub-catchments. Further to this, it has been calculated that the GWI volume from the trunk contributes 9% of the total flow the WWTP annually yet it comprises only 2% of the total Levin network. Figure 14 below depicts these statistics.

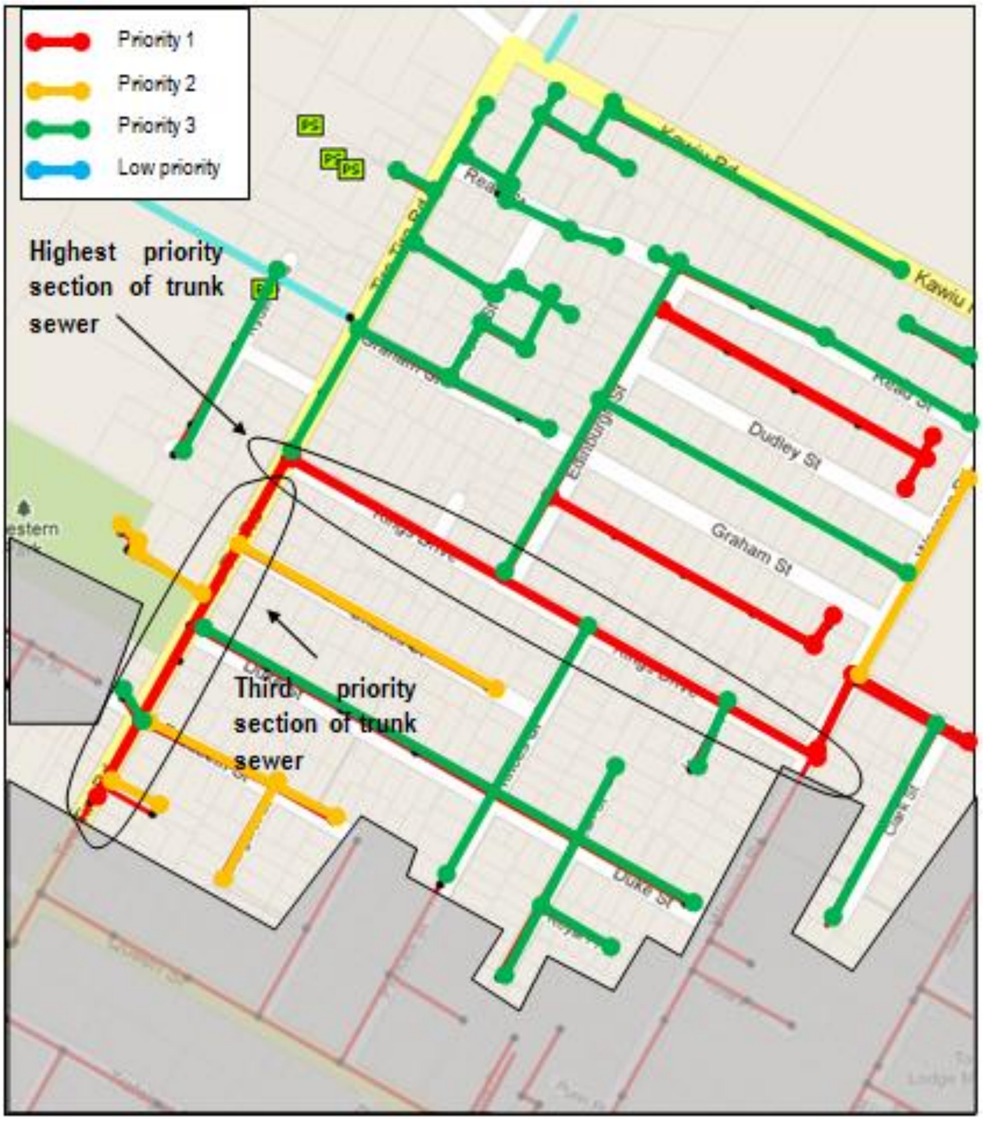
Figure 14: 860 (total) I/I Contributions by Source



5 CONCLUSIONS

The conclusion and output of the studies carried out in Levin was a detailed rehabilitation plan. The plan is based on assigning rehabilitation priority as set out in the methodology (section 3.6). The system was developed to assign priority to specific lengths of pipe that were proven to contribute GWI as well as pipes that are susceptible to GWI due to contributing factors. The development of these plans is the result of intensive studies of night flow and GW submergence that have provided the evidence required to make sound planning decisions. The plan for the most critical area is shown in figure 15 below. These plans were created for the every lengths of pipe in the 860 (total) catchment.

Figure 15: Plan Showing Rehabilitation Priority



Highest priority section of trunk sewer

Third priority section of trunk sewer

For rehabilitation planning it is useful to understand the I/I volume in terms of the contributing pipe length. Doing this enables a clear understanding of the amount of rehabilitation that is required to achieve flow reductions. This analysis was carried out for GWI sources in the 860 (total) catchment using the night flow isolation results and is presented in table 8 below. Viewed with the rehabilitation plans this provides a complete picture of the reduction that can be achieved. It is worth noting the diminishing benefit of rehabilitation per km in Levin due to the very isolated nature of the sources.

Table 8: GWI Contribution and Cumulative Pipe Length

Area/description	**Net pipe length**	**Cum. pipe length**	**Cum. % pipe length**	**Net Night flow**	**Cum. night flow**	**Cum. % of total night flow**	**L/s of night flow per Km (cum.)**
Trunk sewer	1806	1806	5%	9.67	9.7	62%	5.4
Pipes with very high night flow rate	1663	3469	9%	0.65	10.3	66%	3.0
Pipes with high night flow rate	3820	7289	19%	0.71	11.0	71%	1.5
Pipes with low and acceptable night flow rate	31642	38931	100%	4.57	15.6	100%	0.4

From this information it can be concluded that the most effective reductions in GWI under normal winter conditions will achieved by rehabilitating the 1806m of trunk sewer that runs along Kings Dr and York St. Only marginal gains can be achieved if rehabilitation is applied any further and these gains are likely to come at significant cost due to the pipe lengths involved. However, it is important to note that in more extreme GW events, the priority remaining priority 1 pipes and 2 pipes may become a significant contributors due to submergence.

6 VALIDATION OF METHODS

The application of submergence monitoring and night flow isolation techniques for this study proved to be very effective in optimising the rehabilitation plan for Levin based on sound evidence. The results of the night flow isolation confirmed the validity of using GW submergence (along with pipe material, age and soil) to determine susceptibility to GWI. It was clearly shown that the identified pipes in most cases had high night flow rates. See figures 8 and 9. This added confidence to the use of historical submergence data to assign higher levels of rehabilitation priority. The limitation of estimating susceptibility in this way is the assumption that defects will exist in old pipes and not in newer ones. This was proven by the high night flow measured in an area of new MDPE pipe. Despite this instance, it provided very useful data in the absence of flow measurement.

Night flow isolation proved to extremely effective. The key was in timing the studies to capture the specific pipes contributing to background GWI. The isolation of 89% of the total I/I from the 860 (total) catchment to less than 5% of the pipes is proof of the effectiveness. This level of source detection detail could significantly reduce spending on I/I remediation as well as improving flow reductions.

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