INNOVATIVE SOLUTIONS FOR THE REDUCTION OF INFLOW AND INFILTRATION IN SEWER NETWORKS

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ABSTRACT

Limiting inflow and infiltration (I&I) in sewer networks has many economic, environmental and public health benefits. The primary driver for the implementation of I&I reduction programmes has generally been driven by discharge consent conditions from a regional authority and/or by public pressure to eliminate the negative effects associated with sewage overflows and poor quality effluent discharges, rather than economic arguments. Using data from a number of New Zealand's local network operators it has been found that the cost of I&I is significant and there are strong economic benefits for implementing I&I reduction programmes in certain situations. It has also been found that alternative network systems (such as pressure sewer and vacuum systems) offer economic advantages over conventional rehabilitation and replacement solutions.

This paper proposes to:

- investigate and define the economics of I&I in order to assist network owners in their decision making processes; and
- evaluate alternative solutions in terms of lifetime costs when compared to conventional I&I reduction options.

KEYWORDS

Inflow and infiltration, I&I, sewers, wastewater, pressure sewer, vacuum sewer, rehabilitation

1 INTRODUCTION

Inflow and infiltration (I&I) into sewers is a common problem that affects wastewater network operators throughout New Zealand to varying degrees. The most common consequence of I&I are overflows during rainfall from manholes, controlled overflow points, pump stations and treatment plants. I&I can also affect the efficiency of high rate wastewater treatment processes by changing the quality parameters of the wastewater. The addition of I&I to sewer networks also reduces their capacity limiting the potential for growth and/or intensification within a given catchment. As noted by Gibson (2006) every litre per second of stormwater entering a sewer system reduces a catchment's serviceable population by 20 to 30 households.

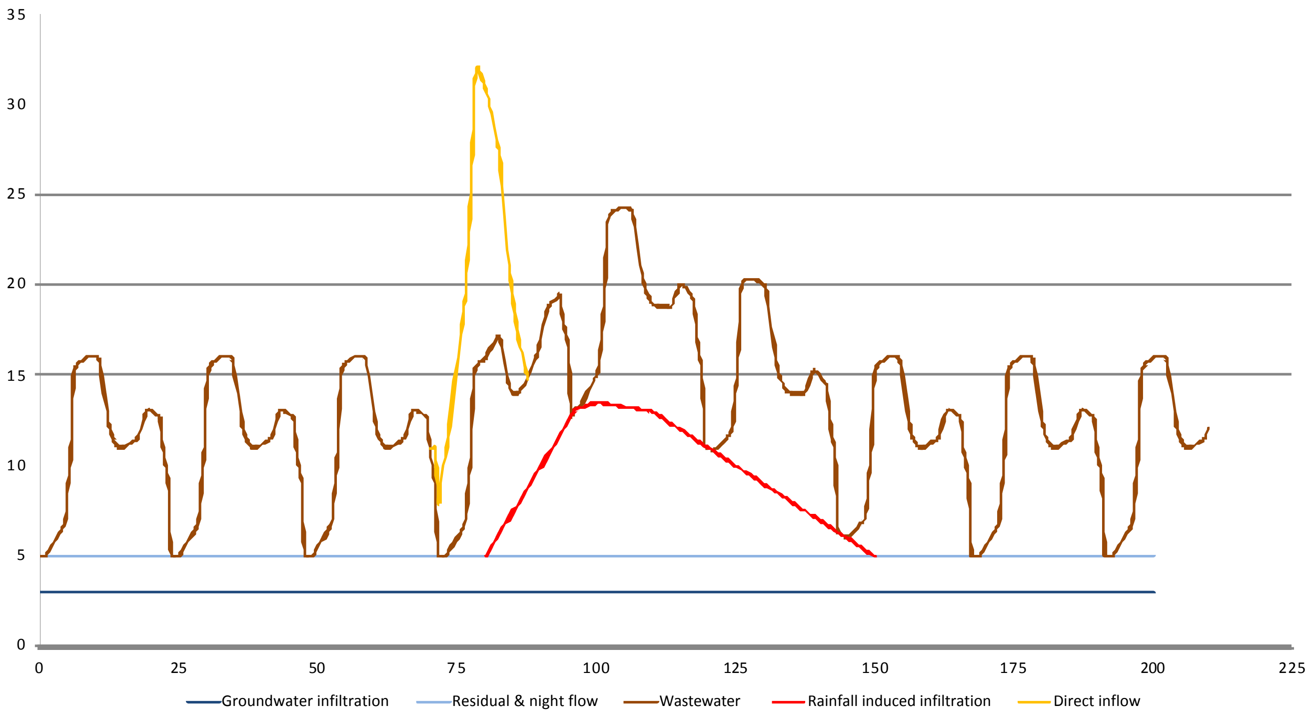
A significant body of research, time and capital has been invested in New Zealand by councils, water companies, consultants and suppliers to understand the effects of rainfall and groundwater induced I&I on sewer systems. The principal methods have been the development of monitoring programmes and dynamic modelling. The outputs from these tools have then been used to develop a business case for the implementation of rehabilitation works focused on the reduction of I&I. A significant issue however has been that I&I reduction programmes have resulted in extremely variable results, which undermines confidence in the value of I&I programmes. This has led to an increasing adoption of full flow conveyance and treatment options to mitigate the effects of I&I.

This paper attempts to develop a costing model for I&I reduction programmes allowing for the variability in outcome and details other, unique approaches to the reduction of I&I including the use of pressure sewer and vacuum sewer systems.

2 UNDERSTANDING I&I

I&I into sewer systems have many sources and are divided into two key components; infiltration is used for water entering from below ground level including groundwater; and inflow used for water that enters the sewer network directly. These components can be seen in Figure 1, a typical hydrograph from a sewer which is subject to both inflow and infiltration.

Figure 1: Components of wastewater in a typical sewer with I&I issues (Dublin City, 2005)



As can be seen in figure 1, I&I can have an effect on a sewer's capacity in both dry and wet weather. Infiltration enters the sewer system through underground defects in both the public and private drainage and includes: cracks and fractures in the fabric of sewers, lateral connections and manhole chambers (Figure 2). Inflow enters through surface features such as faulty or poorly positioned manhole covers, river/tidal backflow from overflows, direct connections to surface water and stormwater drainage, and downpipes.

Figure 2: Common sewer faults contributing to infiltration (Colvin, 2004)

I&I can make up a significant portion of the total flow conveyed by a given sewer network, and is dependent on a number of factors. This may include high groundwater levels, tidal influences, topography, the location of flood plains, poor historic building practices (both public and private), and the age and materials that make up the network. For example areas such as Christchurch have historically experienced a very high levels of groundwater infiltration (particularly in the winter) as the primary source of I&I, while some areas of Auckland experience very high inflow from historic cross connections when the system was combined. The principal concept for understanding I&I is that the behaviour in a given sewer network is highly site dependant, resulting in a complex decision making process to determine whether to proceed with an I&I reduction program.

3 OPTIMISED DECISION MAKING

Optimised Decision Making (ODM) is at the core of advanced asset management practices. This procedure should be used when assessing I&I reduction or other options such as conveyance and treatment. Added to the ODM process should be a consideration of intangible factors and externalities. These factors could include a community's willingness to accept overflows to local streams (intangible); the cost of monitoring harbour water quality; or public health risks and the rate of illness associated with overflows (externality). In practice the intangible factors and externalities are almost impossible to accurately qualify in monetary terms and qualitative scoring criteria could be used to rank options (Roberts et al., 2006). For the purposes of this paper and the associated economic analysis of I&I, intangibles and externalities have been ignored. It is however strongly recommended that these factors are considered when assessed whether an I&I reduction programme is required. The simplified ODM process used for this paper is shown in the flow diagram below (Figure 3).

The methodology applied to this process is a Predictive Modelling Technique which attempts to predict how I&I changes over time in a given sewer network and the cost implications of these changes. The predictive model also shows how various I&I rehabilitation or sewer replacement options change the quantity and effects of I&I on a particular network. Figure 4 graphically demonstrates this principal, the y-axis is the sewer performance in terms of I&I (i.e. the lower the value the more I&I enters the network) over time (x-axis). The figure also show how various options could be implemented at different times during the sewer system's life and the effect of different options on overall performance.

Figure 3: ODM Process (Roberts et al., 2006)

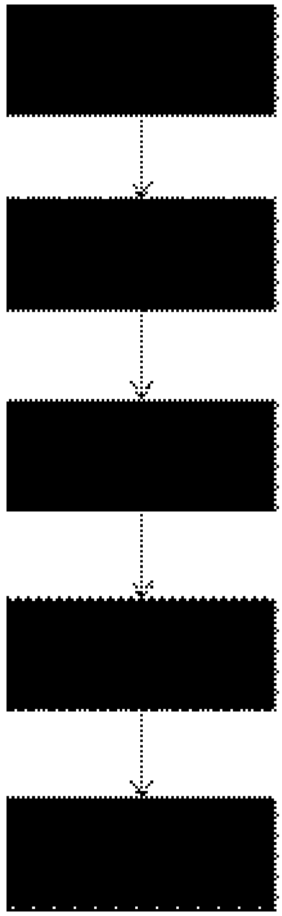
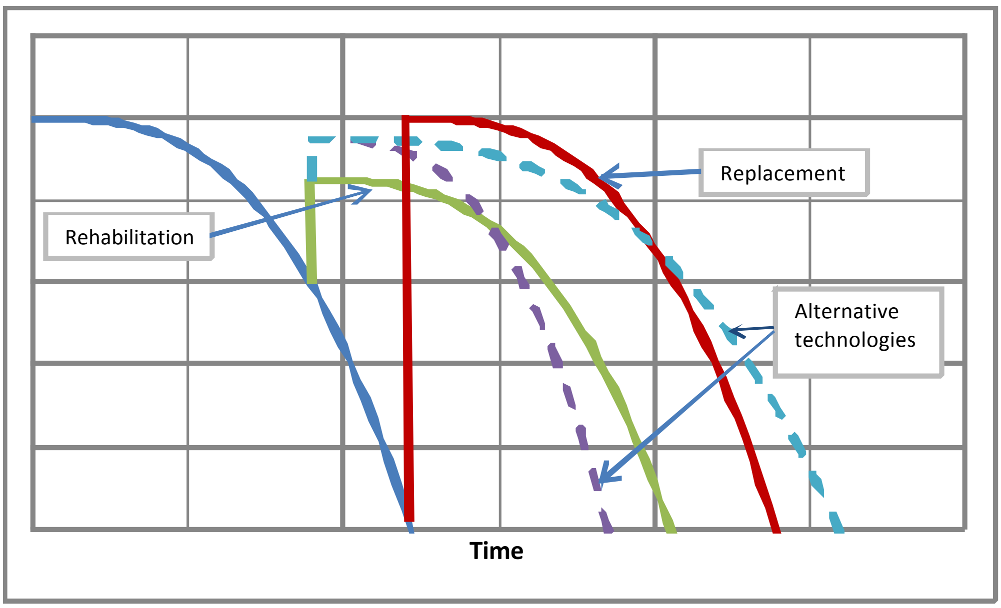
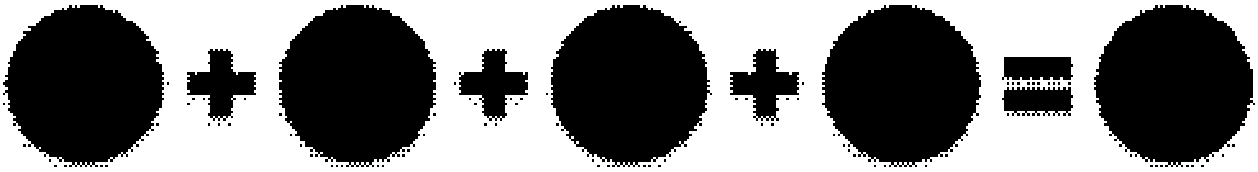


Figure 4: Sewer system performance over time and the effect of various remediation and replacement options



From the sewer system performance (in terms of I&I) the Net Present Value (NPV) of all the options can be assessed. This should determine the optimal option to implement, which may include a "do nothing/status quo" option. The basic equation for calculating these costs is:

Figure 5: The cost of inflow and infiltration



4 THE COST OF I&I

4.1 OPERATIONAL COST

Operational costs associated with I&I are:

- Network pumping and the resulting power costs. This can be estimated by subtracting the dry weather flow from the total flow through a given pump station. In calculating the annual costs any seasonal variations, such as holiday peaks need to be included.

- A portion of the total treatment cost will not be greatly affected by I&I as aeration and chemical addition are unlikely to change significantly (as these are determined by BOD rather than flow). Power costs associated with pumping the additional flow through a treatment plant will increase costs. Consideration of the type and size of treatment plant has the greatest impact in operating costs. For example a simple oxidation pond system is unlikely to have significantly different operational costs with or without the addition of I&I flow. In contrast a membrane plant will have much more variable costs as the additional flow needs to be passed through the membrane.

4.2 MAINTENANCE COST

Additional maintenance costs associated with I&I include:

- Great frequency of pump maintenance (higher run hours)

- I&I can cause the accumulation of grit and other materials in sewers, leading to a higher flushing costs and pump wear.

- Premature membrane replacement.

4.3 OTHER COSTS

Other costs include:

- Clean up costs associated with overflows

- Managing and testing water quality in receiving environments subject to overflows

- Managing beach closures, and effects to shellfish farming and gathering

4.4 INVESTIGATION OF I&I

Another cost of I&I to be defined is the cost to undertake the investigations needed to determine the extent of the I&I, location, sources and option investigations. Depending on the I&I reduction strategy adopted the scope and scale of these investigations will vary. The investigation of I&I needs a structured approach and should include most of the following stages (Dublin City, 2005):

- Site Monitoring
    - Flow and rainfall monitoring
    - Flow gauging
    - River/tide level gauging
- Study
    - Initial data collection and assessment
    - Estimation of I&I
    - Hydraulic modelling, calibration and system performance
    - Option assessment and costings
    - reporting
- I&I reduction programme implementation (apply to both public and private drainage)
    - Source detection
        - CCTV surveys
        - Manhole inspections
        - Isolation testing
        - Salinity testing (conductivity)
        - Dye and smoke testing
        - Jetting
    - Rehabilitation and/or replacement

These investigations require a structured approach as the causes of I&I can vary from a single point source to a wide distribution of sources and failure mechanisms through both the private and public systems. A thorough investigation phase is essential for minimising the cost of future rehabilitation or replacement works. This is because it has been noted that the distribution of I&I has been shown to following the Pareto principal: 80% of the problem will be in 20% of the catchment (Dublin City, 2005). White, M et al (1997) detailed studies which show in the majority of catchments this principal applies to most cases with a 70/30 to 90/10 distribution. Therefore the investment into a comprehensive and well managed I&I investigation can significantly reduce the capital works requirements by identifying the principal sources and location of I&I.

5 I&I REHABILITATION

5.1 CONVENTIONAL REHABILITATION

5.1.1 PRIVATE DRAINAGE

There is a growing body of evidence that I&I from private drainage can be a significant source of the overall I&I flows into a network. Sources can include direct stormwater connections from roofs and other catchpits, low gully traps subjects to flooding, leaking lateral sewers and connections to the public system. Based on an I&I control project undertaken by Metrowater in Hillsborough during 2006 it has been shown that the I&I contribution from private drainage could be between 9% and 43% (Gibson, 2006). This is based on a limited data set and therefore has accuracy issues.

I&I reduction tools for private drainage include: diverting stormwater systems, raising or moving gully traps and either lining or replacing the lateral drainage.

5.1.2 PUBLIC DRAINAGE

I/I within the public sewer networks can be addressed by several rehabilitation and reconstruction methods. These methods can generally be classified under three primary levels:

Level 1 – Repair of known inflow and manhole defects

Level 2 – Sealing or lining sewer mains and undertaking the Level 1 works

Level 3 – Replacement of the network

Level 2 repairs include joint sealing, pipe lining and spot repair techniques. Joint sealing is the process whereby pressurise grout is pumped into leaking joints or sewer fractures. Pipe lining is used to restore sections of sewers between manholes by inserting a liner into the sewer. There are various types of liners which have different advantages and disadvantages. Options include: epoxy spray lining, Cure in Place Pipe (CIPP), slip lining, Swage or die drawing lining, deforming pipe lining, and spiral wound linings.

Spot repairs include specific sewer replacement between manholes. This is applied where there may be a loss of gradient which would not be addressed by lining.

If the condition of the sewer network is extremely poor, a full replacement would be required. This could include various sewer construction techniques such as open trenching, pipe bursting, directional drilling and micro-tunnelling.

5.1.3 EFFECTIVENESS OF CONVENTIONAL REHABILITATION

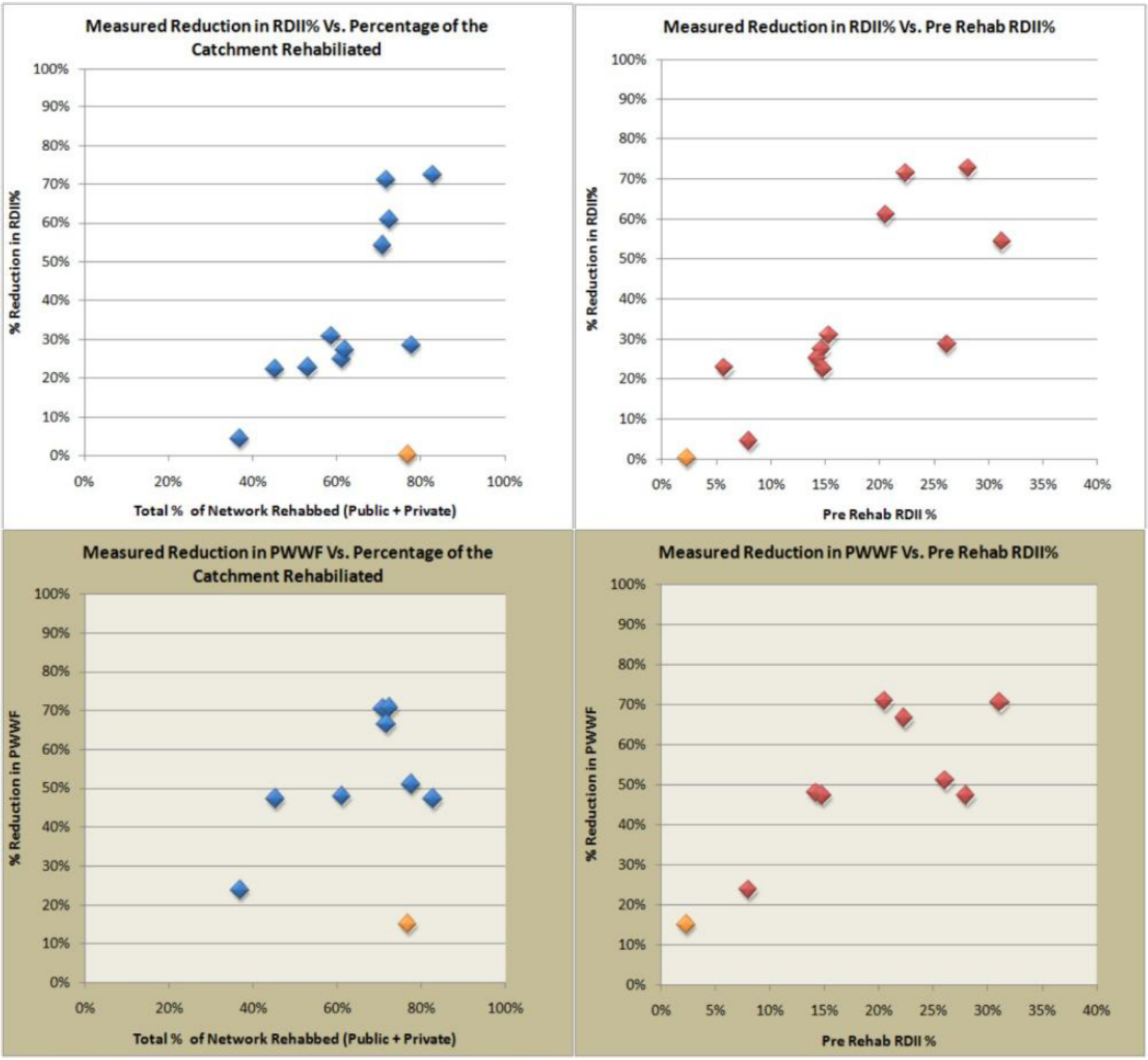
The effectiveness of I&I reduction programmes using conventional techniques typically have very variable results in terms of effectively reducing I&I. The tables below for Metrowater's I&I rehabilitation works carried out in Hillsborough and rehabilitation by North Shore City Council demonstrate the variation that is has been encountered with I&I reduction programmes. This variation adds significant uncertainty to financially modelling the cost benefit of carrying out an I&I reduction programmes.

Table 1: Effectiveness of I&I reduction in Hillsborough, Auckland (Gibson, 2006)

Rehabilitation Technique	Total source detection & rehabilitation costs ('000$/ha)	Total source detection & rehabilitation costs ('000$/km)	Range of measured I&I reduction

Repair of inflow and manhole defects	11.9 – 20.9	70.3 – 96.1	35% – 43%
Sealing/lining all pipes plus above	57.0 – 79.5	383.3 – 415.6	29% - 39.8%
All of the above plus sealing house laterals	114.3 – 209.5	563.8 – 802.9	49% - 72%

Figure 6: Measured I&I effectiveness for complete rehabilitation (public and private) in 14 mini-catchments on the North Shore of Auckland (Shaw, et al., 2009)



The key observations from Table 1 are: targeting sources of inflow and known defects can be more effective and significantly less costly than sealing or lining all sewers and I&I reduction programmes that includes the private drainage can be significantly more effective than works that focus only on the public network. The North Shore rehabilitation experience has shown that the higher the measured the I&I the more likely reductions in total I&I is possible post a comprehensive rehabilitation programme, which includes both the public and private networks.

5.2 ALTERNATIVE REHABILITATION SYSTEMS

Where a network suffers severe I&I that is widespread throughout the system, alternative network replacement options could become a useful method for reducing or even almost eliminate I&I. Two options which could provide economic alternatives to conventional rehabilitation techniques are pressure and vacuum sewer systems. Pressure sewer and to a limited extent vacuum sewer systems are becoming an increasing common and understood technology in New Zealand. A number of Councils and water companies are also collecting data on the performance of pressure sewer systems, which are providing these organisations, for the first time, a clear understanding of the private drainage contribution to sewer networks.

5.2.1 PRESSURE SEWER

As a pressure sewer system is a sealed pressurised system, there are no points downstream of the property pump unit that can allow the ingress of I&I. The only possible sources of I&I are from the pump chamber vent and lid, private drainage, gully traps and direct stormwater connections to the private drainage. Therefore in theory a pressure sewer system should result in less I&I than an equivalent conventional rehabilitation programme.

Furthermore the I&I sources from private drainage can be easily identified by measuring pump unit run hours allowing focused rehabilitation of private drainage sources of I&I. An example of the performance of a pressure sewer network has been investigated for the Point Wells pressure sewer system located approximately 80km North of Auckland city. Research undertaken in 2009 (Haarhoff, 2009) showed that 9% of properties had elevated pump run hours, which were attributed to direct inflow sources such as submerged gully traps, direct stormwater connections, and a submerged pump unit. Furthermore it was shown that 60% of the I&I could be attributed to only three properties. The relative ease of identifying sources of I&I with a pressure sewer system does give proactive water managers a powerful tool to almost eliminate I&I in these networks.

5.2.2 VACUUM SEWER

Vacuum sewer systems could be considered as an alternative to conventional rehabilitation in certain situations such a flat, low lying catchments. Unlike pressure sewer systems vacuum systems can be subject to I&I in both the public and private networks. However, I&I into the public network should be less than a conventional system. Firstly the vacuum sewer will be at a shallower depth than a conventional system (1.2m to 2.0m deep), as such, these systems should be less susceptible to groundwater influences. Secondly, any leaks in vacuum mains will result in continuous vacuum pump operation which will trigger an alarm. Once this alarm occurs a leak detection procedure will be triggered.

Sources of I&I from private drainage will still occur between the vacuum pit and property connections. In general the private drainage associated with vacuum systems are longer than a pressure sewer system and as such have more potential for I&I. Unfortunately, no relevant literature could be found for this paper which quantified the I&I performance of vacuum systems.

5.3 OTHER CONSIDERATIONS

Other options for remedying the principal effect of high I&I, overflows, is to either upgrade the network to convey the additional volume; store the I&I or partially treat the overflows at source. When building the ODM model these options, where appropriate, should be considered. It is important to ensure the ODM model includes all costs related to the sewer system. For example, storing wastewater in a network will not reduce treatment costs and the diluted wastewater, which would otherwise overflow, might adversely affect biological processes at the treatment facility. Furthermore, increasing the capacity of a sewer system will increase costs, as this will reduce overflows, increasing the volume to be transported and treated.

6 OPTIMISED DECISION MAKING MODEL

The Optimised Decision Making Model presented in this paper attempts to capture all principal costs that are associated with a wastewater network. It also works on the premise that sewer rehabilitation for the reduction of I&I must address three objectives:

- **Capacity recovery** – this aims at reducing I&I to restore and maintain available capacity and to control overflows.

- **Damage repair** – The reduction of I&I should also be used as an asset management tool aimed at repairing structural failures in the network.

- **Maintenance reduction** – Portions of the network which are subject to known and repeated maintenance issues from conditions such as root intrusion, improper lateral connections and other network deficiencies.

The emphasis on each of these objectives will vary from project to project depending on the networks' condition and short term objectives. However, a successful long-term I&I reduction program needs to address each objective to maintain system performance at the lowest overall cost.

The Optimised Decision Making Model should be undertaken to determine the portions of the sewer network which the financial return on an investment is greater than the cost of investment. The approach to conduct the evaluation varies slightly for each I&I reduction objective. Therefore, the following sections first present the financial evaluation approach for each objective separately. These objectives are then brought together in the Optimised Decision Making Model.

6.1 CAPACITY RECOVERY

Capacity recovery considers the savings received from reducing I&I from four mechanisms:

- Reduced transport (conveyance) cost

- Reduced treatment cost

- Reduced response cost from wet-weather induced sewer overflows (SO)

- Deferring, reducing or eliminating the need for downstream capital improvements that would be required to eliminated a SO if I&I is not reduced

These costs are location and catchment specific. The key criteria are that all costs are captured from the sources of wastewater through to the treatment and disposal systems. In most cases the catchment identified for I&I works forms part of a wider network. In these cases the individual catchment's contribution to downstream pump stations and the treatment plant can be calculated on a percentage basis.

The conveyance costs should be relatively simple to calculate for a given catchment if comprehensive flow monitoring data is available. This is achieved by multiplying the total volume of wastewater that is produced by the catchment by the $\$/m^3$ pumped by all downstream pump stations.

Treatment costs are highly dependent on the process involved and disposal method. For example, a facultative pond system with a gravity discharge directly to a river will have almost zero cost associated with I&I derived flows (unless these high flows exceed the capacity of the system). Conversely the operating cost of a membrane bio-reactor process with a land disposal system will be directly affected by changes in the volume of wastewater. Table 2 below shows some generic costs to treat wastewater based on different treatment processes and plant capacities. As a general rule of thumb, treatment costs per cubic meter reduce as capacity increases. Disposal costs, like conveyance costs, are related to spatial and topographic features specific to a given system.

Table 2: Treatment Costs for Different Treatment Processes (AWT Water, 2011)

Treatment Process	Cost Range ($\$/m^3$)	Comment
Facultative Ponds	0.10	Costs for one treatment plant capacity of $4{,}100m^3$/day
Activated sludge	0.62	Costs for one treatment plant capacity of $18{,}500m^3$/day

Sequencing batch reactor	0.34 to 0.54	Costs for a capacity range of 5,400 to 1,800m^3/day
Membrane bio-reactor	0.39 to 3.06	Costs for a capacity range of 8,000 to 32m^3/day

The cost from wet weather induced SOs can be significant given the located and size of the overflow. These costs include typical crew and equipment time for a response, site remediation and the cost of public notification and reporting to regulatory authorities. These costs are typically in the range of \$3,000 to \$12,000 per response (Wayne, et al., 2005). The method to consider the SO response savings can be developed from maintenance logs or the probable annual frequency of SOs in the study area. The annual reduction in possible overflows resulting from the post rehabilitation system can be calculated in the same way. For example a reduction in annual SOs frequency from 12 times per year to 0.2 times per year, assuming an average response cost of \$3000, would result in an annual saving of (12-0.2) x \$3,000 = \$35,400.

It is possible to defer, downsize or eliminate future downstream capital improvements by implementing effective I&I reduction programmes. Shaw et al (2009) has shown that on the North Shore reductions in peak wet weather flow of between 40% and 70% were possible through a comprehensive conventional rehabilitation programme. This has potentially the greatest effect on costs and should include capital improvements to both conveyance, treatment and resource consent requirements. The approach for the ODM model is to decrease the cost of the sewer rehabilitation project by the savings from deferring, downsizing or eliminating the alternative downstream capital projects.

6.2 DAMAGE REPAIR

The cost of damage repair is related to the system's condition and is related to the probability of failure multiplied by the estimated repair costs both before and after the rehabilitation. The development of standard condition assessment methodologies has improved asset managers ability to estimate the probability of failure associated with sewer systems.

6.3 MAINTENANCE REDUCTION

The maintenance objective relates to costs that are not necessarily related directly to I&I, but will change before and after the implementation of the rehabilitation option. This may include sewer jetting, dry weather blockages and root cutting. As with the SOs this can be estimated by calculating the difference between existing maintenance frequency and the future maintenance requirements of the rehabilitated system.

6.4 SEWER DETERIORATION

All sewer networks deteriorate over time. The rate of this deterioration and its effect on I&I will vary from system to system and on local environmental conditions (geothermal activity, settlement etc.). It is important to include an assumption of network deterioration in the ODM model to ensure a fair comparison of the options. Unfortunately no relevant literature could be found that has assessed how pressure and vacuum sewer system perform, in terms of I&I, over the long-term.

7 EXAMPLE CALCULATION

To illustrate the ODM process discussed in this report an example based on a theoretical system is demonstrated in this section. It is important to note that these results are highly dependent on each sewer system. However, same generic guidance will be provided as to where some rehabilitation options would be effective.

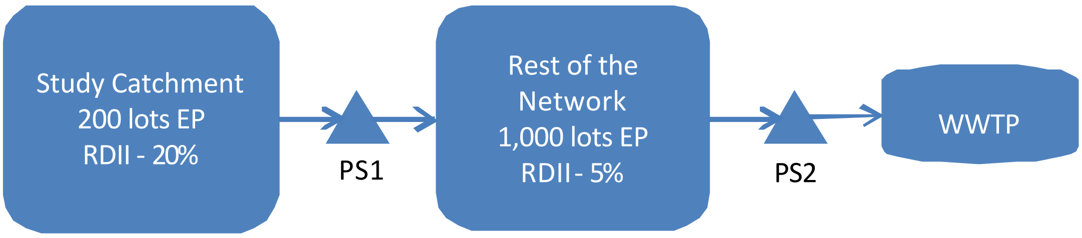
7.1 CATCHMENT PHYSICAL PARAMETERS

For this example the following catchment has been used:

- Catchment area - 20ha
- Land use – 200 residential lots
- Sewer length – 2,000m
- Sewer type and age – 50% vitrified clay (VC) constructed 1930 and 50% PVC constructed 1975
- Sewers require replacement after 100 years of operation
- Average I&I contribution – 200m^3/day
- Estimated sewer overflows per year – 10
- Post rehabilitation overflows per year (conventional) – 0.2
- Post rehabilitation overflows per year (pressure and vacuum) – 0

The network in which this example catchment is sited is serviced by an activated sludge plant and waste is transported to the treatment plant via two pump stations as shown below:

Figure 7: Example catchment network configuration



Other assumptions used for the ODM model include:

- Cost of wastewater treatment - $0.62/ m^3
- Cost of pumping PS1 – $0.10/ m^3
- Cost of pumping PS2 – $0.02/ m^3
- Probability and cost of repair of sewer failure before rehabilitation – 0.1% at $5,000/repair
- Cost of sewer overflows –$3,000/overflow
- Inflation - 2.5%
- Discount rate – 8.5%
- Public drainage contributes 50% of I&I sources by volume
- I&I deterioration rate 1% per annum (by volume)

Table 3: I&I Volume reduction for various sewer rehabilitation options

Option	**I&I Reduction Public**			**I&I Reduction Private**		
	Average	Minimum	Maximum	Average	Minimum	Maximum
Conventional rehabilitation	50%	20%	70%	70%	50%	90%
Pressure sewer	100%	100%	100%	70%	50%	90%
Vacuum sewer	95%	90%	100%	70%	50%	90%

It is assumed that I&I reduction is more effective on private drainage as direct sources of inflow are easier to identify and the drainage is easier to access.

7.2 OPTIONS

Four options have been used for the proposed theoretical catchment. These are:

1. Maintain the existing system (status quo)

2. Upgrade PS1 and the downstream network to convey I&I

3. Conventional rehabilitation (including public and private systems)

4. Pressure sewer system

5. Vacuum sewer system

7.3 PERFORMANCE OF THE EXISTING SYSTEM

In order to have a benchmark for comparing the rehabilitation options the cost of the existing system needs to be calculated. For this case and the following options the Nett Present Value (NPV) has been calculated for a period of 50 years.

Table 4: Existing catchment costs

Item	**Pre-rehabilitation costs (2011 $)**
I&I Conveyance and Treatment	
Conveyance cost	$8,760/yr
Treatment	$45,260/yr
Sewer Overflow Cost	$30,000/yr
Damage repair	$5/yr
Maintenance	
Jetting (1 per 5 years)	$2,400/yr
Root cutting (1 per 10 years)	$1,800/yr
Total Annual Cost (2011)	**$78,225**

Based on the assumption above the NPV has been calculated for the existing catchment as -$2,192,000 over 50 years.

7.4 DOWNSTREAM UPGRADES

For this theoretical case $900,000 of capital works has been identified to achieve a 1 in 5 year overflow standard. This will have no effect to the study catchment's conveyance or treatment costs.

Table 5: Downstream Upgrading Costs

Item	Pre-rehabilitation costs (2011 $)
I&I Conveyance and Treatment	
Conveyance cost	$8,760/yr
Treatment	$45,260/yr
Sewer Overflow Cost	$600/yr
Damage repair	$5/yr
Maintenance	
Jetting (1 per 5 years)	$2,400/yr
Root cutting (1 per 10 years)	$1,800/yr
Total Annual Cost (2011)	**$58,825**

Based on the assumption above the NPV has been calculated for the existing catchment as -$2,546,000 over 50 years.

7.5 CONVENTIONAL REHABILITATION

For the conventional rehabilitation option it is assumed that all public and private sewers are lined and sources known inflow are repaired. For this example an estimated rehabilitation cost of $1,800,000 has been calculated. This cost includes all investigations, professional services and other costs associated with this option. Furthermore, the rehabilitation works defer the need for the proposed capital works downstream until the I&I volume reaches 150m^3/day. For the minimum, average and maximum I&I reduction range the capital works are triggered in 2026 if minimum reduction is achieved and eliminated from the average and high reduction targets.

Table 6: Conventional Rehabilitation Costs

Item	Post rehabilitation cost (average reduction)	Post rehabilitation cost (minimum reduction)	Post rehabilitation cost (maximum reduction)
I&I Conveyance and Treatment			
Conveyance cost	$3,504/yr	$5,694	$1,752/yr
Treatment	$18,104/yr	$29,419	$9,052/yr
Sewer Overflow Cost	$600/yr		
Damage repair	$5/yr		
Maintenance			
Jetting (1 per 10 years)	1,200/yr		
Root cutting (1 per 15 years)	1,200/yr		
Total Annual Cost (2011)	**$24,613**	**$38,118**	**$13,809**
NPV	**-$2,266,000**	**-$2,533,000**	**-$2,051,000**

Based on this example the variability in the extent of I&I reduction achieved by conventional rehabilitation is demonstrated in the significantly different annual costs. Over the 50 year NPV analysis this difference is equal to $635,000 in 2011 dollars.

7.6 PRESSURE SEWER SYSTEM

For the pressure sewer system it is assumed that all public sewers are replaced with a pressure sewer network and a grinder pump unit at each property. The private sewers are also lined and sources known inflow are repaired. For this example an estimated pressure sewer system cost of $2,250,000 has been calculated. This cost includes all investigations, professional services and other costs associated with this option. Furthermore, the pressure sewer system results in the decommissioning of PS1 and eliminates the need for the downstream capital works.

Table 7: Pressure Sewer Rehabilitation Costs

Item	**Post rehabilitation cost (average reduction)**	**Post rehabilitation cost (minimum reduction)**	**Post rehabilitation cost (maximum reduction)**
I&I Conveyance and Treatment			
Conveyance cost	$219	$369	$73
Treatment	$6,719/yr	$11,315/yr	$2,263/yr
Sewer Overflow Cost	$0/yr		
Damage repair	$5/yr		
Operation & Maintenance			
Pumping	$2,000/year		
Call outs and maintenance	$2,500/year		
Total Annual Cost (2011)	**$11,443**	**$16,189**	**$6,841**
NPV	**-$2,294,000**	**-$2,360,000**	**-$2,229,000**

7.7 VACUUM SEWER SYSTEM

For the vacuum sewer system it is assumed that all public sewers are replaced with a vacuum sewer network and one vacuum chamber per two properties. The private sewers are also lined and extended to the vacuum pits, and sources known inflow are repaired. The vacuum sewer system will also require a vacuum pump station which will replace PS1. For this example an estimated vacuum sewer system cost of $2,000,000 has been calculated. This cost includes all investigations, professional services and other costs associated with this option.

Table 8: Vacuum Sewer Rehabilitation Costs

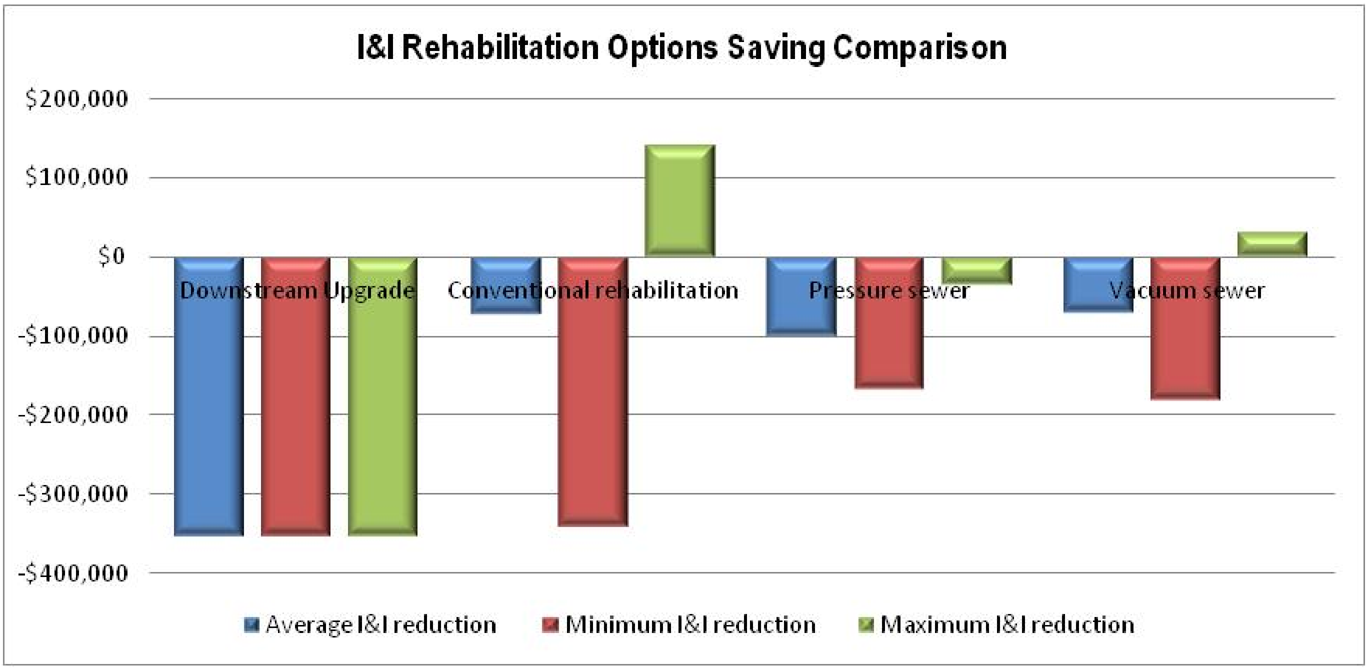
Item	**Post rehabilitation cost (average reduction)**	**Post rehabilitation cost (minimum reduction)**	**Post rehabilitation cost (maximum reduction)**
I&I Conveyance and Treatment			
Conveyance cost	$2,358/yr	$4,162/yr	$694/yr
Treatment	$7,694/yr	$13,578/yr	$2,263/yr
Sewer Overflow Cost	$0/yr		
Damage repair	$5/yr		
Operation & Maintenance			
Vacuum pumping	$2,000/year		
Call outs and	$10,000/year		

maintenance			
Total Annual Cost (2011)	**$22,057**	**$29,745**	**$14,962**
NPV	**-$2,263,000**	**-$2,374,000**	**-$2,161,000**

7.8 SUMMARY

Based on this example savings over the status quo would only be possible for the I&I conventional and vacuum rehabilitation options, and only if the maximum reductions are achieved (Figure 8). In this case the pressure and vacuum system provide narrow band of possible long-term costs which might be more desirable than the conventional rehabilitation which may or may not achieve the desired objective.

Figure 8: I&I Rehabilitation Options Saving Comparison



7.9 SENSITIVITY

The following section demonstrates the sensitivity of the ODM model to changes in various parameters and how this might affect the overall assessment. The options assessed are for the average I&I reduction target and consider the following cases:

Option 1 — Increased treatment and conveyance costs (longer conveyance distance/static head and membrane bio reactor treatment plant) resulting in a per cubic meter cost of $1.50 as opposed to $0.77/m^3.

Option 2 — Reduced treatment and conveyance costs (facultative pond) resulting in a per cubic meter cost of $0.35 as opposed to $0.77/m^3.

Option 3 — Double the I&I volume

Option 4 — Reduced discount rate (5.0%)

The NPV and savings for each of these options is summarised in Tables 9 to 12. The best option for each sensitivity option is highlighted green.

Table 9: Option 1 increased treatment and conveyance costs sensitivity analysis NPV and savings compared to the status quo

Option 1	**NPV**	**Saving**
Existing (Status quo)	-$3,248,000	N/A
Downstream upgrade	-$3,646,000	-$398,000
Conventional rehabilitation	-$2,705,000	$543,000
Pressure sewer	-$2,433,000	$815,000
Vacuum sewer	-$2,387,000	$861,000

Table 10: Option 2 reduced treatment and conveyance costs sensitivity analysis NPV and savings compared to the status quo

Option 2	**NPV**	**Saving**
Existing (Status quo)	-$1,585,000	N/A
Downstream upgrade	-$1,982,000	-$397,000
Conventional rehabilitation	-$2,040,000	-$455,000
Pressure sewer	-$2,252,000	-$667,000
Vacuum sewer	-$2,181,000	-$596,000

Table 11: Option 3 double the I&I volume sensitivity analysis NPV and savings compared to the status quo

Option 3	**NPV**	**Saving**
Existing (Status quo)	-$3,306,000	N/A
Downstream upgrade	-$3,704,000	-$398,000
Conventional rehabilitation	-$2,729,000	-$577,000
Pressure sewer	-$2,440,000	-$866,000
Vacuum sewer	-$2,394,000	-$912,000

Table 12: Option 4 reduced discount rate (5.0%) sensitivity analysis NPV and savings compared to the status quo

Option 4	**NPV**	**Saving**
Existing (Status quo)	-$4,009,000	N/A
Downstream upgrade	-$4,035,000	-$26,000
Conventional rehabilitation	-$2,698,000	$1,311,000
Pressure sewer	-$2,361,000	$1,648,000
Vacuum sewer	-$2,408,000	$1,601,000

For each of the scenarios it is clear that providing additional downstream capacity only increases the overall cost of the sewer system. Where treatment and conveyance costs are high or I&I is very high (Options 1 and 3), there is a strong economic case to replace the example catchment with a pressure or vacuum system; with the vacuum system having the greatest economic benefit. Where conveyance and treatment costs are low the continued operation of the existing system with a standard renewal at the end of the sewers life is the best in terms of the ODM model. Reducing the discount rate in the NPV analysis (Option 4) has a significant effect on the options that reduce I&I the most and hence future operation and maintenance costs. For this case the pressure sewer system has the lowest cost.

8 CONCLUSIONS

The ODM model developed for this paper captures the true cost of I&I in sewer networks. It is shown that all rehabilitation options should be considered, and that the optimal option (in terms of cost) is highly dependent on catchment and sewer specific factors. Increasing the downstream capacity of a network is unlikely to be an economic solution to resolve I&I issues unless the upgrade has a very small cost when compared to rehabilitation and the cost of treatment and conveyance is low. Most importantly asset managers need to understand the tipping point at which replacing or rehabilitating the network will be cheaper than the continued operation of the status quo.

Retrofitting a vacuum sewer system in many cases has been demonstrated to be the lowest cost solution to I&I reduction. However, vacuum sewer system can be limited in application due to their topographic limitations and requirement to be open trenched. Replacing a sewer network in a developed area without the use of trenchless techniques is probably not publically acceptable or feasible in some cases. Pressure sewer systems have also been shown to be less costly than conventional rehabilitation in some cases, particularly where the conveyance and treatment costs are high. In theory, pressure sewer systems will result in a narrow and consistent band of I&I reduction when compared to conventional rehabilitation. This assists decision making process by reducing the uncertainty of outcome associated with conventional rehabilitation.

While economic arguments are used in this paper to justify the implementation of I&I reduction programmes other factors such as environmental effects, public health risk and even political pressures all form part of the complexities of the problem of inflow and infiltration.

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