REDUCING WASTEWATER OVERFLOWS: OPTIMISING CAPITAL INVESTMENT IN CHRISTCHURCH

Joel Wilson (WCS Engineering) and Bridget O'Brien (Christchurch City Council)

ABSTRACT

Christchurch has a large and complex wastewater network serving 384,000 people. Past efforts to reduce wet weather overflows were based on traditional trial-and-error modelling, and the system upgrades stemming from those modelling efforts have not been as effective as hoped, despite costing more than $150 million. Even with those upgrades in place, there remains an overflow volume of 38,000 m³ to waterways and a further 40,000 m³ overflows from 165 manholes during a 3-year ARI (average recurrence interval) storm.

This project's objective was to identify the most cost-effective suite of projects to prevent system overflows for three different return period storms (6-month, 1-year and 3-year ARI).

To best evaluate a broad range of alternatives in the improvement plan, Christchurch City Council (CCC) chose to use genetic algorithm (GA) optimisation, Optimatics' Optimizer WCS^{TM} software, and an experienced optimisation team.

Optimizer WCS^{TM} links to the hydraulic model and life-cycle cost data. Cloud computing is used to run the model continuously and evaluate thousands of combinations of improvement alternatives against total cost and hydraulic performance, enabling the optimisation team to identify solutions that meet the planning criteria at least cost.

The structured process evaluated thousands of possible combinations of pipe upgrades, pump station upgrades, inflow and infiltration (I/I) reduction, increased treatment plant capacity, flow diversion, and new storage facilities. This would not have been possible with a traditional trial-and-error modelling approach.

Improvement alternatives were gradually added in order of complexity (starting from increasing conveyance capacity along existing alignments, then flow controls and diversion options, then storage facilities, and finally I/I reduction options). This strategy enabled the team and CCC to review optimised solutions incrementally and gain appreciation of the potential cost savings associated with various alternatives.

The team first studied existing system performance results of wastewater overflow volume and frequency in the 15-year continuous simulation of rainfall from 2000 to 2015. They then devised a plan to determine the costs to abate the overflows, differentiating between 1) manholes, 2) "Priority 1" outfalls and 3) "Priority 2" outfalls. If the estimated cost was below $500/m³ to abate overflow, the outfall was designated as Priority 1. If the estimated cost was above $500/m³ to abate, the outfall was Priority 2.

Improvement alternatives and associated unit costs were then placed into the model and Optimizer, and numerous optimisation runs were performed. The final, optimised solutions showed the location and size of pipe upgrade, storage, and I/I reduction improvements that would meet the system performance requirements at least cost.

This project achieved capital cost savings of up to 32% to achieve an aspirational target of no overflows in a 3-year annual recurrence interval storm. The optimisation process also gave CCC certainty that the recommended projects were the most cost-effective suite of projects to achieve its target.

KEYWORDS

Collection system, wastewater overflows, consent, optimisation, wastewater modelling, I/I reduction, asset condition, capital cost savings,

PRESENTER PROFILE

Joel Wilson is a collection systems planning specialist and industry leader in optimisation. He has worked with leading utilities, consultants, and professional affiliations to develop industry best practices, and has played a significant role in helping utilities communicate the benefits of optimized plans to community stakeholders.

1 INTRODUCTION

Christchurch has a large and complex wastewater network serving approximately 384,000 people with a single wastewater treatment plant capable of treating 650 megaliters/day (MLD). Past efforts to reduce wet weather overflows were based on traditional trial-and-error modeling. The resulting capital works were not as effective as hoped, despite costing over NZ$150 million. Following those upgrades, there remains an overflow volume of 38,000 m³ to waterways and a further 40,000 m³ of overflows from 165 manholes during a 3-year average recurrence interval (ARI) storm.

Christchurch has two main river systems: the Avon River and the Heathcote River, which both flow into the Avon-Heathcote Estuary which then flows into the Pacific Ocean (see Figure 1). Christchurch City Council (CCC) holds a resource consent (permit) for the overflows to waterways. The resource consent allows an overflow frequency to each of these receiving environments which decreases over time to a 2-year ARI, based on 15 years of long time series modelling. In addition, no overflow site may overflow more than every six months on average, based on the same long time series modelling.

Christchurch experienced large earthquakes in 2010 (Magnitude 7.1) and in 2011 (Magnitude 6.3 and 6.4) which resulted in the loss of 185 lives. The earthquakes also had a massive effect on the city’s infrastructure, particularly the wastewater network. As can be seen in Figure 2, the percentage of pipes with a condition grade of 5 (very poor, expected to fail within 1-2 years) went from zero to 47% as a result of the earthquakes. While $2.22 billion was spent repairing the city’s horizontal infrastructure, not all damage was repaired and 10% of wastewater pipes are still condition grade 5. As a result, inflow and infiltration into the wastewater network has increased significantly. A five-year non-enforcement agreement for the overflow consent was entered into with the regulator after the earthquakes, to allow the city time to repair its infrastructure.

Figure 1: Map of Christchurch

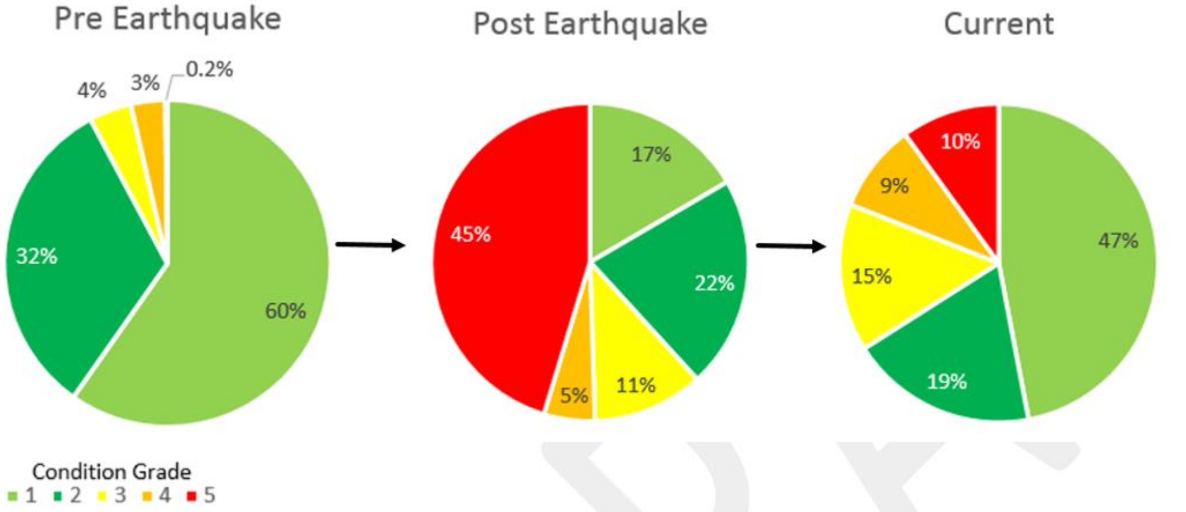

Figure 2: Assessed condition of wastewater mains (percentage by value), before and after the earthquakes and current. Condition Grade 1 = as new, Condition Grade 5 = expected to fail within 1-2 years.

However, CCC did not expect to be able to comply with its overflow consent at the end of the five-year non-enforcement period due to the remaining damage to its infrastructure. The primary cause of capacity deficiencies within the wastewater network is high rates of inflow and infiltration (I/I), attributed to a significant portion of the network being below the groundwater table and significantly earthquake-damaged or deteriorated assets. In some parts of the catchment, stormwater ingress is so severe that the observed dry and wet weather flows suggest that the wastewater network is providing substantial drainage capacity for stormwater and groundwater.

Due to time constraints following the completion of the earthquake repair programme, the project team carried out long time series modelling to determine whether the network complied with the overflow consent. This was done in parallel with the preparation of a new consent application.

CCC wanted to determine the most cost-effective suite of projects to eliminate wastewater overflows to waterways and from manholes for a range of design storms (6-month, 1-year and 3-year ARI), so that it could discuss the costs and benefits of these with its key stakeholders and determine the best approach for reducing overflows in its new consent application. Note that the 3-year ARI synthetic design storm corresponds to an overflow return period of approximately 2 years based on long-term rainfall simulations.

Previous trial-and-error modelling to determine the projects required to reduce overflows to an acceptable level in the Heathcote River did not produce any conclusive results (Opus, 2014). The conclusion of this project was that there was "no silver bullet" and that there would be significant impacts on the downstream network that had not been assessed, as this was beyond the scope of the project. This highlighted the need to take a city-wide approach, considering the impacts of capacity upgrades on the whole network and the wastewater treatment plant.

Christchurch City Council decided to take a different approach to determining projects to reduce overflows, using the power of optimisation techniques rather than trial-and-error modeling. The objective of the city-wide wastewater optimisation project was to identify the most cost-effective suite of projects to prevent overflows for three different return period storms. Many solutions to resolve capacity issues and associated costs were added to the Christchurch wastewater network model.

The city-wide optimisation is being undertaken in several phases, with each phase allowing for additional detail to be progressively included and the scope to be refined based on the outcomes of subsequent phases and the specific requirements of the city. This paper summarises the results of Phases 1 and 2 of the optimisation project.

2 METHODOLOGY

Optimisation is used in wastewater master planning to determine the best mix of capital improvements and operational settings which meet the target level of service at the least cost, while also mitigating risk and meeting multi-criteria objectives. For this project, it provided a structured process through which the effectiveness and cost of many combinations of planning options such as I/I reduction, increased conveyance capacity, increased treatment plant capacity, flow diversion and storage facilities could be evaluated.

A Genetic Algorithm (GA) optimisation process using OptimizerTM software (a product of Optimatics) was undertaken. The process provides a framework for undertaking a comprehensive analysis of overflow reduction alternatives considering system-wide interactions and life-cycle costs. OptimizerTM links to the hydraulic model and detailed life-cycle cost data to evaluate many thousands of improvement alternatives. In a single analysis, cloud-computing is used to run thousands of solution permutations to identify the solution that meets the defined objectives at the least cost.

A systematic approach was used to develop a highly complex optimisation framework. By gradually adding improvement alternatives in order of complexity (starting from increasing conveyance capacity along existing alignments, then flow controls and diversion options, then storage facilities and finally, inflow and infiltration reduction options), thorough quality assurance was completed at each stage to ensure alternatives were evaluated effectively. The process of gradually adding improvement alternatives to the optimisation also had the advantage of allowing the engineering team to review optimized solutions incrementally and gain an appreciation of the cost savings associated with various alternatives as they were added to the range of variables.

The Christchurch city-wide wastewater optimisation project involved the following tasks:

- Existing and future conditions system performance review
- Options identification
- Unit cost rate development
- Preparation of the hydraulic model
- Estimation of rainfall dependent inflow and infiltration for flow gauge catchments
- Formulation of the optimisation model and performance of optimisation runs.

Based on the results of the existing system performance review, workshops were held to identify the possible improvement alternatives to resolve overflows in the 2068, 3-year ARI design scenario. These included parallel sewer pipes, new and expanded pump stations, flow diversions, flow controls, storage tanks, linear storage, treatment facility improvements and inflow and infiltration (I/I) reduction.

Equivalent Uniform Annual Cost (EUAC) was used in the optimisation analysis for economic comparison of alternatives. EUAC is the cost of owning, constructing, operating and maintaining the collection system components converted to the uniform per-year basis. EUAC analysis provides a long-term assessment of project effectiveness, compared to evaluating up-front capital cost (initial cost) alone, and provides a simplified and more accurate approach to comparing assets with different life spans than present value analysis (Hoff 2006). EUAC includes consideration of:

- Capital cost (initial cost) including preliminary and general items (20% of construction cost), construction costs and on-costs associated with designing, consenting, procuring and commissioning the assets.
- Operations and maintenance cost including power costs.
- End-of-life replacement cost.

$$Equivalent\ Annual\ Capital\ Cost = Capital\ Cost \times \frac{Net\ Present\ Value}{Present\ Value\ Annuity\ Factor}$$

$$Present\ Value\ Annuity\ Factor = \frac{1-(1+Effective\ Discount\ Rate)^{-Asset\ Life}}{Effective\ Discount\ Rate}$$

Unit cost rates adopted for the optimisation analysis were planning level estimates developed specifically for CCC based on cost data from recent wastewater projects, which have been extensive following the earthquakes of 2010 and 2011 (GHD, 2015). Gravity main and pressure main improvement options were categorised based on the relevant surface type (local or arterial road). The total length of trenchless construction was also accounted in the cost estimate for sewer mains where this was the likely construction method (e.g. under rail lines). The cost of upgrading the existing wastewater treatment plant (WWTP) to service increased peak wet weather flow was estimated based on consideration of constraints in the WWTP and incremental improvements of key elements of the treatment process to cope with a range of increased flows.

Optimisation was also used to evaluate the rehabilitation of existing gravity sewer and private laterals to reduce wet weather inflow and infiltration (I/I). The rainfall-dependent inflow and infiltration (RDII) was estimated for all 47 flow gauge catchments (FGC) based on flow gauge data and modeling results (Morphum, 2016). All FGC were considered for I/I reduction. For each FGC, five I/I reduction options were considered, ranging from zero reduction up to the maximum percentage reduction achieved if 100% of the catchment is rehabilitated. The following equation (Water Services Association of Australia 2011, Shaw et al. 2009) was used to estimate the percentage reduction achieved based on the percentage rehabilitation complete and the existing ingress (initial RDII factor calculated as the percentage of rainfall volume entering the wastewater network from each FGC).

$$RDII\ \%\ Reduction = Initial\ RDII\ Factor \times Percentage\ Complete$$
$$= (0.257 \ln(-0.0445x + 0.0445 + RDII_{Pre}) + 0.988) \times x^{1.055}$$

Based on this equation, a relatively leaky FGC with an existing ingress of 20%, for example, would have I/I reduction options of 0%, 14%, 29%, 43% and 57%, corresponding to 0%, 25%, 50%, 75% and 100% completion of rehabilitation within the FGC. Similarly, an FGC with relatively low ingress of 5% would have I/I reduction options of 0%, 8%, 14%, 20% and 22%, corresponding to 0%, 25%, 50%, 75% and 100% completion. The cost to achieve each I/I reduction option was calculated based on the total length of sewer main in the relevant FGC (not yet rehabilitated) multiplied by the percentage complete and multiplied by a total project rehabilitation cost of NZ$350/m (US$235), based on work done by North Shore City Council.

I/I reduction costs were discounted based on the average remaining life of gravity sewers in each catchment, such that the effective cost is only the additional present value cost of bringing forward rehabilitation required to maintain structural integrity. This significantly reduces the cost of I/I reduction in the optimisation process and significantly affects the outcome of the optimisation. It generally results in I/I reduction being selected more prevalently due to the recognition of deferred asset maintenance cost.

The improvement options and associated costs were formulated in the OptimizerTM optimisation model together with relevant design criteria. OptimizerTM uses a wastewater-specific customised hybrid of genetic algorithm optimisation and implicit linear programming optimisation (Brown et al, 2011) to automatically evaluate many thousands of potential system improvement option configurations against hydraulic performance and total solution cost.

Optimizer evaluates the possible option configurations and assesses both the cost and hydraulic performance simultaneously. The program automatically configures a complete dynamic hydraulic model simulation of each trial solution and calculates the total project cost based on the CCC unit cost rates formulated in the optimisation model. Ultimately, the optimisation analysis determines combinations of improvement options which meet the specified design and performance criteria at least cost.

3 RESULTS

The existing system performance results are shown in Figure 3 with respect to sewage overflow volume and frequency in the 15-year long time series simulation of rainfall from 2000 to 2015. Wet weather overflow consent frequency targets were assessed based on the results of the 15-year rainfall simulation and found to be compliant. A total of six outfalls had discharges greater than the permitted two events per year. A total of 30 outfalls had discharges greater than once every two years (corresponding to the long-term aspirational overflow abatement target).

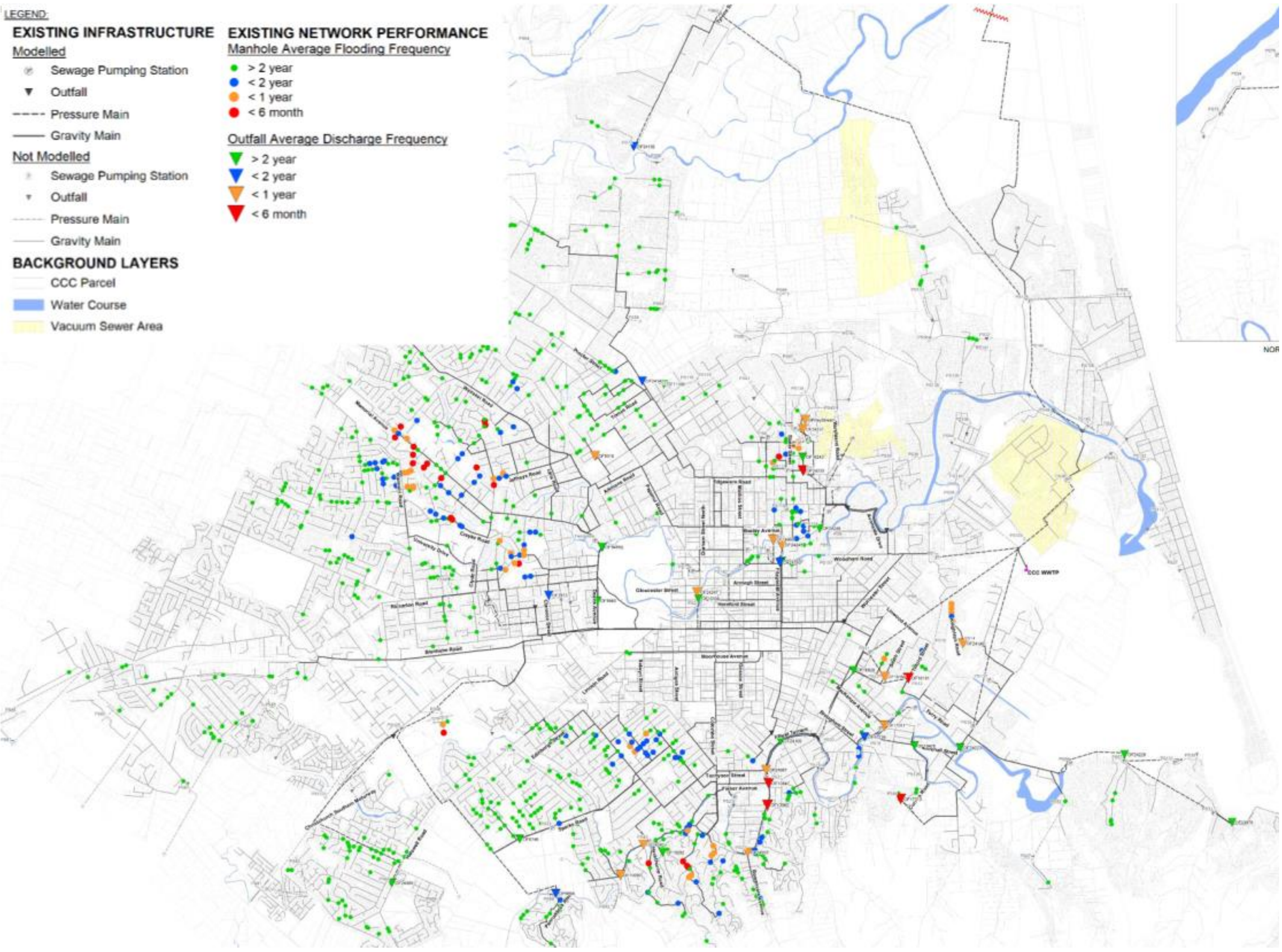

Figure 3: Existing system wet weather overflow frequency – manhole flooding and constructed outfalls

Optimisation scenarios were performed sequentially with an increasing number of allowable improvement alternatives:

1. Conveyance improvements along existing alignments
2. Conveyance improvements along existing alignments, flow controls, flow diversions and storage
3. Conveyance improvements along existing alignments, flow controls, flow diversions, storage, and I/I reduction alternatives

Progressively including additional improvement alternatives helped to demonstrate the cost savings attributed to each type of alternative. This approach also helped to check that the optimisation was effectively evaluating each improvement alternative before additional detail was included.

The total EUAC cost of Phase 2 optimisation scenario solutions are compared in Table 1. Note that optimisation scenarios with I/I reduction alternatives included were only completed for the 3-year ARI design storm. Also note that the Phase 2 optimisation was based on preliminary estimates for asset condition to discount the effective cost of I/I reduction; further detailed asset condition data are to be included in the Phase 3 optimisation. System improvement alternatives are shown in Figure 4.

Table 1: Comparison of Phase 2 optimisation solutions

ARI Design Storm Scenario	**Initial Capital Cost ($ million)**		
	1. Conveyance Only	2. Conveyance + Storage	3. Conveyance + Storage + I/I Reduction
6-Month	11	11	N/A
1-Year	88	62	N/A
3-Year	191	147	123

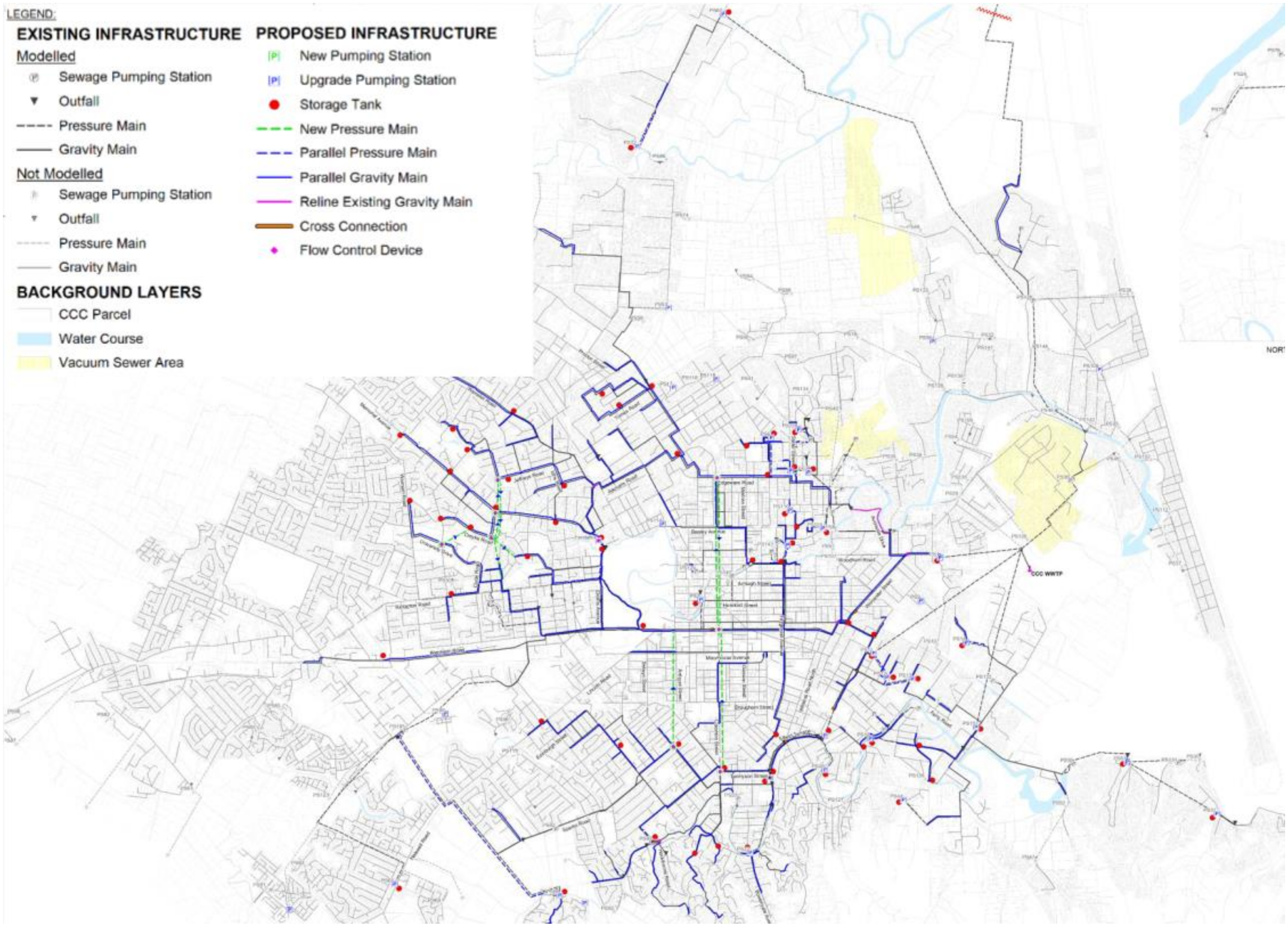

Figure 4: System improvement alternatives considered in Phase 2 Optimization

The Phase 2 optimisation results presented in Table 1 demonstrate cost savings on the order of 23% and 32% (based on total life-cycle cost) when the optimized solutions for Scenarios 2 and 3, respectively, are compared to the Scenario 1 baseline solution in the 3-year ARI design storm.

The Scenario 3 optimized solution is presented in Figure 5. This figure shows the cost-effective combination of conveyance, flow diversions, storage and I/I reduction. Comparing this solution to the Scenario 2 solution demonstrates that I/I reduction was selected strategically by the optimisation at locations that help to eliminate large, high-cost storage tanks.

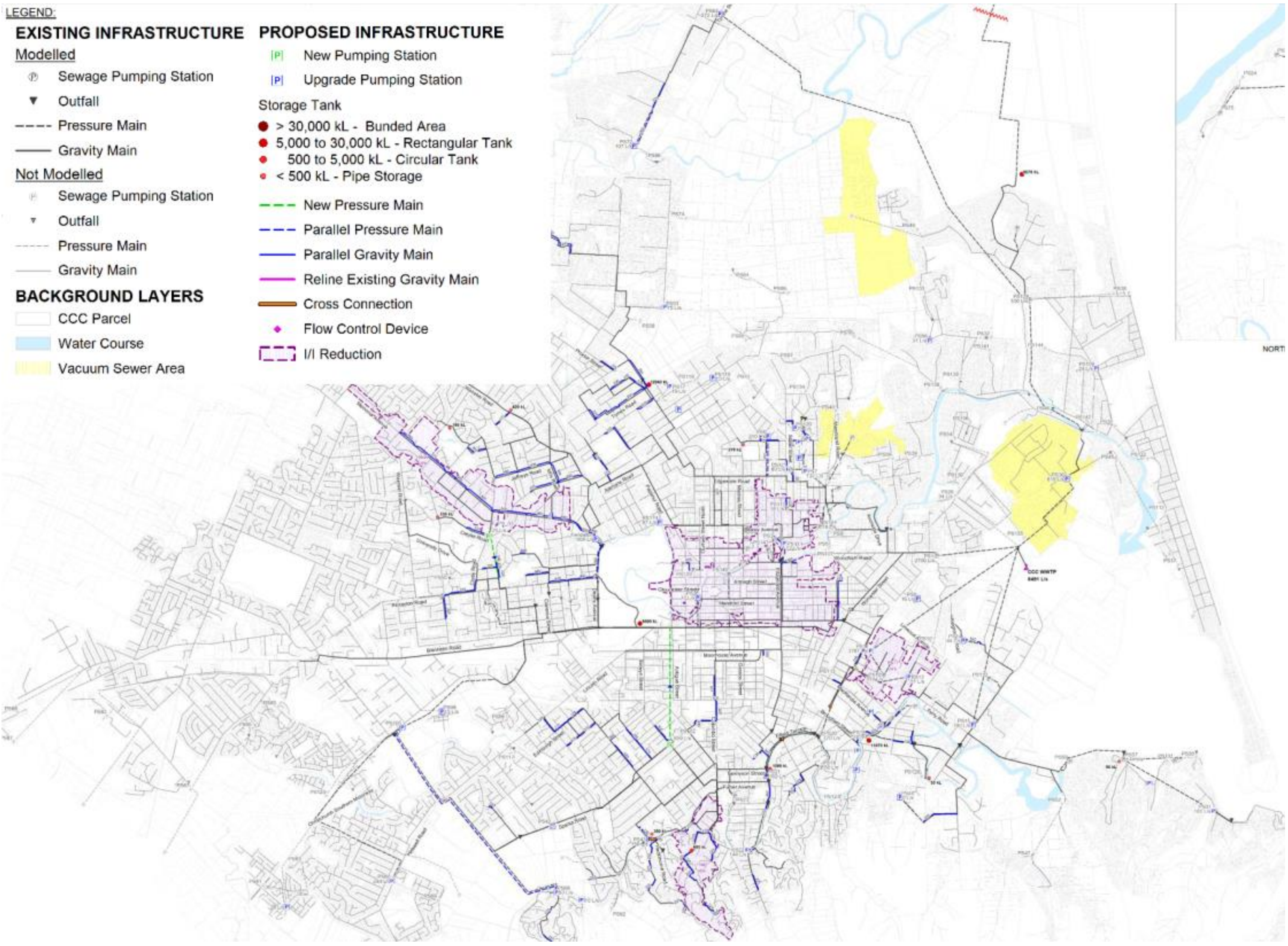

Figure 5: Phase 2 preliminary optimized solution to achieve 2 year ARI overflow frequency

The long time series modelling demonstrated that CCC was largely compliant with its overflow consent, except for six overflow sites that overflowed more frequently than the permitted twice per year. The results of the optimisation project were used to determine the upgrade projects needed to resolve these overflows, and the total estimated capital cost of these is NZ$10 million (US$6.7 million). Comparing this with CCC's budget of $68 million (US$46 million) shows a saving of 85%. The regulator agreed that it was better that CCC undertook physical works to fully comply with its existing overflow consent, rather than going through the process of applying for a new consent.

4 DISCUSSION

A preliminary assessment of the capital works schedule that would maximize return on investment based on overflow volume reduction was completed in Phase 2. This assessment was completed for all constructed outfalls (wet weather emergency relief structures) by correlating each outfall with the projects required to eliminate overflows during the 3-year ARI design storm. This assessment was completed on the basis that all projects required to eliminate manhole flooding were implemented.

The preliminary prioritisation assessment results are shown in Figure 6 and Figure 7. Figure 6 shows the outfall discharge volume and cost to abate overflows at each outfall for the 2-year and 1-year ARI design storms. The data are shown from left to right in order of return on investment. That is, outfalls with relatively low cost to eliminate large outfall volumes are shown toward the left on the figure.

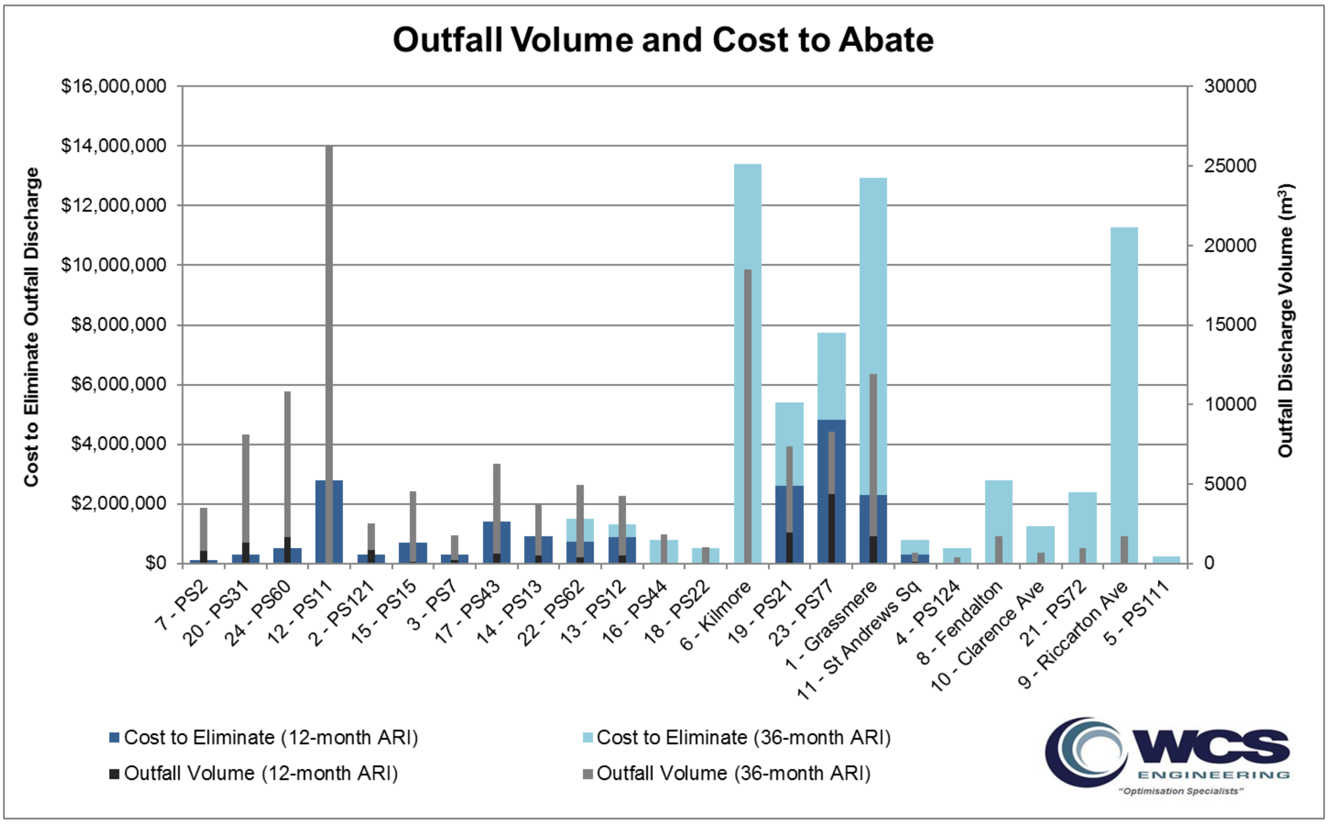

Figure 6: Outfall volume and capital cost to abate overflow

Figure 7 shows the cumulative reduction in overflow volume and cumulative cost if capital improvements are completed in the order shown from left to right in Figure 6. Figure 7 shows the diminishing return on investment when abating overflows with relatively high cost to abate small outfall volumes.

The preliminary prioritisation results are based entirely on outfall volume. Future phases of the city-wide optimisation are likely to include refined alternatives based on peer review of the Phase 2 solution, revised design storms based on the results of long-term rainfall simulations, integration of detailed asset condition data, and multi-objective prioritisation of the capital works schedule using either a risk-based or effects-based framework.

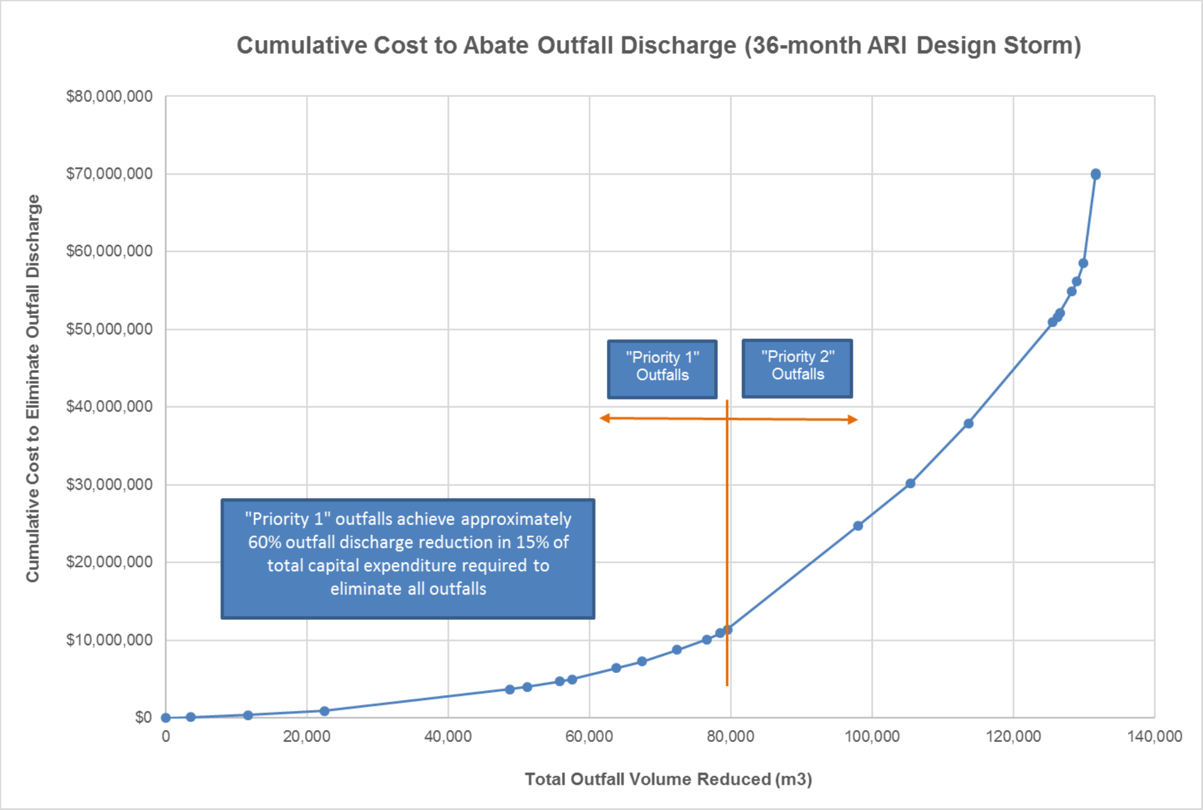

Figure 7: Return on investment profile for overflow abatement based on capital cost (assuming projects to abate manhole overflows are already implemented)

5 CONCLUSIONS

To address overflow concerns in a large and complex wastewater network, traditional trial-and-error modeling does not tend to deliver a cost-effective solution. In the case of Christchurch, this resulted in a large spend of over NZ$150 million with little overflow reduction achieved. By adopting a systematic optimisation approach using Optimizer^{TM} and cloud computing, thousands of solution combinations can be trialled and compared simultaneously, resulting in the most cost-effective solution for a given set of improvement parameters.

The Christchurch optimisation project clearly identified the cost benefits achieved through optimisation and included additional improvement alternatives to the standard conveyance solutions, resulting in a cost savings upwards of 32%. Optimisation further allowed for sensitivity analyses to be undertaken to further justify proposed improvements and demonstrate solution resilience. Applying genetic algorithm optimisation is a complex proceedure that requires the experience of a specialist engineering consultant.

This approach of coupling Optimizer WCS with wastewater network models could be applied to other cities seeking to optimize their capital, operating and maintenance expenditure on wastewater networks, and is more broadly applicable than for just reducing wastewater overflows.

REFERENCES

N. Brown et al. 2010. Cost Optimal Wastewater System Improvements – 2009/2010 North Shore City Wastewater Optimisation Project. Water New Zealand, Christchurch, New Zealand.

GHD 2015. Wastewater Optimisation Costs Report. Technical report prepared for Christchurch City Council.

J. Hoff, 2006. Equivalent Uniform Annual Cost: A New Approach to Roof Life Cycle Cost Analysis. RCI 21st International Convention, Phoenix, Arizona.

Morphum Environmental Ltd, 2016. Inflow and Infiltration Assessment. Technical report prepared for Christchurch City Council.

N. Shaw et al., 2009. Confidently Predicting Effectiveness of Sewer Rehabilitation. Water New Zealand, Rotorua, New Zealand.

Opus International Consultants Ltd, 2014. PS20 Catchment Modelling. Technical memo prepared for Christchurch City Council.

Water Services Association of Australia – Management of Wastewater System Infiltration and Inflow, 2011

WCS Engineering Pty Ltd 2016. City-Wide Wastewater Optimisation Phase 1 – Preliminary Conveyance-Only Optimisation. Technical report prepared for Christchurch City Council.

WCS Engineering Pty Ltd 2017. City-Wide Wastewater Optimisation Phase 2 – Preliminary Solutions. Technical report prepared for Christchurch City Council.