OPTIMISATION AND MULTI-CRITERIA ANALYSIS FOR PIPE NETWORK INTERCONNECTIVITY PLANNING

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ABSTRACT

The Network Water Security Program (NWSP) is currently being carried out by the South Australian Water Corporation (SA Water) with the dual purpose of improving interconnectivity of the Adelaide water distribution network and achieving real-time operational management of the water network through use of advanced decision-making tools. The feasibility works for the NWSP interconnectivity project developed infrastructure augmentation options and produced a preferred concept development plan. These works considered a mix of objectives relating to supply reliability, business continuity, infrastructure and operations cost, and customer service levels. This paper tracks the development of the feasibility works and demonstrates how a formal optimisation framework can significantly improve the financial, hydraulic, sustainability and reliability outcomes for complex infrastructure development projects.

KEYWORDS

Network interconnectivity, infrastructure planning, network reliability, genetic algorithm optimisation.

1 INTRODUCTION

Australia is currently experiencing a prolonged drought of unprecedented severity. This has resulted in the construction of several large desalination plants to augment supplies to cities around the country. Adelaide, South Australia, is particularly vulnerable to drought during which it relies on the River Murray for supply of up to 85% of its potable water needs. To address water security issues for Metropolitan Adelaide, the South Australian State Government and the Australian Federal Government are funding the construction of a 100 GL/annum desalination plant to provide up to half of Adelaide's current potable water needs.

Adelaide’s water supply system is roughly split by the River Torrens into a northern system and a southern system, with each system independently supplied from nearby Mt Lofty Ranges storages, and separate pipelines from the River Murray. The SA Water distribution system does not currently have the capability for large volume inter-zone transfers required for business continuity planning and operational flexibility. If water could be transferred between the major water treatment plant zones it would result in significantly increased overall system flexibility and optimisation of operations, including the ability to supply water in the event of:

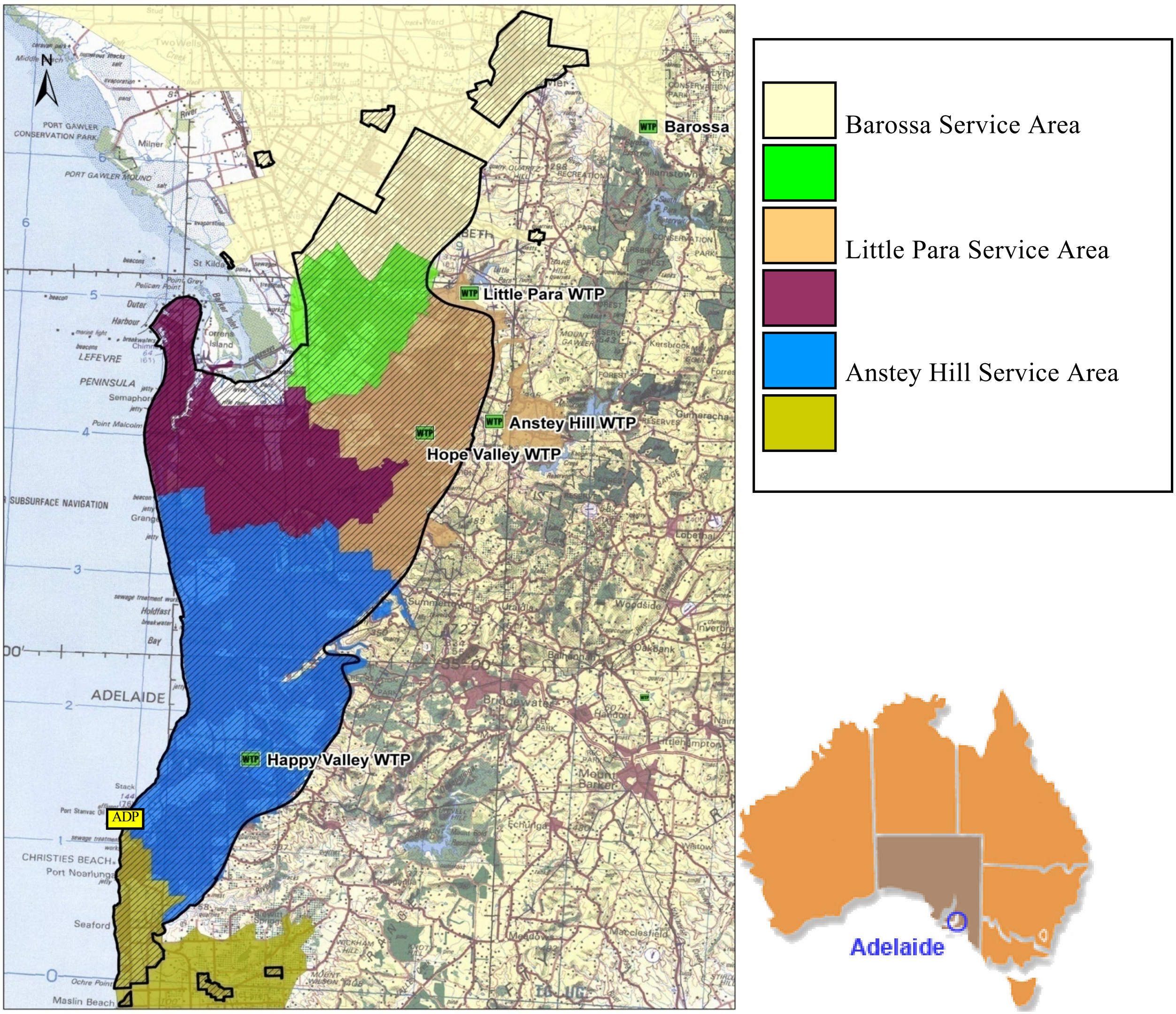
- Water treatment plant outages
- Water quality problems/bacteriological outbreaks
- Algal blooms in Mt Lofty Ranges reservoirs and the River Murray
- Security breaches or attacks on the water supply system

In late 2007, the State Government announced a water security strategy which included the proposed Adelaide Desalination Plant (ADP). In 2009, the State and Federal Governments announced that the 50 GL/a desalination plant would be upgraded to 100 GL/a by 2012. A capacity of 100 GL/a is significantly greater than the annual demand in the southern half of the network (Happy Valley system), and the equivalent daily flow of 300 ML/day is greater than the demand in the Happy Valley system for over half the year. As such, bulk quantities of water will need to be transferred between the southern and northern systems in order to allow full utilization of the desalination plant as needed. Figure 1 shows the project area.

The optimisation project scope therefore had a number of core objectives:

- Full utilization of water from the Adelaide Desalination Plant (ADP)
- Provide interconnectivity between the north and the south to satisfy different business continuity objectives
- Ensure that system demands during 2012 and 2050 peak day conditions can be met
- Minimise the impact on the Adelaide Metro Water Distribution Network (i.e pressures, water quality)
- Minimise the cost of new infrastructure and maximise the flexibility of operations

Figure 1: Project Locality: Adelaide Metropolitan Area



2 OPTIMISATION

Central to the options analysis and optimisation process was the application of Genetic Algorithm (GA) optimisation for pipe network planning (Simpson et al. 1994; Dandy et al. 1996). This technology was used to maximise the efficiency of the network, minimise rework, and make savings in terms of costs and time of implementation for the project.

Using *Optimizer WDS*, Optimatics has carried out an optimisation analysis of the Adelaide metro system with the aim of developing a range of optimal designs which meet the core objectives. The optimisation was linked directly to SA Water's extended period simulation hydraulic model of the Adelaide network.

Optimizer WDS uses Genetic Algorithm (GA) optimisation, a directed search technique that evaluates tens of thousands of candidate network augmentation approaches as it converges on the best combination of infrastructure options and operational strategies to satisfy system demands, meet the design constraints (pressures, flows from water treatment plants and ADP, etc) and minimise costs (capital and operating costs). The GA optimisation approach contrasts with traditional simulation analysis where the designer uses trial-and-error to evaluate a handful of candidate solutions. Although a hydraulically feasible solution can usually be found, it is very likely the cost of the resulting design is much higher than it needs to be.

The following sections of this paper outline the methodology used to develop a range of optimal solutions for the north-south interconnectivity project for SA Water. The steps listed below were the key inputs to the optimisation process. Comprehensive data or information from each of these steps ensured that the Genetic Algorithm search process could proceed in the most efficient way and produce the desired low-cost feasible solutions which met all of SA Water's objectives.

1. Hydraulic model of the network
2. Demand scenarios
3. Design constraints (pressures, etc)
4. Decisions (allowable infrastructure options - pipe routes, pump station sites, etc)
5. Cost Rates (unit cost rates for pipes, etc, pump operating cost rates)

2.1 HYDRAULIC MODEL

SA Water maintains one full detailed metropolitan hydraulic model as well as separate hydraulic models for each of the pressure zones. For the optimisation analysis it was necessary to consider the full metropolitan network so that options across the entire system could be considered together to find the best combination of infrastructure and operations to meet the design objectives.

The full metropolitan model has over 67,000 pipes and a level of detail that was not necessary for the optimisation. SA Water provided a skeletonized model of the network for use in the optimisation. This reduced the number of network pipes from 67,000 pipes to approximately 11,000. The skeletonized model contains all pipes over 200 mm in diameter, plus some smaller diameter pipes needed for connectivity or to service demands. All pump station, storage and control valves remained in the skeletonized model which was set to run for a 24-hour extended period simulation.

2.2 DEMAND SCENARIOS

With the different design objectives to be considered (full ADP utilization, south to north transfer, peak day demands for 2012 and 2050, business continuity scenarios, etc) the critical demand case for the design of new infrastructure to meet these objectives had to be determined.

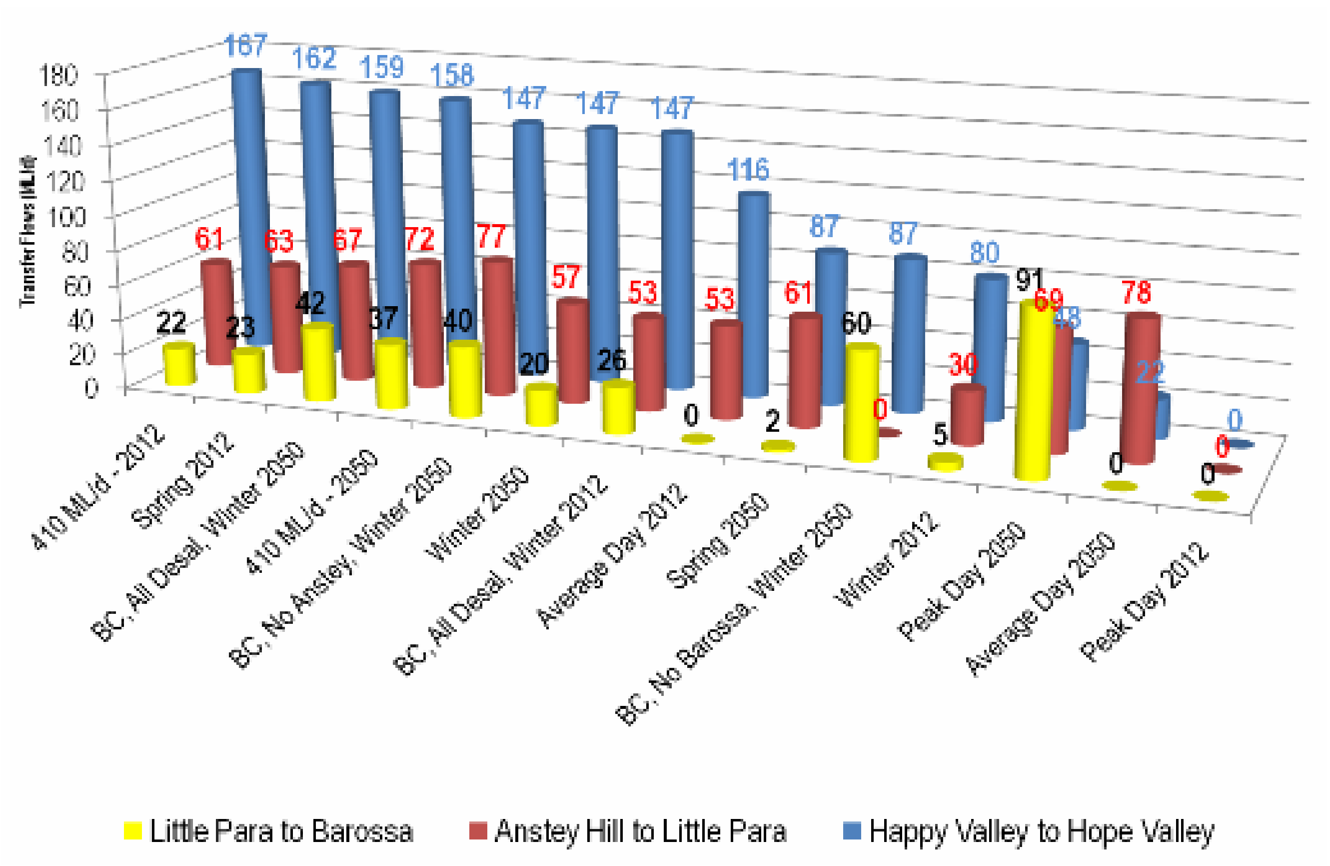
To do this, demand projections for 2012 and 2050 were provided by SA Water and limits on the minimum and maximum flows available from each of the water treatment plants were also identified. The SA Water metropolitan network has five water treatment plants within the project area, a sixth treatment plant and service area at Myponga was not included in the project as it can operate as a separate system.

Using the demand data provided, the differences between demand and supply for each water treatment plant service area were calculated. Analysing the transfer flows required from one service area to the next helped to identify which demand scenario would be critical for sizing new infrastructure to deliver these transfer flows. Figure 2 shows the transfer flow rates calculated for each of these demand cases.

Business Continuity scenarios were also considered when reviewing the transfer flows required. These emergency outage cases considered major infrastructure such as water treatment plants to be offline. Water restrictions would be in place under such outages, so only demands equivalent to Winter 2050 levels needed to be served. Transfer rates for the Business Continuity scenarios are also shown in Figure 2.

The minimum water treatment plant flows scenario was found to be the critical case for transfer of ADP water across the network from the Happy Valley service area to the Hope Valley service area and then on to the Anstey Hill service area. This minimum treatment plant capacity scenario has a total supply of 410 ML/d (110 ML/d from existing treatment plants plus 300 ML/d from ADP). A 410 ML/d scenario is close to a 2012 Spring Day demand case. Figure 3 illustrates the transfers from Happy Valley/ADP to the north of the network for this 410 ML/d scenario.

Figure 2: Flow Transfer Rates for Adelaide Metropolitan Water Distribution Network



The 2050 peak day was the critical day for transfer flows into the Barossa service area in the north, however transfer volumes through the rest of the system were less than required during the minimum WTP flow scenario. During a 2012 peak day it was assumed that the network would revert back to normal operation as treatment plants have enough capacity to supply their local demands and that transfers would not be required to fully utilize the ADP water.

The analysis also showed that for the Business Continuity scenarios considered (Anstey Hill Water Treatment Plant outage, Barossa Water Treatment Plant outage and a severe drought all ADP scenario) transfers required through the main body of the network would be less than seen under a minimum flow scenario where full utilization of the ADP is the main objective.

Figure 4 illustrates the methodology used for the optimisation to cover each of these demand cases and ensure the optimised designs developed could meet the ADP utilization, peak day 2012, peak day 2050 and Business Continuity objectives.

Most of the new infrastructure and operational changes needed to be designed for the minimum flow case (410 ML/d scenario). This scenario was therefore run first. The designs were then checked against the 2012 peak day to ensure no reduction in system performance with the new upgrades in place. A 2050 peak day optimisation was then run to re-size just the infrastructure in the north of the system (where 2050 peak day demands resulted in the more critical transfer flow rates), with new infrastructure in the south was locked in at the sizes required for the 410 ML/d scenario. Business Continuity scenarios were then checked on the solutions and any localized upgrades identified.

Figure 3: Transfer Flows for Minimum Water Treatment Plant Flows Scenario (410 ML/d)

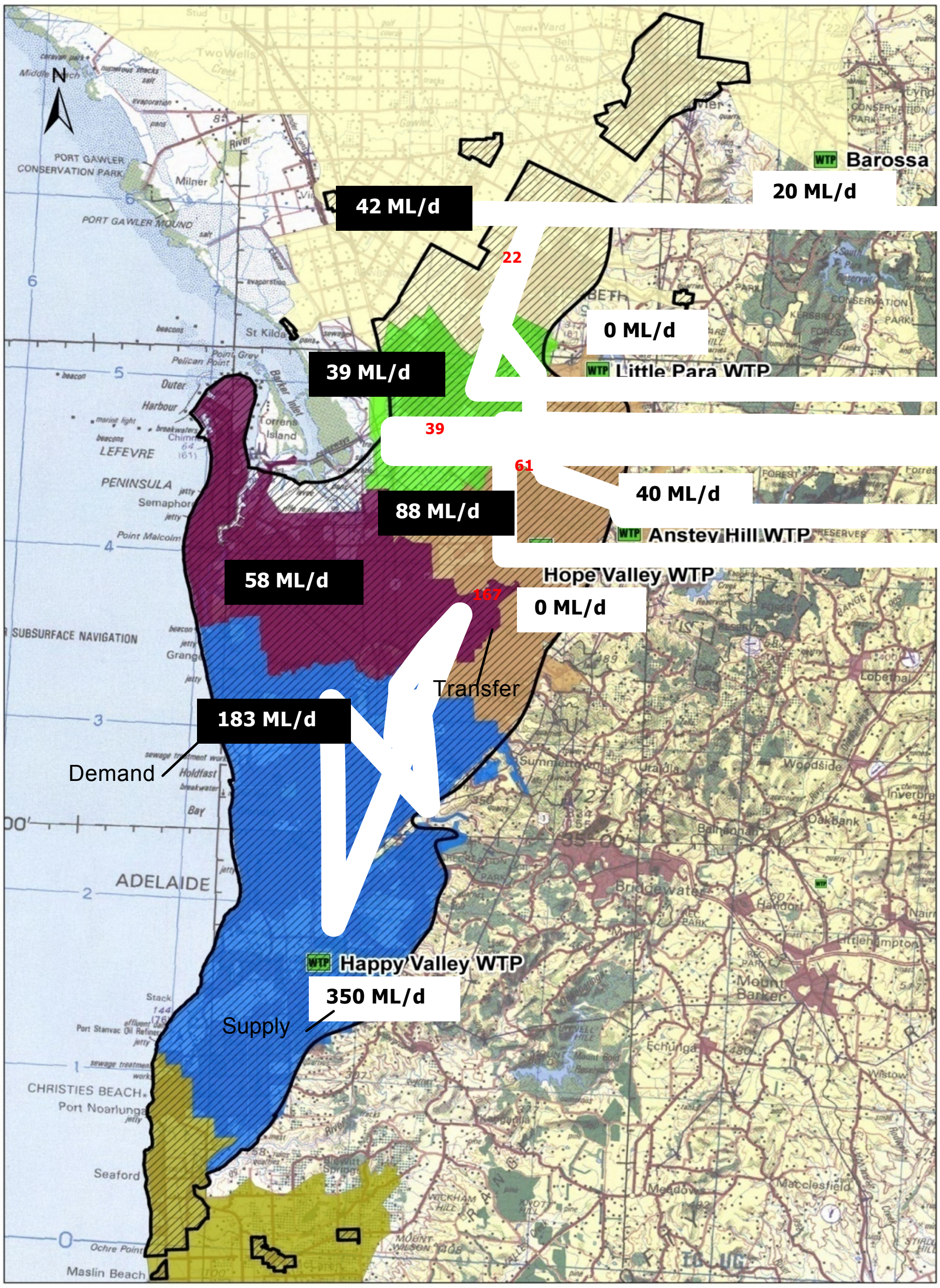
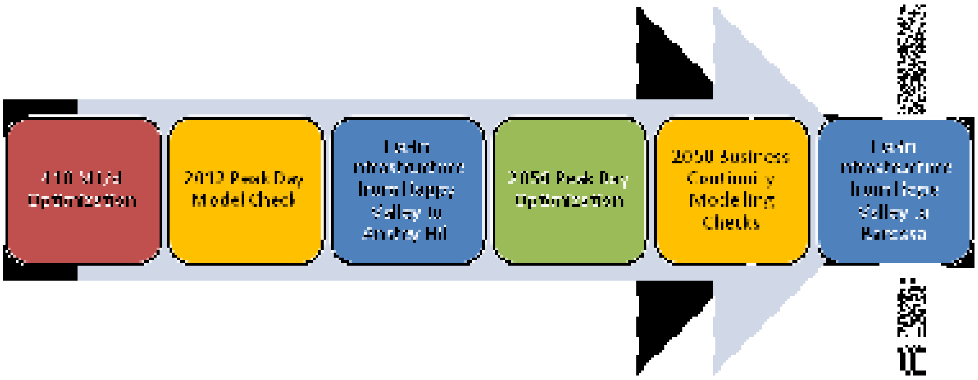


Figure 4: Optimisation Methodology for Demand Scenarios



2.3 DESIGN CONSTRAINTS

Different design constraints were considered as part of the project. These were setup as a number of different optimisation scenarios to be run. The aim of this was to develop a range of different solutions that meet the different or combined design criteria. The utilization of water from the ADP was also a core objective of all scenarios. As seen in the development of the demand scenarios, full utilization of water from the ADP for a minimum flow scenario also meets the objectives of growth and business continuity for the majority of the water distribution network.

The design constraint variables considered were:

- Minimum allowable pressure constraint or existing pressure requirements
    - Cost vs impact on customers
- Allow asset replacement options or not
    - Cost vs risk/difficulty and customer impact
- Flow reversal restrictions
    - Cost and flexibility vs water quality and impact on customers

Considering each of these design constraint variables (and combinations) there were eight different scenarios to optimise. These are illustrated in Figure 5.

Figure 5: Optimisation Scenarios for Variable Design Constraints

[redacted]

The minimum allowable pressure criteria involved applying a global minimum pressure criterion of 25 m to all demand nodes, whereas the existing pressure criteria considered the minimum pressures that customers currently experience. An existing peak day model was used to identify minimum pressures that customers across the network currently receive.

In considering asset replacement, a list of pipelines due for replacement in the next 5 years was provided by SA Water (around 10 alignments – mix of trunk main sections and larger reticulation main sections). In scenarios allowing pipeline asset replacement, these pipelines could be replaced and upsized from their current planned replacement sizes. The cost of replacing these mains in the optimisation was considered to only be the additional cost of upsizing the main.

The aim of the flow reversal criteria was to develop solutions that minimised the risk of water quality issues in the network. Using existing models, larger diameter pipelines (>375 mm) with flow always in the same direction were identified. The flow reversal criteria (or flow direction criteria) was then applied to these alignments in the relevant scenarios. Any new pipeline options did not have flow reversal criteria.

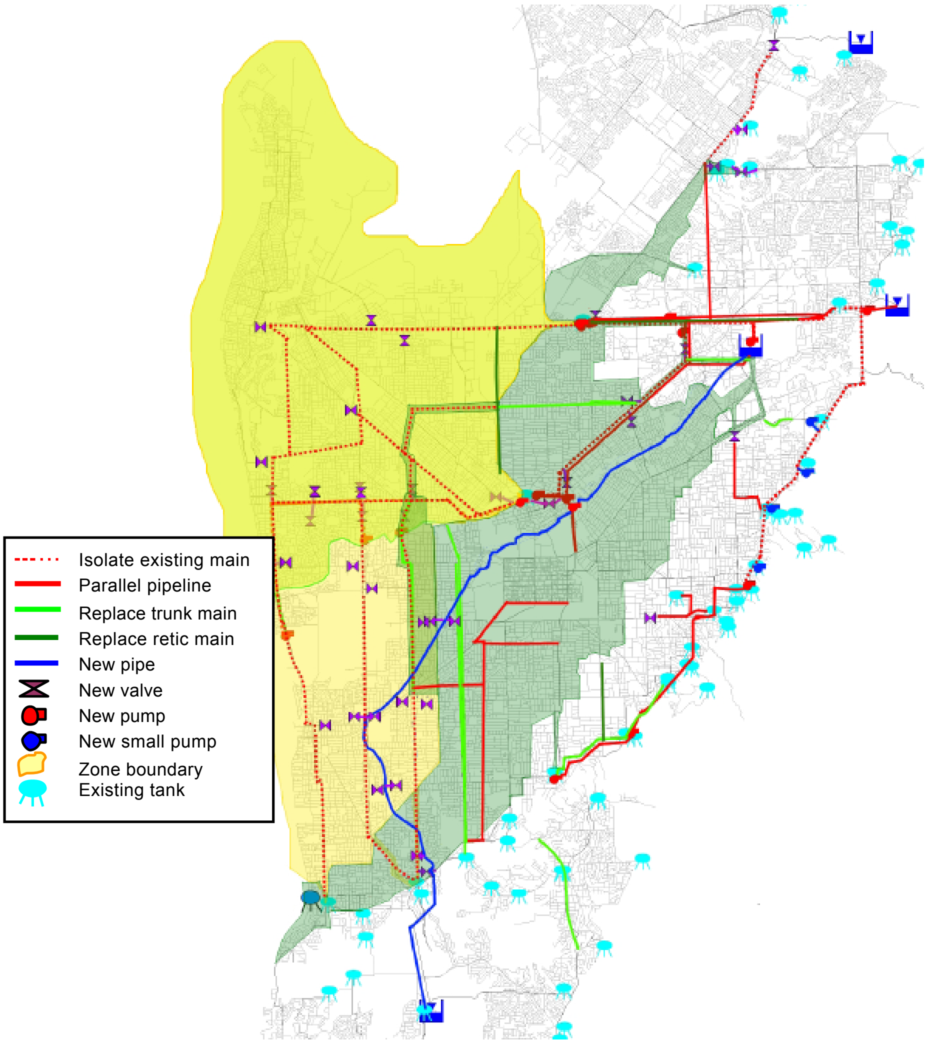
2.4 DECISION OPTIONS

In the optimisation a range of allowable new, expanded or replacement infrastructure options were identified and input into the optimisation model setup. These options include pipelines, pumps, tanks or valves. Decisions around system operations were also input as decision variables in the optimisation (these include pump and valve controls, flow rates or pressure settings). It is from this full range of allowable decision options that an optimal subset of infrastructure locations and sizes and operational changes is selected to meet the network demands and the design constraints.

A series of workshops were carried out with internal SA Water stakeholder groups to develop allowable infrastructure options for consideration in the optimisation. The main stakeholder groups consulted during this phase of the project were Systems Planning, Assets and Operations. Input from these groups helped to develop the following options (see Figure 6).

- New pipeline route options
- Replacement pipeline options
- Express main options (use isolated sections of existing pipelines as pumped mains)
- New pump station/booster options
- Expanded pump station options
- New or expanded storage options
- New pressure reducing valve/ pressure sustaining valve options
- Changes to existing or new zone boundaries
- Changes to existing zones hydraulic gradeline

Figure 6: Decision Variables for Optimisation



2.5 COST RATES

Unit cost rates for a range of sizes were required for each of the infrastructure options considered in the optimisation. Using data from an internal SA Water cost database, data from recent large pipeline and pump station projects carried out by SA Water and engaging an external consultant to develop some additional cost data, SA Water and Optimatics collated the cost data required for the optimisation. As well as costs for a range of pipe sizes and materials, the pipeline cost data was also separated into major road, minor road and greenfields costs. Costs for new control valves, pump stations and storages were just given for a range of sizes. Pump operating costs over the design life of the system were also included in the optimisation. This involved using an energy tariff rate that captured projected energy costs and also an allowance for environmental costs (carbon costs).

These cost rates allowed each of the solutions within the one optimisation run to be compared against other solutions as part of the Genetic Algorithm search process. It also allowed solutions developed for different design criteria or constraints to be compared against each other as part of the preferred solution selection. Some variation in cost to the final solution is expected as detailed construction costs are prepared by estimators and by the detailed design team as further on site conditions are captured and incorporated into the costs. Costs prepared by estimators to date show that all of the optimised solutions developed were within the original budget set by SA Water.

3 INTERIM OPTIMISATION SOLUTIONS

Interim optimisation runs using the cost rates, decision options and hydraulic model provided were carried out for each of the eight design scenarios (outlined in Figure 5). Up to four solutions were developed for each of the eight scenarios. The differences between the four solutions centered on options around the western side of the network.

A. Boosted pumping into an existing pipeline to be used as a higher pressure pipeline for transfer
B. Create new boosted zone using 1-3 booster pump stations using boosted zone for transfer
C. Increase HGL of entire western pressure zone using entire zone for increased transfer
D. Convert entire western trunk main to higher pressure express main for transfer

Solutions developed with flow reversal restrictions were more expensive as more new pipe was used to avoid large transfers through existing pipelines. These solutions also tended to have infrastructure and operational strategies that sent the largest volumes of transfer water through the foothills system that runs along the eastern side of the network. The foothills system has a large diameter trunk main that supplies numerous tanks along its length which then supply customers via gravity. Transfers through the foothills impact customer connections much less directly than transfers through the central EL103 zone or the western EL51 zone.

As expected, solutions developed with a minimum pressure criterion were less expensive than solutions developed using an existing system pressure criterion. Increases in pipe sizes as well as additional booster pump stations to spread ADP transfer across a number of flow paths through the EL51 and EL103 zones were seen in these “existing pressures” solutions.

As part of the interim solutions design cycle, feedback on the solutions from SA Water internal stakeholders was sought so that a set of preferred solutions or solution setups could be identified for the final set of optimisation runs. From the 32 interim solutions developed, 18 solutions were selected for the final optimisation phase. Typically it was solutions that did not consider pipeline asset replacements that were eliminated and not considered in the final set of optimisation runs.

As part of the optimisation methodology shown in Figure 4, each of the interim solutions were checked for 2012 peak day operations, 2050 peak day operations and a set of Business Continuity scenarios (water treatment plant outages). The solutions adequately performed for the 2012 peak day, one additional booster pump station was required in the far north of the system for the 2050 peak day and some local pumping was all that was required for the Business Continuity scenarios.

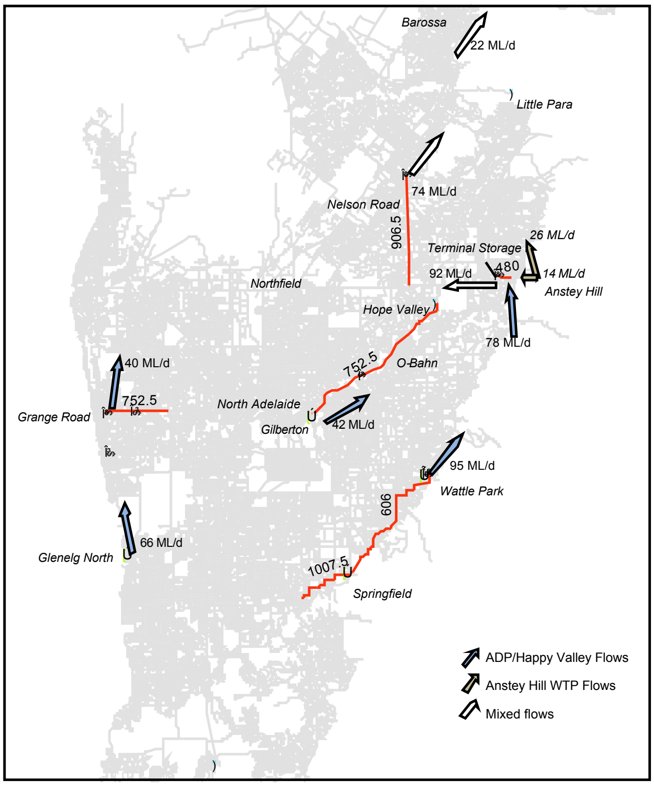
4 FINAL OPTIMISATION SOLUTIONS

Final optimisation runs were carried out for the preferred 18 interim solution setups. The final runs considered some slight updates to cost rates, changes to the locations of some of the allowable infrastructure options, updates to some closed existing pipelines in the network that are not planned to be replaced within the next five years, as well as comments on feedback on preferred and non-preferred aspects of the interim solutions.

The 18 final optimised solutions developed met the transfer objectives and allowed full utilization of ADP water during the minimum flow demand scenario. With the upgrades identified for growth and localised upgrades for the different Business Continuity scenarios, these final solutions also meet the security of supply and growth allowance objectives of the project.

The optimisation developed a range of solutions to minimise infrastructure and operating costs, whilst meeting the set design criteria, demands and transfer requirements. To select a preferred final solution for implementation, internal SA Water stakeholder groups reviewed the outcomes of the optimisation and applied a structured multi-criteria analysis (MCA) to rank the solutions. United Water International (UWI), as Owners’ Engineer on the project was engaged to develop and lead the MCA process. The MCA considered categories such as environmental impact, impact on assets, operational flexibility, constructability and costs. Figure 7 shows one of the top ranked solutions from the MCA.

Figure 7: Example of a Final Solution Developed through Optimisation



This solution utilizes the foothills systems to transfer over half of the required transfer volume. This flow path helps to minimise the impact on customer pressures in the network, avoids flow reversals in reticulation mains and also takes advantage of existing large diameter trunk mains along this route towards the Anstey Hill service area. Some expansions to existing pump stations are required as well as some sections of pipe duplication and replacement.

In the west, a new booster pump station and sections of existing trunk main utilized as a pumped express main, transfers the required 40 ML/d to the Hope Valley service area. This configuration minimises the impact on customer pressures in the west as the majority of the pressure zone will still be supplied via gravity from existing tanks. Through the centre of the system, a new booster pump station and a new pipeline sees transfers of up to 42 ML/d into the Hope Valley service area. Utilizing a new pipeline for the transfer meant that any flow reversals through the central system were minimised. This new pipeline and pump station operates as a separate pumped main to the surrounding pressure zone, which also minimises the impact on customer pressures.

5 CONCLUSIONS

This project has used a formal optimisation process and Genetic Algorithm optimisation design tool to develop a range of feasible low cost solutions that meet core objectives set by SA Water for the Network Water Security Program (NWSP). As part of the optimisation, the critical demands scenarios for each of the core objectives were identified and different design criteria were investigated to develop a range of solutions and understand the trade-offs between cost and performance. SA Water stakeholders were involved throughout the process and design cycle to provide input into feasible infrastructure options to consider, review the outputs of the optimisation and finally select and rank the final solutions using a formal multi-criteria analysis.

The use of an automated design tool, such as Genetic Algorithm optimisation allowed many more solutions to be considered and developed within the project timeframe. It also allowed solutions to be tailored to the design criteria, demand scenarios and unit cost rates inputs for each optimisation run. The combination of the right people, the right process and the right technology were seen by SA Water to be the key to the success of this project.

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