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Staging of Master Planning of Water Distribution Systems Using Genetic Algorithm Optimization

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Abstract

Master planning of water distribution systems usually involves a long-time horizon of 25 to 50 years into the future. Estimates of future water demands are made as well as the configuration of the ultimate build-out of water distribution system. The difficulty with the results of a master planning study is that the near term needs for system expansion may not match the long-term plans. An approach of using genetic algorithm (GA) optimization for developing two master plans, one for the short term and one for the long term is presented in this paper. In addition, an approach for optimizing the staging of construction to link the short and long term master plans is also presented. This paper highlights a genetic algorithm (GA) master plan study carried out for the Barossa Valley water distribution system in South Australia. First the infrastructure needs (transmission and distribution pipelines) for 2010 were optimized using genetic algorithm optimization for the near term planning of facilities. Pipes in parallel to existing pipes and replacement pipelines were sized. New and expanded pump stations were also considered. Once the 2010 master plan was developed, a staging analysis was carried out to identify a solution to satisfy the current demands (year 2005). A master plan to satisfy year 2025 demand predictions was also developed as part of the study. In the year 2025 master plan, improvements were sized to use components that would have been used to extend the system from year 2010 to 2025

Introduction and Background

Master planning of water distribution systems is a common activity undertaken by water utilities. Often the focus of the master plan is to consider the system as the ultimate build out condition. Genetic algorithm analysis has previously been developed and applied to numerous systems from the optimization of simple networks to quite complex systems (Simpson et al. 1994; Savic and Walters 1997; Wu and Simpson 2002; Roberts et al. 2004). An approach of using genetic algorithm (GA) optimization for developing two master plans, one for the short term and one for the long term is presented in this paper. Previous work on staging was presented by Dandy et al. 2003.

The approaches to GA optimization of the staging of the construction presented in this paper are illustrated for a case study water distribution system in the Barossa Valley of South Australia.

The Barossa Valley is a wine growing region north of Adelaide. The local water authority, SA Water, are currently reviewing the Barossa Valley water distribution system. Pipes in the system are generally in good condition but there are a number of existing low pressure problems including supplying the Belvidere and Greenock tanks, and also supplying Seppeltsfield and its surrounding areas. It is also believed that the existing system will not be able to cope with increased demands in the area in the future.

This paper describes a Genetic Algorithm optimization study for SA Water to develop a staged design for the Barossa Valley system up to year 2025. Future demands in five year increments were analysed. As there is some uncertainty in the demand predictions beyond 2010, a different approach was taken to developing a staged optimized design. The Barossa system model analysed contained over 2,000 pipe elements and over 830 km of existing pipeline. The preferred 2010 and 2025 solutions were developed through a number of cycles of optimization runs and discussions with SA Water.

Typical staging methods include a "build to target" approach or a "build up" approach. In a "build to target" approach an optimal design is developed for the ultimate demand case. The end design is taken as the optimal configuration, but in the intermediate years expensive and oversized pipes may need to be implemented. If growth is lower than predicted then pipes will be oversized in the intermediate years and in the ultimate design. The "build up" approach involves analysing each design period in sequence. The design for the first period is taken as the optimal configuration, however, for subsequent periods multiple pipe duplications may be required to increase capacity along some alignments. Designs for these periods are usually not optimal and the overall cost is more expensive. However there is some advantage in implementing smaller pipes in early design periods if the future demand predictions change.

In this study a combined "build to target" and "build up" approach to staging of construction was taken. The year 2010 design was developed first and from this a "build up" approach was taken to develop a design for 2025. A "build to target" approach was then taken to develop a GA optimized 2005 design based on the 2010 design. A "build to target" approach was also taken to develop designs for 2015 and 2020 based on the 2025 design. With this approach, improvements were not oversized in the early design periods and multiple duplications in consecutive design periods were avoided.

Optimization Analysis

The genetic algorithm (GA) optimization approach performs a structured computerised search for the most economic combination of network components for a water distribution system design. For the Barossa Valley case study, this included sizing new and parallel pipe alignments and replacing smaller diameter pipes or pipes in poor condition. Replacement pipe sizes were determined as part of the analysis. New and existing pump stations were also sized for future demands.

In the genetic algorithm approach the search technique is used to identify low-cost solutions that satisfy the given design criteria (Simpson et al. 1994). Basic GA operators of selection, crossover and mutation are used to efficiently search through and evaluate hundreds of thousands of solutions in every GA run. Low cost solutions quickly emerge in the optimization process. Using a "survival of the fittest" approach, the selection operator discards solutions in each generation that have poor hydraulic performance or comparatively high capital costs. The GA operators of crossover and mutation then "breed" together solutions with desirable characteristics to produce the next generation of solutions.

The GA optimization was also used in the staging analysis to determine which improvements were required in which intermediate years. For the 5 demand periods analysed (2005, 2010, 2015, 2020 and 2025), assets were only sized from a range of allowable sizes and capacities that had been optimally determined by the GA for years 2010 and 2025. In the remaining years, options were limited to those required in future years (either 2010 or 2025). Figure 1 shows a flow chart of the staging analysis.

An optimized design for 2010 was developed first so that the staged design would not contain oversized pipes based on the ultimate 2025 demand predictions. SA Water had more confidence in the 2010 demand predictions than the 2025 demand predictions. From the optimized design for 2010, an optimized design for the existing system (year 2005 demands) was developed. Only improvements identified in the 2010 design could be implemented in the 2005 design if they were required to satisfy the minimum allowable pressure criteria, tank inflow/outflow criteria and maximum allowable velocity criteria.

An optimized design for 2025 was developed next considering the improvements required by 2010 as existing. Improvements required to satisfy the year 2025 demands, in addition to the 2010 improvements, were identified and sized. From the year 2025 design, subsets of improvements required for the intermediate years (2015 and 2020) were identified.

All of the staged solutionswere developed using the 2010 design as a basis. A final design for 2010 was developed with a number of cycles of optimization runs. This allowed feedback from SA Water on a preferred type of design for 2010. The improvements required in the 2005 design are a subset of the 2010 final design. The 2015, 2020, 2025 staged designs all consider the 2010 improvements as existing and used additional improvements to satisfy the design criteria as the system demands increased.

Optimization Results

Year 2005 Staged Design

The year 2005 staged design was developed once the year 2010 GA optimized design had been finalized. New, parallel and replacement pipelines and new and expanded pump stations were identified and sized considering the year 2010 demand case. For the year 2005 demand case, the GA was setup such that only improvements used in the 2010 final solution could be implemented. Therefore, for each improvement option the GA had the choice of implementing it at the sizes of pipes and facilities used in the 2010 design, or not at all. As each option only had 2 choices (either install or not) and the number of options were limited to the improvements required by 2010, the solution space for the year 2005 staging runs was greatly reduced, which helped convergence of the GA optimization process to an optimal solution. Figure 2 shows the improvements required in the year 2005 design. The major townships in the area are also labelled in the figure.

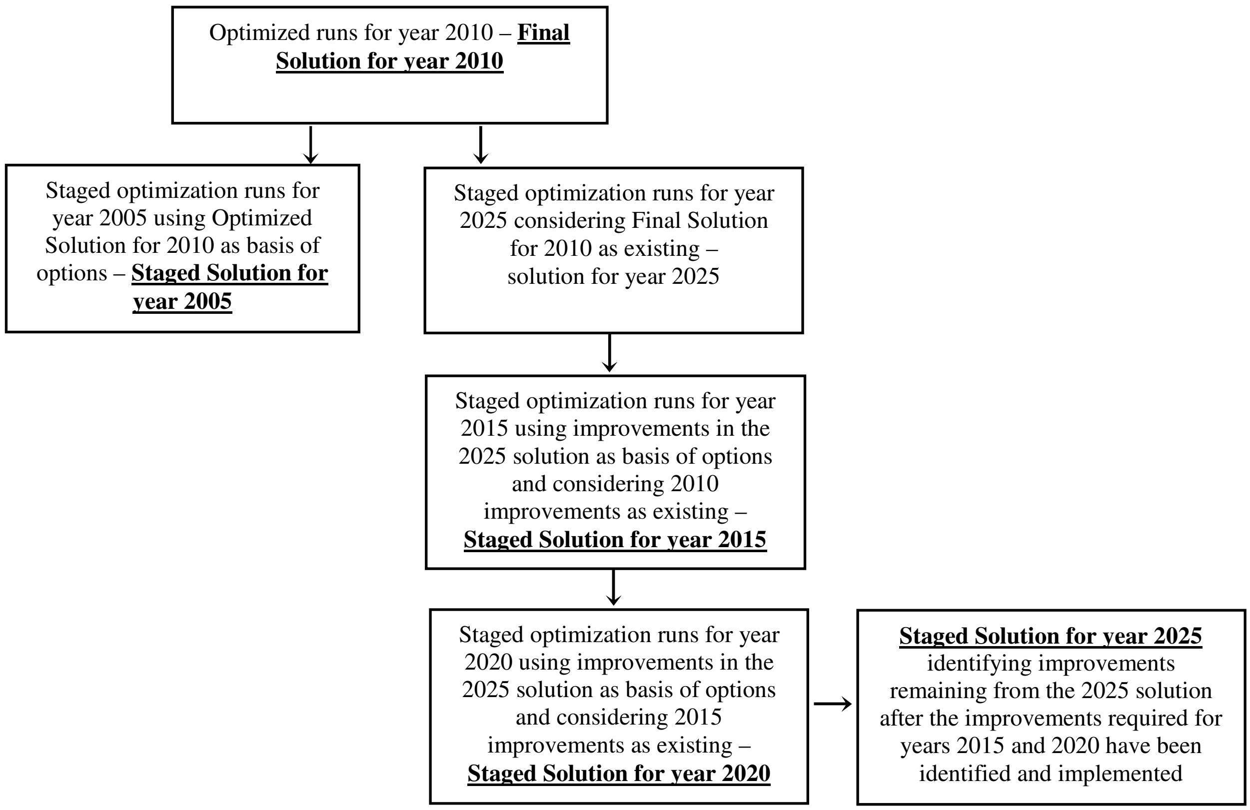

Figure 1 – Flow Chart of Staged Optimization Runs and Solutions

The total capital cost of the year 2005 design is $6.8 million, this includes $6.7 million in pipe capital cost and $0.1 million in pump station cost. Of the $6.7 million in pipe capital cost, the cost of new or parallel alignments is $1.6 million and the cost of replacement pipelines is $5.1 million. Over 44 km of pipeline has been replaced in the 2005 design. Over half of the pipelines replaced were less than 100 mm in diameter.

Year 2010 Staged Design

The year 2010 design was the first GA optimized solution developed for the Barossa system. Only pipe alignments currently in the ground were considered as existing. A number of new, parallel and replacement options were identified in the optimized system. The GA was used to select and size an optimal mix of pipe and pump station improvements to satisfy the system design criteria. There were 10 allowable pipe diameters ranging from 100 mm to 800 mm and there was also a range of capacity settings available for the new and expanded pump station options.

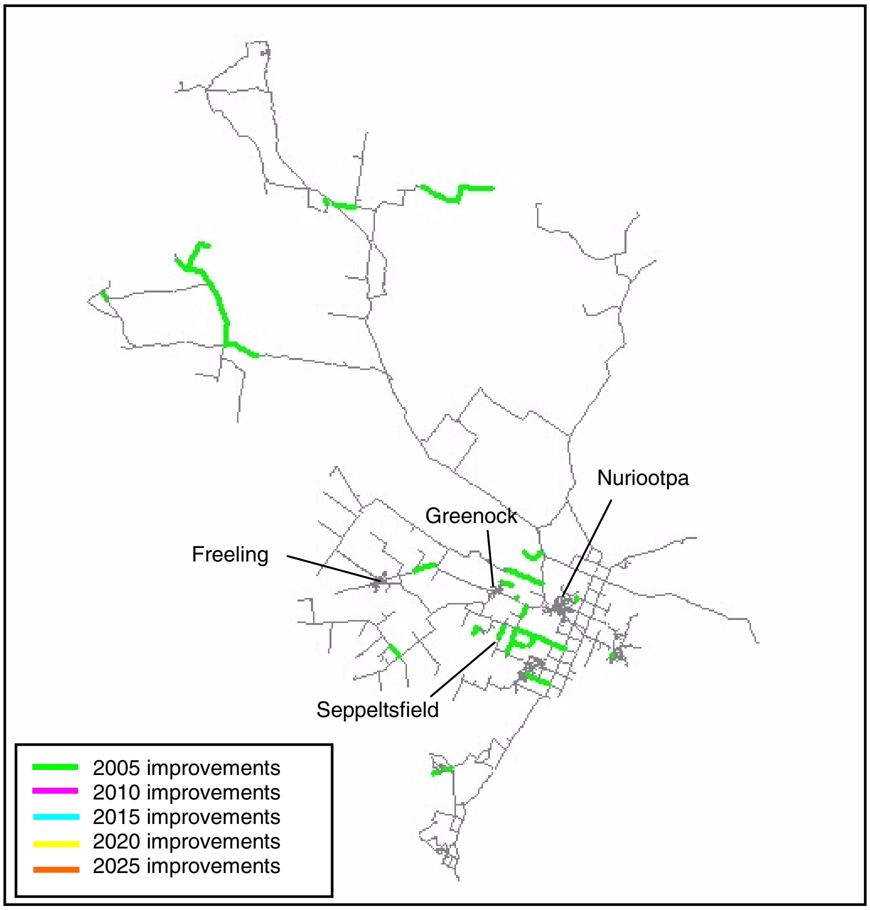

Figure 2 – Year 2005 Staged Design for the Barossa System

In the final design for 2010, the improvements required to satisfy the minimum allowable pressure head of 20 m, maximum allowable velocity criteria of 2.5 m/s and the Belvidere tank minimum allowable inflow rate of 6 L/s, for year 2010 demands were identified. From this design a subset of improvements required by 2005 were identified using the GA. The remaining improvements in the 2010 final design were required by 2010 and make up the year 2010 staged design. Figure 3 shows the improvements required in the year 2005 and year 2010 staged designs.

The total capital cost of the year 2010 GA optimized staged design is $20.1 million, this includes $3.0 million in new and parallel pipe capital cost, $17.1 million in replacement pipe cost and $0.03 million in pump station cost. Over 103 km of pipeline was replaced in the 2010 staged design.

Year 2015 Staged Design

The year 2015 staged design was originally to be developed after the year 2010 optimized GA design was finalized, as a "build up" approach was originally envisaged. In the year 2015 analysis, improvements required for the 2005 and 2010 staged designs were to be considered as existing and additional new, parallel and replacement pipelines were to be identified and sized from a range options and sizes. However, it was soon clear that with this approach small diameter duplications would be required along some alignments in 2015, but by 2020 and 2025 these alignments would need to be duplicated again to satisfy the system design criteria under increased demands.

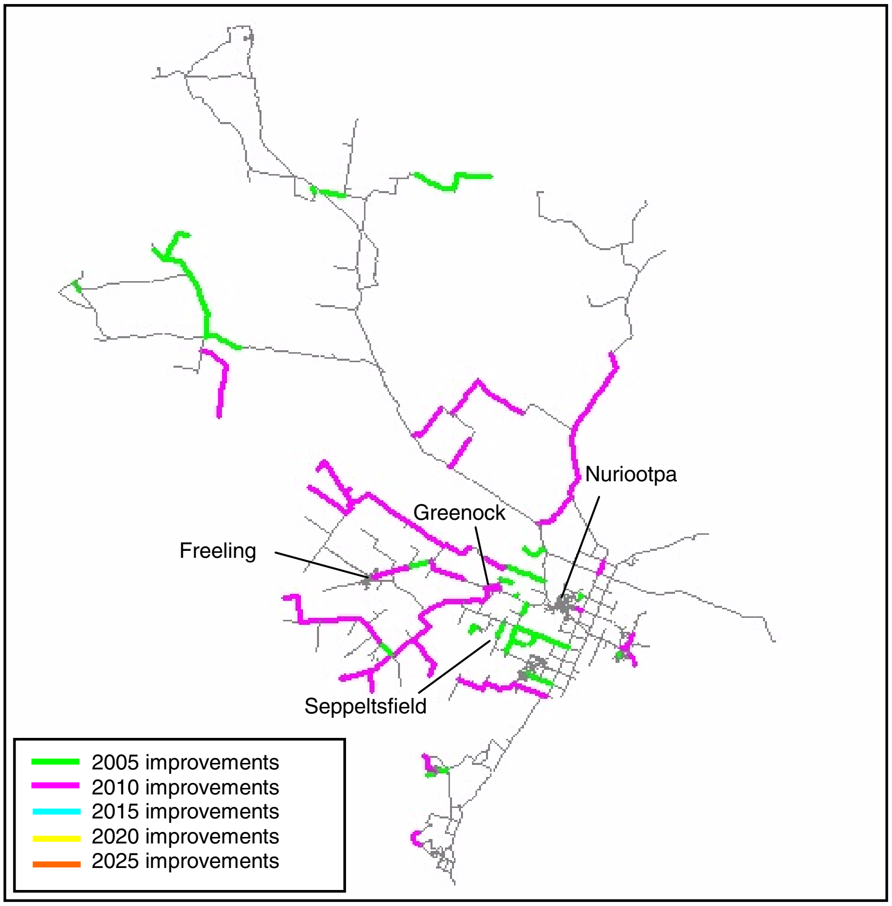

Figure 3 – Year 2010 Staged Design for the Barossa System

Implementing a number of small diameter improvements in 2015 is a lower cost option when 2015 is considered in isolation, however, there would not be enough capacity to satisfy the 2020 and 2025 demand cases. Implementing small diameter duplicate pipelines in every 5 year design period would be more expensive and inconvenient overall and is therefore non-preferred.

To avoid multiple duplications, a year 2025 solution was developed instead after the 2010 design was finalized. Improvements in the 2005 and 2010 designs were considered as existing, and the GA identified and sized additional improvements to take the design from 2010 to 2025. The year 2025 design was then used to develop the 2015 staged design. Figure 4 shows the layout of the 2015 staged design.

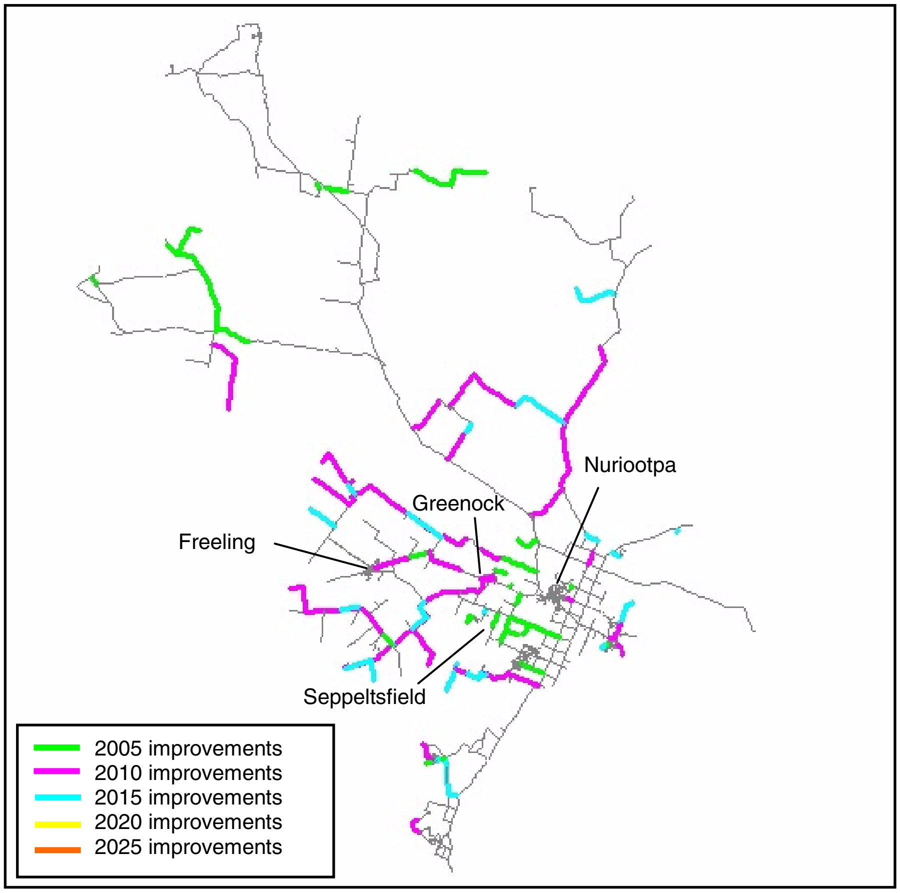

Figure 4 – Year 2015 Staged Design for the Barossa System

Like the 2005 staged optimization runs, in the 2015 staged optimization runs the GA had a limited number of options and each had only 2 choices - implement at the size in the 2025 solution, or not at all. With this approach some improvements in the 2015 may have been oversized, however, multiple duplications will be avoided in years 2020 and 2025. Only a subset of the 2025 solution was required in the 2015 staged design. The total capital cost of the 2015 staged design is $6.2 million, this includes $3.1 million in new and parallel pipe cost and $3.0 million in replacement pipe costs and $0.1 million in pump capital costs. Just over 24 km of pipeline was replaced in the 2015 staged design.

Year 2020 Staged Design

In the year 2020 staging optimization runs, improvements identified in the 2005, 2010 and 2015 staged designs were considered existing. Only improvements identified in the 2025 design (and not implemented in the 2015 staged design) were allowable options. Like the 2005 and 2015 staged optimization runs, each option only had a choice of implementation at a future sized already identified or not at all. In the 2020 staged design a subset of the remaining improvements in the 2025 final design were implemented. The 2020 staged GA optimized design has a capital cost of $7.5 million, this includes $5.1 million in new and parallel pipe costs and $2.4 million in replacement pipe costs, there are no pump capital costs. Figure 5 shows the layout of the 2020 staged design.

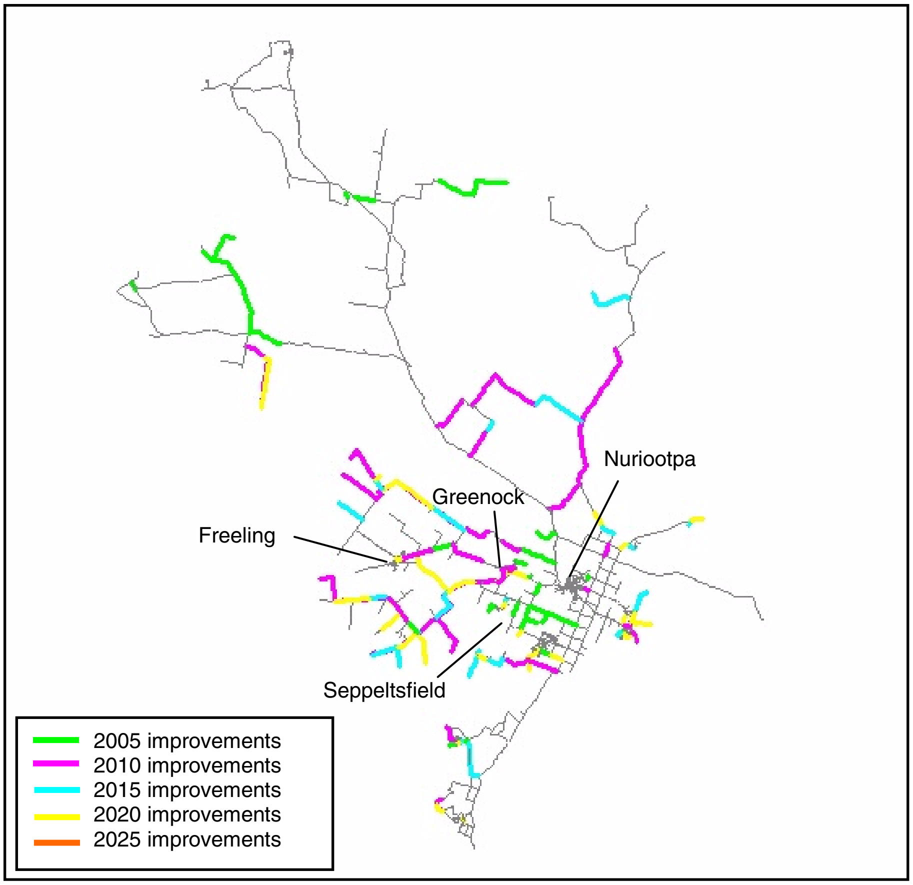

Figure 5 – Year 2020 Staged Design for the Barossa System

Year 2025 Staged Design

A GA optimized design for year 2025 was developed after the year 2010 design was finalized. Improvements in the 2015 and 2020 staged designs were subsets of the 2025 solution developed. In the optimization runs for 2025, additional new, parallel and replacement pipe options were identified. Pipe options not implemented as part of the 2010 solution were also allowable options. For each of the pipe options there was a range of allowable pipe sizes. New pump stations and pump station expansions were also included as options in the 2025 optimization runs.

Of the improvements identified in the 2025 solution, subsets of improvements required by 2015 and by 2020 were identified in the 2015 and 2020 staging optimization runs. The remaining pipe improvements make up the 2025 staged design. Multiple duplications along the same alignments were avoided in the 2015, 2020 and 2025 staged solutions because the year 2025 solution was developed based on the year 2010 solution. In the 2025 solution there was some duplication of pipelines replaced in the 2005 or 2010 staged solutions, but these could not be avoided. Figure 6 shows the 2025 staged design.

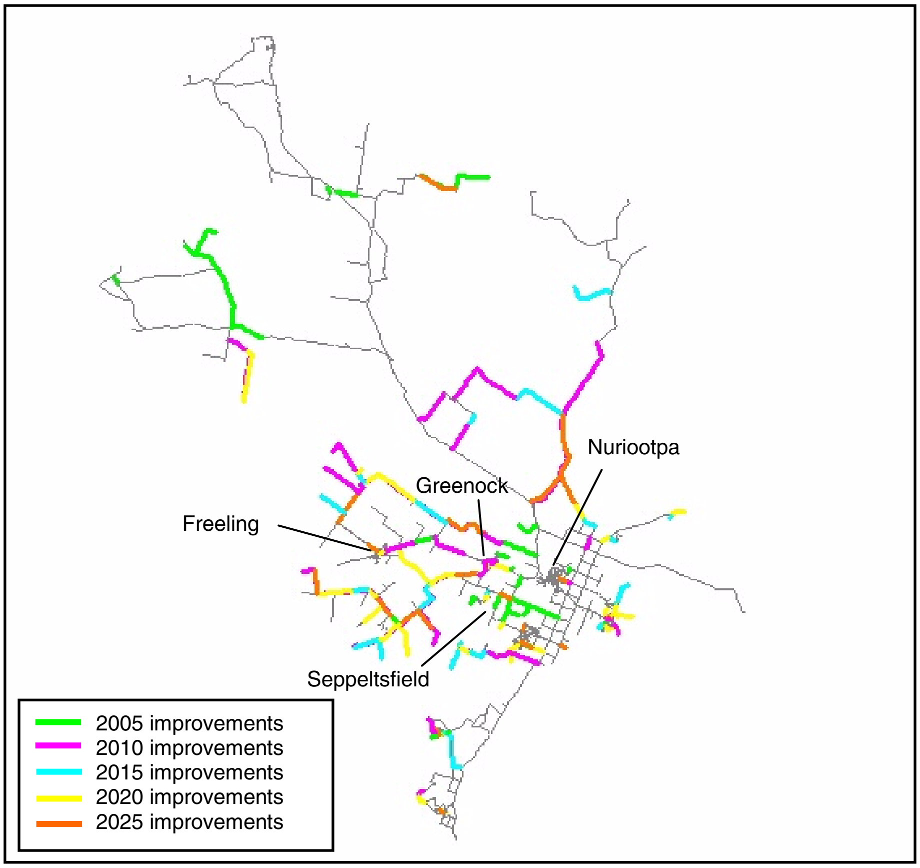

Figure 6 – Year 2025 Staged Design for the Barossa System

The total capital cost of the year 2025 staged design is $7.3 million. This includes $6.0 million in new or parallel pipe costs, $1.3 million in replacement pipe costs and $0.03 million in pump station capital costs. In the 2025 staged design over 12 km of existing pipeline was replaced.

Year 2025 Non-Staged Design

A GA optimized non-staged solution for the Barossa system was also developed as part of the study for comparison purposes. In the non-staged analysis, the year 2025 demand case was analysed and only the current infrastructure was considered as existing in the system. The non-staged solution used larger diameter parallel and replacement pipes in many of the same locations as the year 2010 solution that was developed as part of the staged analysis (see Table1). As there is some uncertainty of the future demands, SA Water were reluctant to develop staged solutions in 5 year increments based on a year 2025 design. This is why the year 2010 final solution was used as the basis for the staged solutions.

Much of the non-staged solution would have to be implemented in the short term due to alignments that require replacement or duplication. As such, a net present value analysis of the staged and non-staged solutions shows the staged solution to be lower cost in present value terms. In the staged solution, smaller diameter pipes are implemented in the short term and then duplicated in future periods when extra capacity is required. With this approach some capital cost is delayed into the future resulting in a lower net present value. Table 1 shows the NPV costs of the staged and non-staged solutions for the Barossa system. These costs include pipe capital and pump capital costs. In calculating a Net Present Value (NPV) cost for the non-staged solutions it was assumed that at least $7 million of the total cost would be required by 2005 and the rest by 2010. Some sections of the system would be oversized in 2005 and 2010, however, the staged solutions showed that improvements along certain alignments were necessary by 2010. A NPV cost of the non-staged solution assuming all costs are incurred by 2005 is also shown.

Table 1– Staged and Non-Staged Cost Breakdowns

	2005	2010	2015	2020	2025	TOTAL
Staged Solution						
Future cost	$6,846,796	$20,084,300	$6,323,664	$7,515,753	$7,302,692	$48,073,203
NPV	**$6,846,796**	**$14,319,828**	**$3,214,630**	**$2,724,055**	**$1,887,154**	**$28,992,463**
Non-Staged Solution – assumption #1						
Future cost	$38,717,396	$0	$0	$0	$0	$38,565,531
NPV	**$38,717,396**	**$0**	**$0**	**$0**	**$0**	**$38,565,531**
Non-Staged Solution – assumption #2						
Future cost	$7,000,000*	$31,717,396	$0	$0	$0	$38,565,531
NPV	**$7,000,000***	**$22,614,065**	**$0**	**$0**	**$0**	**$29,614,065**

**Note – A $7million upfront capital cost was assumed as at least this much would need to be spent from the non-staged solution, considering over $6.9 million in capital cost is required in the staged solution.*

Conclusions

This paper has presented a new approach to the staging of the construction of water distribution systems using genetic algorithm optimization for master planning. In this approach a combined "build to target" and "build up" approach is used. Excessive duplications of existing pipes are avoided by the new approach. A case study has been used to illustrate the new approach. Staged solutions for the Barossa water distribution system were developed. A Genetic Algorithm (GA) was used to develop optimal solutions for years 2010 and 2025 and stage these designs for the existing system (2005) and intermediate years (2015 and 2020).

The GA optimization considered new, parallel and replacement pipe options and new and expanded pump stations. In the year 2010 and 2025 GA optimization runs a large range of pipe and pump options were considered. Each option had a range of pipe size choices or pump station capacity choices, leading to a large solution space. The final solutions for 2010 and 2025 were the basis of the remaining staged solutions, so it was important that these solutions suited SA Water's needs.

In the year 2005, 2015 and 2020 optimization runs the number of pipe and pump station options were restricted to the improvements implemented in the 2010 or 2025 solution and there were also limited choices for each option. Typically the pipe or pump option could only be implemented at the size or capacity used in the future design, or not at all. This reduced the search space in the year 2005, 2015 and 2020 optimization runs. Solutions within each set of runs usually converged to the same or similar designs.

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