CHANNEL-TO-PIPE CONVERSIONS IMPROVE WATER USE EFFICIENCY, DECREASE ENERGY AND MINIMIZE CAPITAL COSTS

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ABSTRACT

Irrigators in Australia have suffered severe drought conditions for a number of years which has focused their attention on water efficiency measures. Many irrigation systems are moving away from the use of inefficient open channel irrigation systems in favor of pressure pipe networks to reduce losses due to seepage and evaporation. Murrumbidgee Irrigation in New South Wales utilized an innovative optimization approach that enabled significant improvements in the economic viability and environmental sustainability of its channels-to-pipe conversion.

In designing a large-scale irrigation or stock and domestic pipe networks, there are many decisions that need to be made to satisfactorily achieve the design criteria—to satisfy customer and environmental demands, minimum allowable pressure, maximum allowable velocity, etc. It is also desirable that the design decisions are made so these criteria are achieved at the least possible cost to society and the environment.

Once the objectives and criteria have been defined, the basic decisions that are made when designing a hydraulic network include the location of pipes, pump stations, valves and delivery points; the size, material and class of each pipe segment in the network; and the capacity and pumping regime of each pump station in the network.

In contrast to a traditional trial-and-error simulation analysis to design its pipe network, Murrumbidgee Irrigation elected to utilize an optimization approach that investigated hundreds of thousands of trial solutions to determine a least-cost network that satisfied the stated objectives. The resulting design exhibited better hydraulic performance and significantly reduced capital, operating and environmental costs.

BACKGROUND AND SETTING

Climate change, rising energy costs and limited water resources are issues gaining increased attention globally as they affect much of the world's population. Over the past decade, Australia has been particularly impacted by severe drought conditions in many parts of the country. This has forced the federal and local governments, urban and rural

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water providers, irrigators and individuals to become acutely attuned to the need for conservation and water efficiency.

The role of irrigators in Australia is recognized in the Blueprint for a Living Continent released by the Wentworth Group of Concerned Scientists in November 2002 (www.wentworthgroup.org/about, May 2009). It sets out a five-point plan for securing a sustainable future for the continent and its people:

1. Clarify water property rights and the obligations associated with those rights to give farmers some certainty and to enable water to be recovered for the environment.
2. Restore environmental flows to stressed rivers, such as the River Murray and its tributaries.
3. Immediately end broad-scale land clearing of remnant native vegetation and assist rural communities with adjustment. This provides fundamental benefits to water quality, prevention of salinity, prevention of soil loss and conservation of biodiversity.
4. Pay farmers for environmental services (clean water, fresh air, healthy soils). Where we expect farmers to maintain land in a certain way that is above their duty of care, we should pay them to provide those services on behalf of the rest of Australia.
5. Incorporate into the cost of food, fiber and water the hidden subsidies currently borne by the environment, to assist farmers to farm sustainably and profitably in this country.

In 2004, the Wentworth Group released its Blueprint for a National Water Plan. The document outlines solutions for the protection and restoration of fresh water ecosystems, water conservation, and the restoration of environmental flows to catchments such as the Murray Darling Basin. The Blueprint contributed to the National Water Initiative; a historic agreement by the Prime Minister, Premiers and Chief Ministers, resulting in the establishment of the National Water Commission and a $2 billion commitment from the Australian Government (www.wentworthgroup.org/about, May 2009).

BENEFITS OF CHANNEL TO PIPE IRRIGATION OPTIMIZATION

As billions of dollars are being committed in Australia to water supply, water conservation and water efficiency, the high proportion of water used for irrigated agriculture has become subject to more and more scrutiny. The situation is certainly similar in other countries including the U.S. western states. The increased focus on water efficiency measures in Australia has sparked interest in alternatives to inefficient open channel irrigation systems. One measure that is gaining favor in spite of its high initial capital cost is the use of pressure pipe networks in order to reduce losses from seepage and evaporation. Pressure pipe networks not only conserve water and increase water efficiency but they also provide far greater control and flexibility in irrigation applications.

The design of irrigation systems or stock and domestic pipe networks requires that specific design and performance criteria be satisfied. The criteria include meeting customer and environmental demands, and meeting minimum allowable pressures and maximum allowable velocities. The design should achieve these and other specified criteria at the least possible cost to society and the environment. It turns out that developing least-cost network designs is difficult especially when using the modern industry-standard approach that relies on a network hydraulic simulation model.

The steps involved in a network design are first to define the design objectives and criteria. Next the basic design decisions for the pipe network are identified, including:

1. the network layout including location of pipes, pump stations, and valves,
2. the size, material and class of each pipe segment in the network, and
3. the capacity and pumping regime of each pump station in the network.

Even when dealing with small-scale pipe networks, it is impossible for an engineer or modeler to explore all combinations of the decisions in trying to determine a least-cost network that satisfies the specified design and performance criteria. Usually a small number of different pipe network layouts are trialed until a satisfactory design is achieved, but such designs developed through trial-and-error and engineering judgment alone are often far from the best that could be achieved.

More powerful tools are available that can be applied to readily solve the least-cost irrigation network design problem. For example, Optimatics' genetic algorithm optimization technology is being used in Australia to help rural water authorities and irrigation districts develop superior solutions. The optimized network designs have resulted in water systems that both perform better hydraulically while significantly reducing capital, operating and environmental costs. The innovative optimization approach described in this paper has enabled significant improvements in the economic viability and environmental sustainability of channels-to-pipe projects worth over a billion dollars in total.

The benefits in converting from open channel to pipe irrigation and in applying a formal optimization technique to prepare the network design include more than just water conservation, reduced water losses and more efficient water delivery. Benefits have also included decreased energy use for pumping, a lower carbon footprint, and near-optimal designs that can save tens of millions of dollars in new infrastructure costs. With network designs that significantly reduce the required pumping effort, energy savings also contribute to cost reduction. As an added benefit CO2 emission levels over the life of the project have been significantly reduced. Several of these key benefits are illustrated in the case study presented below for Murrumbidgee Irrigation in New South Wales, Australia.

CASE STUDY — MURRUMBIDGEE IRRIGATION, AUSTRALIA

The Murrumbidgee Irrigation Area is located in the state of New South Wales within the Murray-Darling River Basin in southeast Australia (see Figure 1). The basin covers over 1 million square kilometers, which is equivalent to 14% of Australia's total area. The Murray-Darling Basin drains into the Darling (2740 km), Murray (2530 km) and Murrumbidgee (1690 km) Rivers, which are Australia's three longest rivers. The total area of crops and pastures irrigated in the Basin is almost 1.5 million hectares, which is 71% of the total area of irrigated crops and pastures in Australia (www.mdbc.gov.au/about/ basin_ statistics).

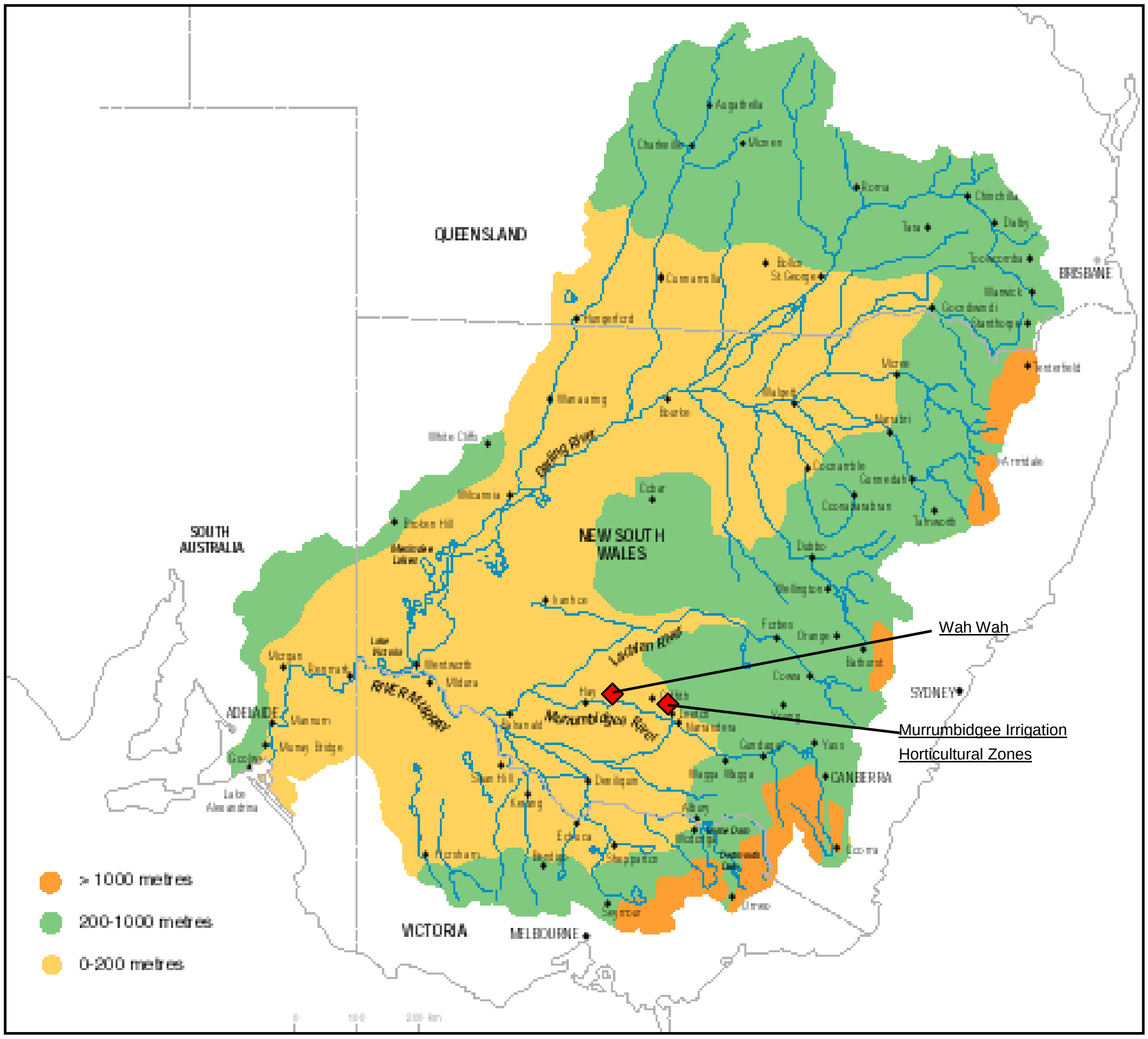

Figure 1. Murray-Darling Basin and Irrigation Study Locations

The Murrumbidgee Irrigation Area (MIA) was created under government ownership in the early 1900's to control and divert the flow of local river and creek systems for the purpose of food production. Irrigation water started flowing in 1912. MIA covers an area of 3,624 square kilometers with a local population of about 35,000. The topography is mostly flat open plains with Mirrool Creek draining the area. Two major storage dams with a combined storage of 2,654,000 ML supplies the irrigation flows. In 1999, MIA devolved from government ownership and is now owned and controlled by those who use the water (www.mirrigation.com.au/AboutUs/Water_for_Life.htm).

Figure 2 shows the Murrumbidgee Irrigation Area with the Mirrool and Yanco Irrigation Areas to the east and the Wah Wah Irrigation District to the west. Large area farms ranging from 200 to 320 hectares grow rice, corn, wheat and vegetables, prime lamb, wool and beef. The horticultural districts are scattered throughout the MIA and are characterized by good soils, concrete lined channels and high water security to suit high value crops like wine grapes, oranges, lemons, peaches, apricots, grapefruit, cherries, prunes and plums. Their average farm size is 16 to 20 hectares. Until recently furrow irrigation was the irrigation application method of choice.

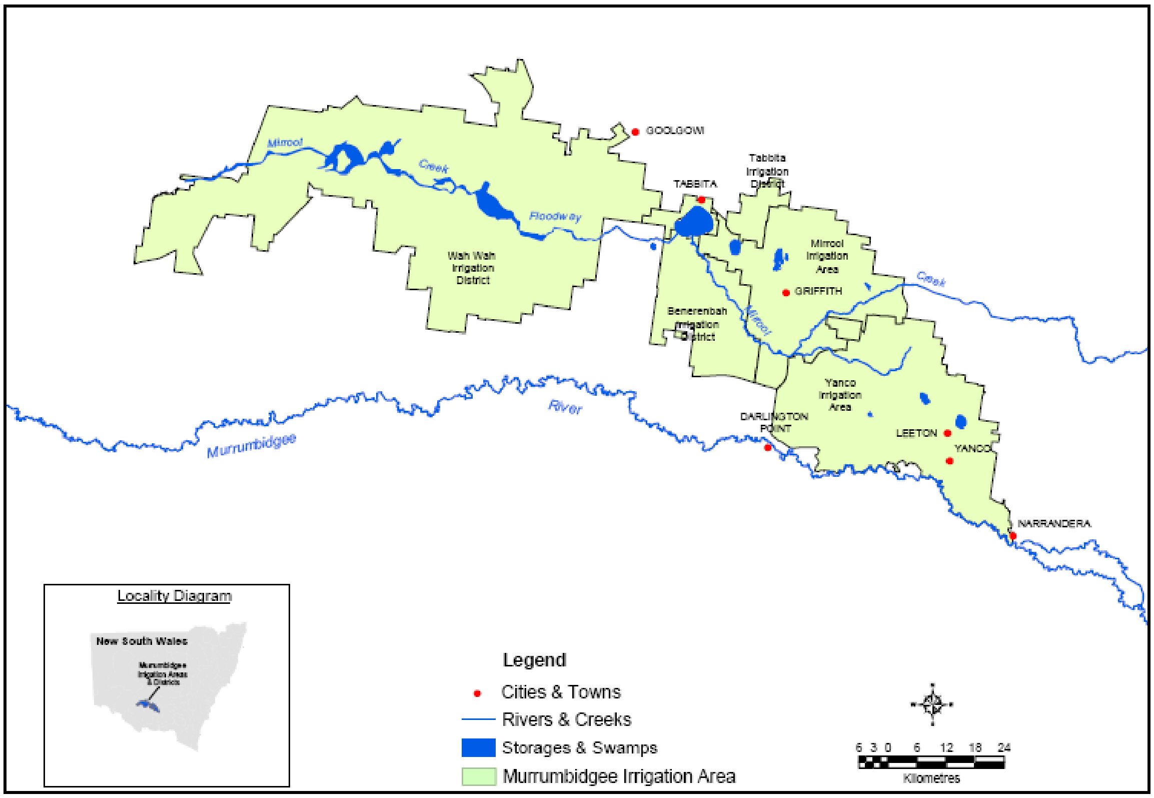

Figure 2. Murrumbidgee Irrigation Area

The recent extensive and severe drought has significantly impacted New South Wales and the farming communities of Murrumbidgee Irrigation Area. Water supplies have been drastically reduced and irrigation flows have been cut back. Murrumbidgee Irrigation has responded with a number of off-farm and on-farm initiatives to optimize available capital and water.

For example a community-wide plan called MIA EnviroWise is aimed at improving the integrated management of land, water and biodiversity. The program is concerned with ensuring the environmental and economic sustainability of the region.

MIA EnviroWise promotes water use efficiency programs designed to more accurately measure water supplied to crops and decrease the amount of water entering the underground system. Using water more efficiently means irrigators have water available for more cropping, and the environment benefits through decreased impacts from higher water tables. MIA EnviroWise programs also target water quality with initiatives that will improve the quality of water returned to the Murrumbidgee and Murray Rivers.

MIA EnviroWise Incentive Programs give farmers an opportunity to access a range of financial and other incentives for implementing improvements to their on-farm works. Efficiencies that have been implemented in the MIA include conversion to drip irrigation systems, soil moisture monitoring systems and soil suitability tests.

MI's Optimized Pipe Irrigation System Design Problem

A key component of Murrumbidgee Irrigation's (MI) capital works program targets the replacement of open channels in the horticultural districts. Conversion of these delivery systems to pipe systems reduces "off-farm" water losses, but also forms an important catalyst for "on-farm" water savings because centralized pumping and a high pressure delivery system enables cost-effective uptake of efficient drip and micro sprinkler irrigation.

A key part of the strategy for maximizing water savings and beneficial use of capital is the optimized design of the pipe systems. MI engaged Optimatics to plan, design and optimize the replacement of channel irrigation networks with more than 450 km of a new pipe system covering 30,000 hectares. The pipe network system was optimized to the minimize resources required (considering pipe diameter sizes and pumping energy needs) and the project capital costs and lifetime operating expenditures. Initially the optimization was formulated to determine optimal boundaries between the new distribution systems which unlike the channels, would no longer be constrained by contour. The number and location of pump stations was optimized and the relationship between cost and service level (peak flow rate per area, and minimum pressure) was also investigated. This required concurrent optimization of the locations of farm outlets which were not constrained to the existing outlet location from the supply channel.

With thousands of hectares of farm land to supply, MI required pipe network designs which covered thousands of square kilometers at a potential cost of hundreds of millions of dollars. MI's aim in choosing to apply a proven formal optimization approach was to identify least-cost, hydraulically robust designs. This could only be accomplished by considering a wide range of design options (pipeline diameters, pump stations, outlet locations) and optimizing each element in the designs.

The steps involved in the irrigation system optimization involved first creating hydraulic simulation models for each of the pressurized pipe networks to be designed. The models represented Murrumbidgee Irrigation's customers in 22 of its total 28 horticultural zones. To represent these customers, MI's GIS data was used to automatically determine the coordinates of each farm, and also calculate each of the farm areas so that demands could be developed. Through discussions with MI, three irrigation water demand loading cases were developed to represent peak loading, spur loading and average loading.

Once the models were created, potential pipeline and pump station options were identified for each area taking into account information provided by MI on existing open channel routes, roadways and farm boundaries. Preferred delivery points for each farm were also noted, and not constrained to the existing delivery points which were on the high side of the farm to suit gravity flow to on-farm furrow irrigation. MI requested consideration of a number of outlet locations for each farm based on the midpoints of the individual farm boundaries.

The optimized designs had to satisfy the design criteria specified by MI:

- Minimum allowable pressure criteria of 40 m
- Maximum flow rate criteria on some supply channels
- MI's spur loading rules (3 tail end outlets)
- Least present value of capital and future (discounted) energy costs

Two additional criteria were included but they did constrain the solutions:

- Maximum allowable pipe flow velocity criteria of 3 m/s
- Maximum allowable pressure criteria based on pipe class (72 m for Class 9)

<u>Making Use of a Powerful Optimization Technique</u>

Each of the 22 horticultural zones and additional stock and domestic areas to be designed represented a significant design problem. There were many variables (pipe locations and sizes, pump stations, pumping heads, outlet locations, etc.) and many potential viable solutions. Genetic algorithm (GA) optimization is a proven search technique that can handle such large problems to enable designers to find least-cost viable solutions.

Genetic algorithm (GA) optimization was first developed in the 1970's by Professor John Holland at the University of Michigan. It has since been applied to many industries to identify near-optimal solutions to complex engineering problems. GA optimization was first applied to water distribution system by researchers at the University of Adelaide in 1990. Optimatics has been applying GA technology to the optimization of water systems since 1996.

Genetic algorithm optimization is an evolutionary technique based upon the mechanisms of natural selection and genetics. "Survival of the fittest" relentlessly drives the genetic algorithm towards improved solutions. The GA process involves the selection, combination and manipulation of possible solution options represented by strings of numbers analogous to chromosomes.

GA optimization is a tremendously powerful and efficient optimization technique. Starting from an initial population of trial solutions (at generation 0), the GA uses certain operators to derive a subsequent population of off-spring solutions (at generation 1, 2, etc.). The three operators of selection, crossover and mutation act on successive generations to drive a process akin to natural selection. The fittest solutions in each generation have the greatest probability of surviving and then breeding to "evolve" better and better solutions. Fitness is a measure of each solution’s cost and hydraulic performance.

With thousands of hectares of farm land to supply, thousands of potential pipeline routes and dozens of pump station sites to consider, the industry-standard trial-and-error simulation approach for the Murrumbidgee Irrigation Area is unlikely to identify least-cost solutions. A simulation-only approach cannot easily be applied to minimize capital and operating costs, while also satisfying the many hydraulic criteria (peak demands, minimum allowable pressures, maximum allowable pipe flow velocities). By applying GA optimization to the problem, Murrumbidgee Irrigation was assured that hundreds of millions of potential solutions were evaluated in the search for the best designs that suited their needs.

MI Horticultural Zones Optimized Design

One focus of the project was on supplying water to MI’s Horticultural Farms in the Mirrool and Yanco areas, which mainly cultivate stone fruit, citrus and vines. By converting from open channels to pressure pipe delivery systems, the estimated water savings for MI Horticultural Zones are in the order of 50,000 ML/yr in off-farm and on-farm irrigation.

As described above, the optimization of horticultural zones involved large-scale hydraulic simulation model building covering many hectares of farm land, development of farm demands, and improved application of MI’s spur loading demand rules. As the project proceeded, it also included optimization of additional farm irrigation water outlet delivery locations, and a greater number of decision variables (pipeline diameters, pump station sizes and locations, outlet locations) per optimization run.

Figure 3 illustrates the hydraulic model construction for Zone 18 (Tharbogang). The irrigation pipe location options for the most part follow existing open channels and farm boundaries. Six options to locate one or more new pump stations were considered as shown. Alternative outlet locations along each farm boundary are represented by the nodes in the model. Each optimization model run was carried out taking into account several demand loadings to ensure the selected pipelines and pumps could deliver the full range of anticipated irrigation flows and pressures. Each optimization run was formulated to evaluate and minimize project life-cycle costs considering both capital costs and lifetime operating costs.

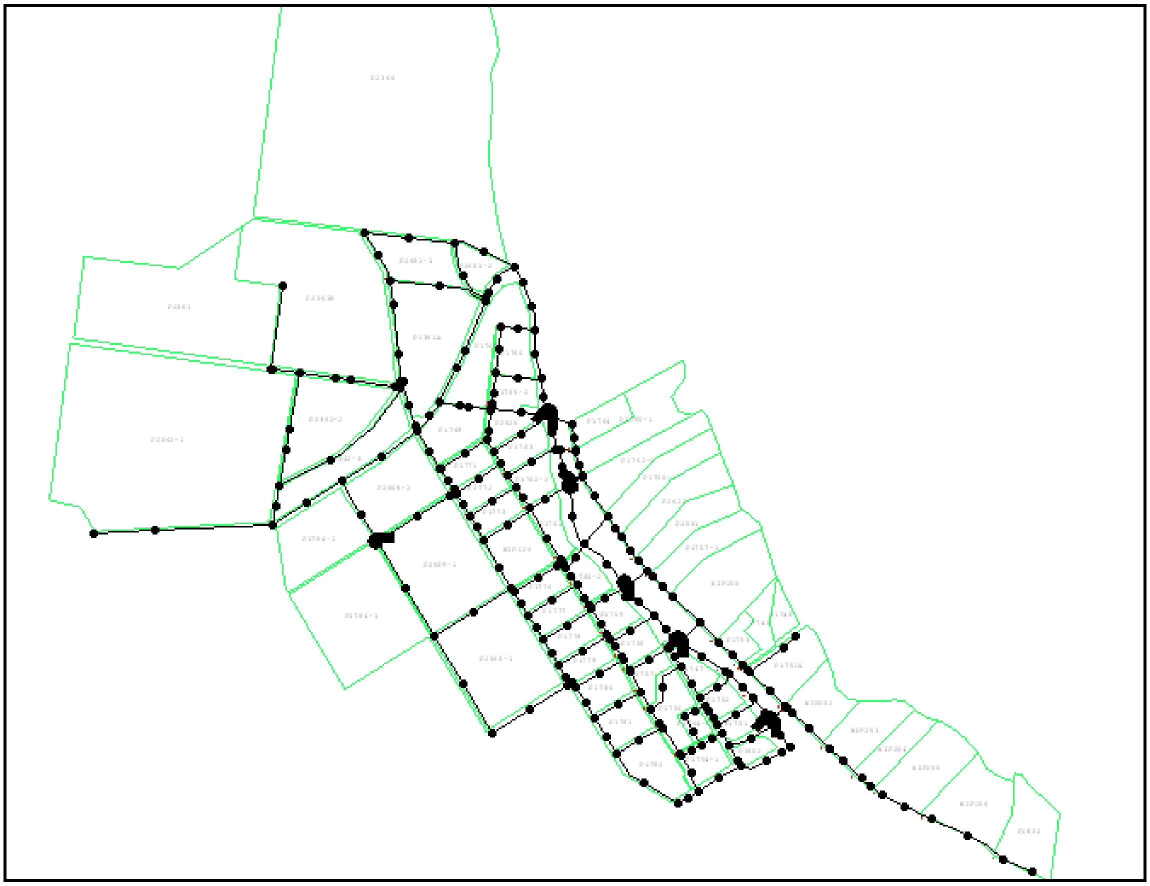

Figure 3. Zone 18 Hydraulic Model with Pipe and Pump Options

From the mix of allowable decision variable choices, the optimization created and evaluated in the hydraulic model millions of trial solutions as it searched for the best combination of options to satisfy the design criteria at the lowest cost. The final solution costs for each optimized area were critically important as the cost of the pipe schemes are being passed onto the growers through water purchase costs.

After optimization, Murrumbidgee Irrigation continued consultation with growers in Tharbogang and awarded a public tender for detailed design to HydroPlan. Following survey and site investigations, Optimatics revisited the analysis to ensure the latest pipe material and cost information was considered and to pin-point optimal pumping pressures. The final station is effectively two in one to respond to demand at farms which are higher and lower than the pump station. One delivers from 0 L/s at 45 m to 584 L/s at 78 m, and the other delivers from 0 L/s at 86 m to 460 L/s at 117 m.

Figure 4. The pump station at Tharbogang has 11 pumps to respond to demand

The overall MI channels to pipe optimization has the potential to pass on lower costs to hundreds of growers, as well as providing a more efficient scheme to water their crops and reduce water losses through evaporation and seepage that are systemic in open channel flow delivery systems.

Table 1 summarizes the final results of the optimized pipe network designs for 22 of Murrumbidgee Irrigation's 28 Horticultural Zones.

Table 1. Solution Cost Breakdown for 22 MI Horticultural Zones

Zone	Total pipe length (m)	Total pipe capital cost ($ million)	Total pump capital cost ($ million)	Total pump operating cost ($ million)	Total solution cost ($ million)
Zone 4,5,6	49,646	$2.78	$2.08	$4.39	$9.25
Zone 7&8	12,981	$1.00	$1.01	$2.02	$4.03
Zone 9	71,945	$9.02	$6.56	$11.07	$26.65
Zone 10	10,205	$0.93	$0.87	$1.59	$3.39
Zone 11	47,670	$3.88	$2.41	$4.31	$10.59
Zone 16	35,336	$3.90	$1.72	$3.35	$8.97
Zone 17	26,330	$3.49	$2.00	$3.34	$8.84
Zone 18	13,980	$1.18	$0.97	$1.62	$3.77
Zone 19&20	25,706	$1.26	$0.96	$1.77	$3.99
Zone 21&22	76,840	$7.20	$6.36	$11.33	$24.88
Zone 24	13,435	$0.65	$0.51	$1.21	$2.37
Zone 25&26	53,660	$4.05	$2.54	$5.08	$11.67
Zone 27	17,268	$0.94	$0.69	$1.31	$2.94
Total	455,000	$40.28	$28.69	$52.38	$121.35

Note: Total pump operating cost is the estimated present value over the project life.

MI Wah Wah Stock and Domestic Optimized Design

Optimatics also assisted Murrumbidgee Irrigation with the design of a large stock and domestic system for the Wah Wah area. The Wah Wah stock and domestic system is currently supplied through open channels which again are to be replaced with a pressure pipe system. The estimated water savings are in the order of 10,000 ML/yr during dry years.

Whereas many of the larger Horticultural Zones had demands exceeding 5,000 L/s and required multiple large capacity pump stations and large diameter pipelines, total demand for the Wah Wah stock and domestic system is just 65 L/s. However, the Wah Wah system covers a much larger area than the entire Horticultural zones of Mirrool and Yanco—resulting in 1,600 km of pipelines compared to 455 km of pipe network for the Horticultural Zones.

The optimization of the Wah Wah stock and domestic system was complicated by the large area the system covers (long sections of pipeline to be sized and optimized), the flexibility of outlet locations, potential booster pump station locations and a number of different source and storage options. Over a dozen different solutions were developed and optimized for the Wah Wah system. These solutions considered different sources, storage, booster pump stations, consideration of on-farm costs, plus sensitivity to demand peaking factors. Total solution costs for the Wah Wah system ranged from A$32 million to A$84 million. Figure 5 shows the range of solution costs. The ease with which the optimization analysis was able to develop near-optimal solutions for a large number of alternative scenarios illustrates a further significant benefit to utilizing optimization to design pipe irrigation systems.

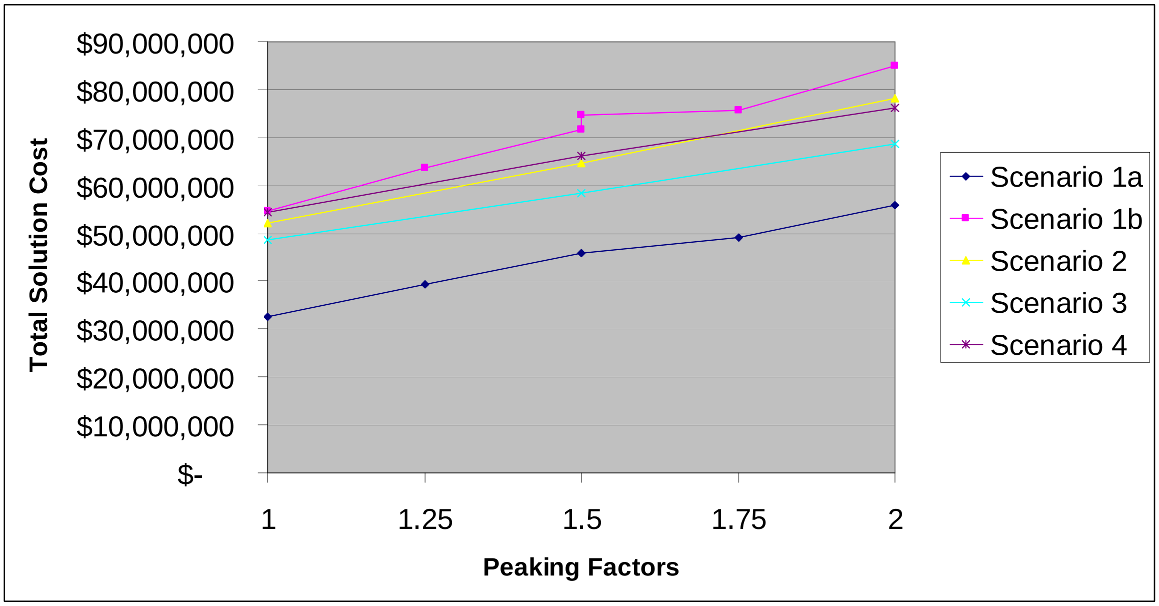

Figure 5. Wah Wah Optimized Solution Costs for Different Scenarios and Demands

SUMMARY AND CONCLUSIONS

The Murrumbidgee Irrigation case study presented in this paper describes how a powerful formal optimization technique was applied to develop optimized pipe irrigation project designs for both horticultural and stock and domestic irrigation systems. Other irrigation authorities in the area, such as Lower Murray Water, Coliban Water and Goulburn Murray Water, have also carried out irrigation optimization projects. In each case the optimization objective was to design a pressurized pipeline system to replace inefficient open channel irrigation systems.

Water losses in open channels through seepage and evaporation are the cause of major inefficiencies in irrigation systems. Replacing open channels with efficient pressure pipe systems is essential to the on-going sustainability of water resources, particularly under changed climate conditions as New South Wales, Australia feels that it has experienced. The savings in water are certainly significant for the case studies cited above:

- Murrumbidgee Irrigation Horticulture Zones - 450 km of new pipe for 50,000 ML/yr in estimated water savings
- Wah Wah Stock and Domestic – 1,600 km of new pipe for 10,000 ML/yr in estimated water savings

The power of the optimization used in designing the pressure pipe networks allows various objectives and options to be optimized. For example, these systems require hundreds of miles of pipelines to be routed and sized, exhibit complex spur loading rules, require trade-offs between pumping capacity and pipeline capacity, and require pipe class considerations to be taken into account.

By optimizing the pipe network designs for these irrigation system, irrigation authorities can implement more efficient systems that can better respond to a range of demand conditions. The optimization is able to evaluate the system sensitivity to various assumptions including high pressure system versus low pressure system, different source options, different demand rates, different outlet locations, different pump options, etc). Finally the irrigation authorities and the growers benefit from lower cost designs.

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