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Adaptation to water shortage through the implementation of a unique pipeline system in Victoria, Australia

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Abstract Water resource development has played a crucial role in the Grampians, Wimmera and Mallee regions of Australia, with the main source of surface water located in several reservoirs in the Grampians mountain ranges. Historically, water was delivered by gravity through a vast 19 500 km earthen channel system from the reservoirs to the townships and farms. As a result of the severe and protracted drought experienced in the region over the past 13 years and the projected drying climate, there have been fundamental changes made to the management of water in order to better cope with water scarcity. The primary strategic effort to sustainably manage water resources was by removing the unsustainable transport of water via the open channels which resulted in very high losses through seepage and evaporation. This inefficient system has been replaced by a pressurised pipeline, the largest geographical water infrastructure project of its type in Australia, spreading across an area of approximately 20 000 km^2. To manage the change in water balance as a result of the pipeline and drying climate, the regions water corporations and environmental agencies have designed a scheme for water allocations intended to sustain local communities, allow for regional development and improve environmental conditions. This paper describes the unique pipeline system recently completed, provides a brief summary of water sharing arrangements and introduces the research program currently underway to optimise the performance of the pipeline system.

Keywords drought; water supply; water distribution system; Wimmera Mallee Pipeline; water sharing; optimisation

INTRODUCTION

The Grampians, Wimmera and Mallee regions in western Victoria, Australia, extend across an area of approximately 62 000 km^2 and can be characterised as a semi-arid landscape with very limited water resources. The regions population of approximately 70 000 is concentrated in small rural towns. The land is used mainly for dryland agriculture (grazing and cropping).

The regions geological history has resulted in highly saline groundwater (Wimmera CMA, 2008) which was also too deep to extract and distribute. Therefore, the regions development has historically been mostly dependent on surface water for its water supply. The main source of this water supplying the regions needs is located in the south, where water is harvested in and around the Grampians mountain ranges and stored in numerous reservoirs.

HISTORICAL BACKGROUND

The Grampians reservoirs were built between 1890s and 1970s to supply a growing agricultural industry and population. To distribute water across the region, a vast 19 500 km gravity earthen channel system was constructed across an area of

28 500 km^2 from 1890s to 1940s (Fig. 1). This Wimmera-Mallee Domestic and Stock Channel System supplied water from the Grampians reservoirs to about 22 000 farm storages on 15 760 rural properties, and to 51 towns and villages (AQUA, 1984) as far north as the Murray River (Fig. 2).

Fig. 1 Construction of the Wimmera-Mallee Domestic and Stock Channel System.

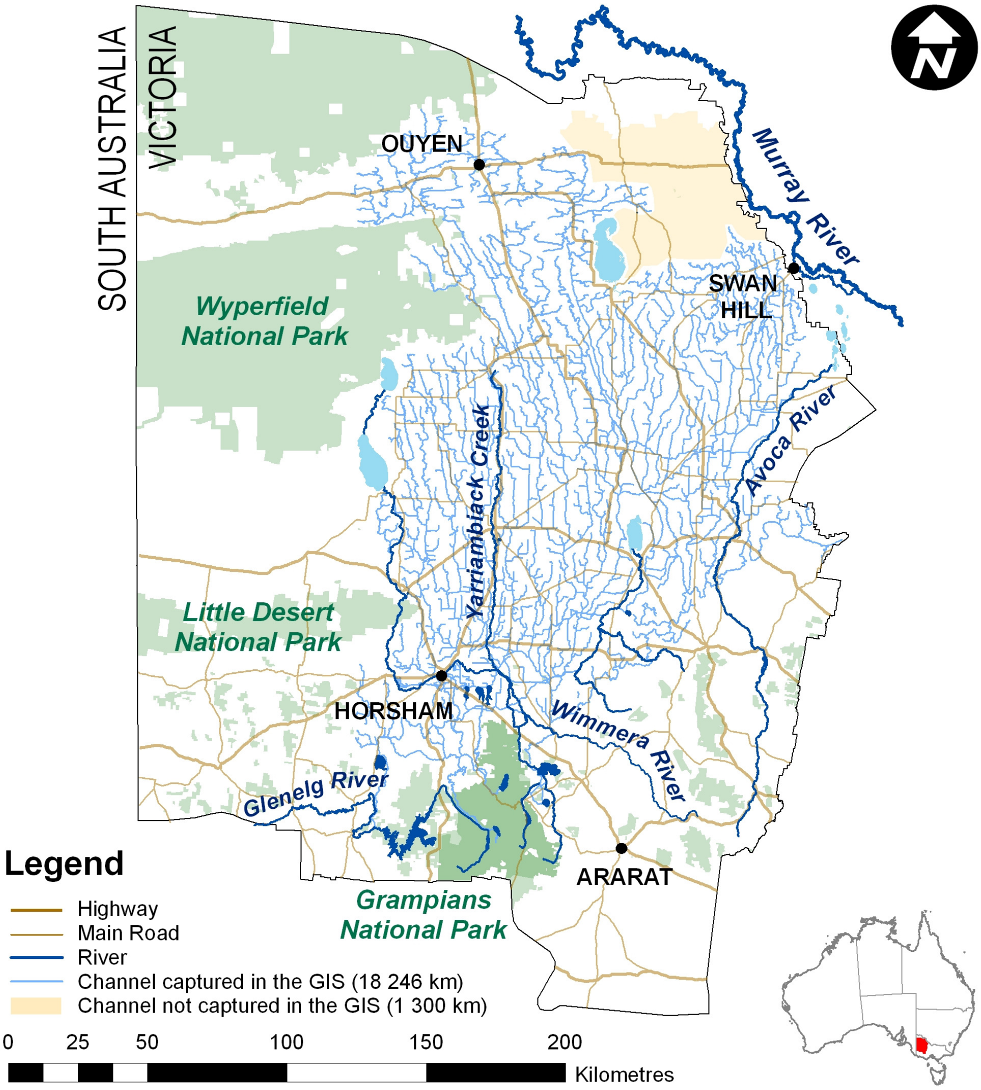


Fig. 2 Location map of the Wimmera-Mallee Domestic and Stock Channel System.

Water was delivered to earthen town storages and farm dams on a seasonal basis. Yearly volumes in the order of 120 mil. m^3 were required to satisfy both water consumption, and transmission losses in the channel system through seepage and evaporation which could account for up to 85 % of water entering the system.

Over the past decade, drought has highlighted that this mode of water delivery is no longer sustainable. The combination of low rainfall to replenish reservoirs and the inefficiencies of the channel system resulted in the steady decrease in stored water held in the Grampians reservoirs. This decline started in 1997 with reservoirs holding 75.3 % of their capacity (562.2 mil. m^3) and fell to just 3.3 % of their capacity (24.6 mil. m^3) in May 2008 (Barton *et al.*, 2009).

During this period, it was recognised by water managers and government that, in order to improve the ability of the region to sustainably manage its water resources, a new and more efficient water distribution network was needed. During the early part of 2000, a business case was developed and presented to government to replace the open channel system with 8 800 km of pressurised pipeline (GWMWater, 2003). The success of this business case led to the Wimmera Mallee Pipeline (WMP) project which commenced construction in November 2006. At that time, the Grampians reservoirs were at 5.7 % capacity (42.6 mil. m^3). The construction of the pipeline was initially expected to take 10 years. However, due to continuing drought conditions (Table 1) and the severely restricted water supply situation, construction of the pipeline was fast tracked and scheduled for completion by mid 2010.

Table 1 Grampians reservoirs.

Reservoir	**Build (year)**	**Catchment (km^2)**	**Contents full (mil. m^3)**	**Current contents (May 2010)**	
				(mil. m^3)	**(%)**
Batyo Catyo	1961	200.0	2.250	0	0
Bellfield	1966	96.0	78.56	21.87	28
Dock	1935	225.0	4.42	0	0
Fyans	1916	13.2	18.46	5.55	30
Green	1935	220.0	5.35	0	0
Lonsdale	1903	1 015.0	65.48	2.60	4
Moora Moora	1934	147.0	6.30	2.65	42
Pine	1923	25.1	62.00	0	0
Rocklands	1953	1 355.0	348.31	6.37	2
Taylors	1923	80.6	33.70	22.92	68
Toolondo	1953	99.0	92.43	0	0
Wartook	1887	75.0	29.30	15.69	54
Total			**746.56**	**77.65**	**10.4**

The WMP is now complete with more than 80 % of customers serviced by the old channel system connected to the pipeline. Its success is already evident by regions adaptation to prolonged water shortages. Early studies suggest that the Wimmera Mallee community is reacting positively to the WMP and its broad benefits are beginning to be realised (WIDCORP, 2009) through a more reliable supply to customers and increased water to the environment.

Climate change modelling suggests significant reductions in available water over the next several decades (CSIRO, 2007). Hence it is increasingly important that major water reform such as this is used to meet the social, economic and environmental needs of regions into the future. Projects such as the WMP will assist regions to adapt to less water availability thus mitigating some of the impacts of climate change.

WIMMERA MALLEE PIPELINE

System overview

The WMP is a 8 800 km pressurised pipeline system for transferring water over an area of approximately 20 000 km^2 in the Wimmera and Mallee regions. The WMP conveys raw water sourced from the Grampians reservoirs in the south and Murray River in the north to a variety of customer groups including 38 towns and other water users.

The WMP is organised into distinct supply systems referred to as Supply System 1 (SS1) through to Supply System 7 (SS7) (Fig. 3). The SS1 to SS4 and SS6 are sourced from Grampians reservoirs Bellfield, Moora Moora, Rocklands, Taylors and Wartook. SS7 is a major transfer pipeline between the reservoirs Bellfield and Taylors, and SS5 is sourced from the Murray River.

Based on historical inflows into the Grampians reservoirs and projected demands, it is estimated that the WMP will save on average 103 mil. m^3 per year. It is expected that the majority of this water will be returned to the environment (Barton *et al.*, 2009).

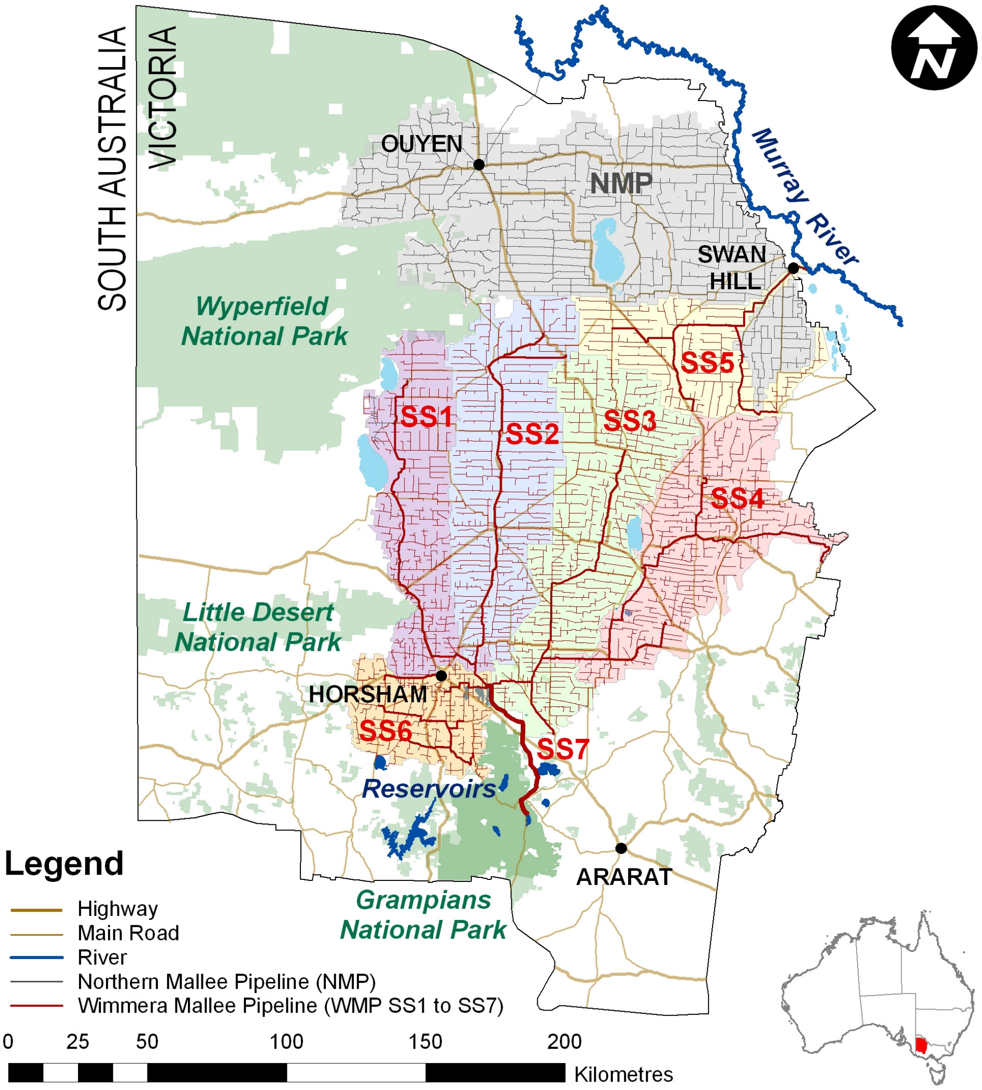


Fig. 3 Location map of the Wimmera Mallee Pipeline.

The WMP consists of 1 200 km of trunk mains, 7 600 km of distribution mains, 32 pump stations incorporating 45 transfer and booster pump sets, 22 HDPE lined open earthen balancing storages and 29 lined covered steel tanks (Fig. 4). Further details are listed in Table 2.

Fig. 4 Wimmera Mallee Pipeline: Left: A typical tank (before lining and roofing). Middle: A typical balancing storage (left lined, right before lining). Right: Pump station.

The trunk pipelines transfer water between the balancing storages and to the local distribution network. The storages are typically situated along the trunk pipelines in the near vicinity to urban centres. They provide water for the towns and also to downstream rural customers. The distribution pipelines branch off the trunk mains to supply rural properties. Transfer pump stations ensure bulk water supply between storages and also provide pressure throughout the distribution networks. Booster pump stations are installed in local distribution systems to maintain minimum pressure requirements (GWMWater, 2006).

Table 2 Wimmera Mallee Pipeline system details (based on design and as constructed information).

Pipeline infrastructure	
Diameter (mm)	**Length (km)**
25	210
50	1 740
63	2 650
80	1 460
100	960
110	90
150	560
200	300
225	40
250	110
300	110
375	230
450	220
575	30
711	30
1 016	50

Storage facilities	**Number**	**Volume (m^3)**
Earthen lined storage	22	37 000
Covered steel tank	29	522 000
Total	**51**	**559 000**

Pump Sets	**Number**
Trunk pump sets	21
Distribution pump sets	16
New town pump sets	8
Total	**45**

Other pipeline infrastructure	**Number**
Air valve	16 886
Scour valve	1 225
Hydrant	355
Tapping connection	9 000

System demands

The WMP was designed to service 38 towns, 2 822 rural residences (farms), numerous rural stock, agricultural and industrial customers, recreational lakes and environmental water bodies (Table 3). These customers use water for either non-potable or potable supplies.

The pipeline was designed to deliver 22.63 mil. m^3 per year with allowance for a seasonal variation in the demand (Fig. 5). The remaining 9.00 mil. m^3 per year for recreational lakes, environmental water bodies and future growth was designed to be delivered during the off peak period.

Table 3 Wimmera Mallee Pipeline design demands (GWMWater, 2004 and GHD, 2009).

Customer type	**Allocation (mil. m^3 $year^{-1}$)**	**Comment**
Urban	8.62	Based on actual measured bulk meter data from 1995 to 2002 including additional allowances: • 12 % on the peak annual demand to account for uncertainties in metered data • 10% growth on the peak annual demand
Rural domestic	2.06	2 822 × 730 kL $farm^{-1}$ $year^{-1}$ Includes components for in-house and garden consumption. • In-house peak day demand: 2 000 L $farm^{-1}$ day^{-1} • Garden peak day demand: 3 000 L $farm^{-1}$ day^{-1} • Total peak day demand: 5 000 L $farm^{-1}$ day^{-1} • Total average day demand: 2 000 L $farm^{-1}$ day^{-1} *Note: Majority of homes are fitted with evaporative air coolers which can use up to 1 000 L* day^{-1} *in the Wimmera Mallee region on a hot day*
Rural stock	5.15	Based on a dry sheep equivalent (DSE) stock density multiplier which varies from about 4.0 DSE ha^{-1} in the south to 1.0 DSE ha^{-1} in the north. • Peak day demand: 7.0 L DSE^{-1} day^{-1} • Average day demand: 4.25 L DSE^{-1} day^{-1}
Rural growth	5.00	Equitably distributed within the supply systems at 250 kL km^{-2} at peak times
Supply by agreement (SBA) and intensive industry	1.80	Based on volumes in existing agreements. Includes piggeries, poultry, cattle feedlots, golf/racing clubs, schools and other. • SBA applies to customers whose demand is > 6 000 m^3 $year^{-1}$ • Intensive industry applies to customers whose demand is > 2 000 m^3/250 ha and < 6 000 m^3 $year^{-1}$
Subtotal	**22.63**	
Recreational lakes	3.00	Off peak season supply. Volumes assessed on a case by case basis.
Environmental water bodies	1.00	Off peak season supply. Includes channel-fed wetlands. Volumes assessed on a case by case basis.
Future growth	5.00	Off peak season supply.
Total	**31.63**	

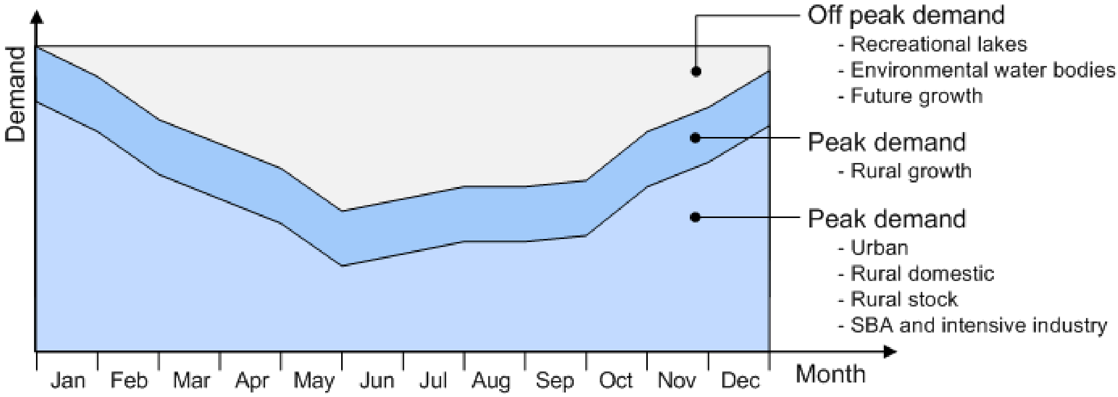


Fig. 5 Seasonal demand pattern for pipeline design purposes.

Hydraulic design

The system was designed to ensure that acceptable pressure and flow rates will be delivered under various demand conditions. The specified levels of service, design requirements and constraints are listed in Table 4.

Table 4 Wimmera Mallee Pipeline design requirements (GHD, 2009).

Design requirement	Value
Minimum allowable service pressure at each supply point at the customer property boundary	200 kPa (20 m)
Maximum allowable service pressure at each supply point at the customer property boundary	900 kPa (90 m)
Maximum allowable operating pressure in pipelines	1 000 kPa (100 m)
Minimum residual pressure in trunk mains at storage inlets	50 kPa (5 m)
Maximum flow velocity in pipelines	1.2 m s^{-1}
Maximum flow velocity in pump stations	2 m s^{-1}
Minimum internal diameter of trunk mains	100 mm
Minimum internal diameter of distribution mains	50 mm
Minimum pressure class for trunk mains	Class 12 (120 kPa)
Minimum pressure class for distribution mains	Class 9 (90 kPa)

For the purpose of design, the hydraulic models were developed using EPANet (www.epanet.com). During the design process, these models were regularly updated.

The trunk system was designed to provide a flow rate of peak three month average flow for SS1 and SS7. As better system understanding developed, SS2 to SS6 design was altered to supply a flow rate of peak month average flow. The distribution system was designed to provide peak day average flow (GHD, 2009). Pipe materials used were MSCL, PVC and PE.

Sizing of pipes was based on the expected internal roughness of aged pipes. The pipe friction losses were calculated using the Hazen-Williams formula. Hydraulic roughness coefficients of between $C = 120$ and $C = 130$ were adopted.

Balancing storages were designed to accommodate the fluctuations in demands and cater for periods when demand exceeds the maximum available supply rates from upstream. They were designed as inline storages to ensure sufficient turn over of water to maintain water quality. The design also allowed for some to be bypassed if required. The capacity of a particular storage was determined to cater for both balancing and emergency volumes.

Pump stations were equipped with variable speed pumps. The pumps ensure the delivery of the required pressure across a large range of flow rates. The pump stations were also fitted with automated bypasses which are used under low flow conditions when there is sufficient natural (gravity) pressure from the upstream Grampians reservoirs. For upstream supply interruptions or serious water quality issues, pump stations and pipe work were equipped with valve arrangements which allow "reverse pumping." This involves water in balancing storages being pumped back upstream to pressurise the distribution network and maintain supply to customers.

Townships are supplied from the balancing storages using the already existing urban reticulation systems. These storages provide urban customers with the instantaneous peak flow through either a variable speed drive booster pump station or an existing elevated tank.

Farms are supplied from the distribution pipeline network to the property boundary. They were required to install their own balancing tank(s) sized to hold three peak day farm consumption to provide for their instantaneous peak demand. Extensive customer liaison and education programs were undertaken to ensure customers correctly installed appropriate infrastructure on their property (Caris, 2005).

For fire fighting purposes, hydrants were located approximately every 5 km along trunk pipelines of 150 mm in diameter or greater. Along smaller distribution pipelines, fire fighting water is provided from strategically situated roadside tanks enabling quick filling of fire trucks and/or water tankers. Water can also be supplied from the emergency volume held in each balancing storage (GWMWater, 2004).

Typical pump station operation

A pump station typically consists of an inlet control valve (ICV) assembly (Fig. 6), balancing storage, pump set and pump set bypass arrangement.

There are three main modes of operation for water entering a pump station from a trunk main:

- Storage fill mode, which enables water to be directed to the balancing storage whilst pumps are pumping water downstream.
- Boost mode when water is directed to the pumps and the incoming pressure is raised.
- Bypass mode when the incoming pipeline pressure is high enough that the pump set can be bypassed to the downstream pipeline.

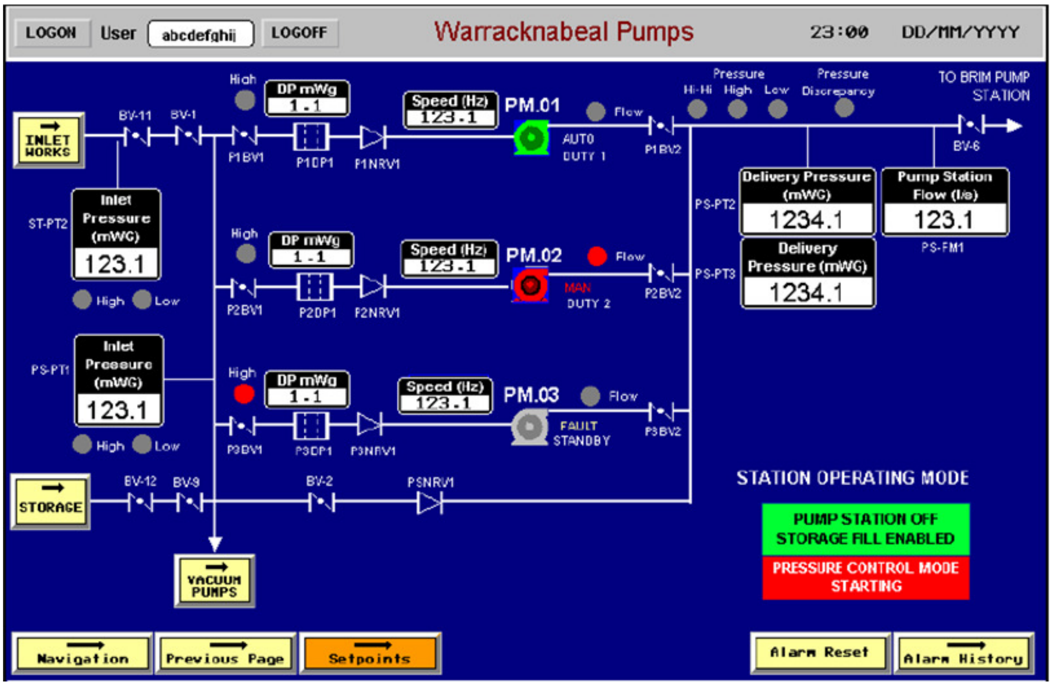
Fig. 6 Wimmera Mallee Pipeline: A typical inlet control valve (ICV) assembly.

The ICV assemblies are located on the incoming pipeline to a pump station. They consist of a pressure reducing valve (PRV) in series with a flow control valve (FCV). They direct incoming water either into storage, the pump set, or pump set bypass. The main purpose of each of these valves is to reduce or maintain pressure in the downstream pipe, sustain pressure in the upstream pipe and also control flow when water is directed to balancing storage.

Pump sets consist of two duty pumps and one standby pump. The pumps, which all have dedicated variable speed drives, operate at a pressure set point which is matched to suit the downstream system pressure and flow requirements. When the incoming pressure to the pumps is below the set point, the pumps operate in boost mode. If the incoming pressure is at or above the discharge pressure set point, water is bypassed around the pumps to the downstream pipeline.

A sophisticated control system monitors and controls all aspects of pump station operation ensuring that the pumps respond to a wide range of system demands and conditions. Pump station set points and other control parameters can be adjusted locally (Fig. 7) or remotely via Supervisory Control and Data Acquisition (SCADA).

The use of SCADA makes the operation of the pipeline system particularly conducive to optimisation techniques discussed in a subsequent section.



User abcdefghij

Inlet Pressure (mWG) 123.1

Inlet Pressure (mWG) 123.1

DP mWg 1.1

Speed (Hz) 123.1

DP mWg 1.1

Speed (Hz) 123.1

DP mWg 1.1

Speed (Hz) 123.1

Delivery Pressure (mWG) 1234.1

Pump Station Flow (l/s) 123.1

Delivery Pressure (mWG) 1234.1

PUMP STATION OFF
STORAGE FILL ENABLED

PRESSURE CONTROL MODE
STARTING

Fig. 7 Control panel in pump station: HMI (Human Machine Interface).

WATER SHARING ARRANGEMENTS

Water resources in the region are managed through an entitlement and allocation framework which takes a "whole of system" water management approach (DSE, 2009). It considers all water resources for both consumptive and environmental purposes.

The bulk entitlements applicable to this area originally came into effect in 2004. There are four bulk entitlement holders for the surface water resources including the environment and three water corporations namely Grampians Wimmera Mallee Water (GWMWater), Wannon Water and Coliban Water.

The bulk entitlements are based on a "resource sharing" approach in which the available water in the system is shared amongst all entitlement holders using an agreed set of rules (DSE, 2004). These rules are the outcome of protracted negotiations, sometimes stretching for years, and are heavily influenced by the government of the day.

Table 5 shows how the available water is shared amongst the entitlement holders under a range of water scenarios. This table shows the regulated entitlements (released from reservoirs), and there are also additional unregulated entitlements for the environment which is water that cannot be harvested.

Construction of the WMP has afforded the ability to change the water balance. At the time of writing this paper, the bulk entitlements for region were being amended to reflect new water sharing arrangement post construction of the WMP. Hence table 5 only approximates how water will be shared. It should be noted that a hierarchy or priority of water to different users is assumed in this table. The highest priority is for basic human needs. As the available water increases, water becomes available for other users, including for high priority environmental sites. WMP water products have the highest reliability, irrigation by channel has the lowest reliability.

Table 5 Approximate water sharing arrangements showing how water is shared between entitlement holders as available water diminishes from left to right.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Available water (mil. m^3) →	**125.550**	**119.950**	**109.510**	**103.790**	**92.180**	**69.500**	**63.656**	**58.142**	**53.011**	**37.979**	**30.223**	**0**
Grampians Wimmera Mallee Water												
System operating water - irrigation losses	9.000	7.200	5.400	4.500	2.250	0.000	0.000	0.000	0.000	0.000	0.000	0
System operating water - pipeline and balancing storage losses	2.960	2.960	2.960	2.960	2.960	2.960	2.960	2.960	2.960	2.960	2.960	0
Urban demand off pipeline & headworks	13.820	13.820	13.820	13.820	13.820	13.820	13.213	12.435	11.234	7.950	7.950	0
Rural demand supplied by pipeline	6.580	6.580	6.580	6.580	6.580	6.580	6.291	5.921	5.349	3.785	3.785	0
Supply by agreement (for industry)	6.670	6.670	6.670	6.670	6.670	6.670	6.377	6.002	5.422	3.837	3.070	0
Irrigation supplied by channel	19.000	15.200	11.400	9.500	4.750	0.000	0.000	0.000	0.000	0.000	0.000	0
Glenelg compensation flow	3.300	3.300	3.300	3.300	3.300	3.300	0.050	0.050	0.050	0.050	0.050	0
Recreation water delivered by pipeline	2.590	2.590	2.590	2.590	2.590	2.590	2.476	2.330	2.105	1.490	0.000	0
Wetland water delivered by pipeline	1.000	1.000	1.000	1.000	1.000	1.000	0.956	0.900	0.813	0.575	0.000	0
Growth water (off headworks or by pipeline)	17.650	17.650	17.650	17.650	17.650	17.650	16.875	15.881	14.347	10.153	8.123	0
Total	**82.570**	**76.970**	**71.370**	**68.570**	**61.570**	**54.570**	**49.198**	**46.479**	**42.280**	**30.800**	**25.938**	**0**
Coliban Water												
Total	**0.300**	**0.300**	**0.300**	**0.300**	**0.300**	**0.300**	**0.287**	**0.270**	**0.244**	**0.173**	**0.173**	**0**
Wannon Water												
Balmoral	0.120	0.120	0.120	0.120	0.120	0.120	0.115	0.108	0.098	0.069	0.069	0
Hamilton	2.000	2.000	2.000	2.000	2.000	2.000	1.912	1.800	1.626	1.151	1.151	0
Total	**2.120**	**2.120**	**2.120**	**2.120**	**2.120**	**2.120**	**2.027**	**1.908**	**1.724**	**1.220**	**1.220**	**0**
Environment (regulated)												
Northern Mallee Pipeline (NMP)	32.240	32.240	27.400	24.480	19.870	4.190	4.190	2.000	2.000	1.000	0.500	0
Wimmera Mallee Pipeline (WMP)	8.320	8.320	8.320	8.320	8.320	8.320	7.955	7.486	6.763	4.786	2.393	0
Total	**40.560**	**40.560**	**35.720**	**32.800**	**28.190**	**12.510**	**12.145**	**9.486**	**8.763**	**5.786**	**2.893**	**0**

PIPELINE SYSTEM OPERATION OPTIMISATION

Due to relatively low demand and restrictions in water use, the WMP is presently being operated well under its design capacity. A research program is currently underway to optimise the performance of the pipeline system to allow adaptation to the low demands and other scenarios.

In order to optimise pipeline system performance a mathematical model of its operation is developed using an optimisation approach. The main components of such an optimisation model are objective and constraint functions. The objectives can be, for example, the minimisation of pumping cost, total operational costs, water treatment costs, maintenance costs etc. The main decision variables include pump pressures, pump operation schedules (either on or off), amount of chemicals used to treat water, maintenance schedule etc. The main constraint functions include restrictions on decision variables (for example, upper and lower bounds for pressures on each pump), customer demands and the governing hydraulic equations.

The resulting optimisation problem is multi-objective and contains both integer (scheduling of pumps) and continuous (such as pressure) variables, and the number of variables may be very large. To solve such a complex optimisation problem, it is reduced to a single objective function problem, for example the minimisation of pumping costs. The other objective functions are then reformulated as constraint functions. This approach has been used to model the optimisation of the performance of a similar pipeline system north of the WMP called the Northern Mallee Pipeline (Bagirov *et al.*, 2008).

These optimisation problems, which are known as mixed integer nonlinear programming problems, are most difficult to solve. In the research program underway new algorithms are being developed for solving these specific optimisation problems together with integrating the optimisation solutions to dynamic hydraulic models. It is anticipated that the integrated use of optimisation and hydraulic models will allow for improvements in pipeline system operation efficiency.

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