Benefits of improving water use efficiency

A case study within the Murrumbidgee Irrigation Area

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Government initiatives, toward more efficient allocation and pricing of water, including trade in water entitlements and the allocation of water for the environment, are expected to increase the opportunity cost of irrigation water in the future. More efficient water application technologies, water management practices and water reuse and on-farm storage are means of moderating the negative impacts of higher water values on farm incomes. Increasing irrigation and water use efficiency can also result in higher farm incomes through the use of saved water on-farm and environmental benefits from reduced river diversion, groundwater accession and off-site pollution due to a reduction in runoff of contaminated water.

In this study, a modelling framework, which can be used to evaluate the impact of on- and off-farm options for increased irrigation and water use efficiency within an irrigation system, was developed. The model was specified for the Yanco and Mirrool irrigation areas of the Murrumbidgee Irrigation Area (MIA) and Districts system covering most irrigated agriculture in the MIA. The model has three linked components: the farms in the area, an off farm water delivery system and a water authority. Model solutions provide the optimal uniform price of water for all farms, the allocation of water between divisions and, within each division, the optimal allocation of resources between alternative production activities and, for each cropping activity the optimal mix of water application technologies.

There has been limited uptake of more efficient water application technologies and management practices in southern New South Wales regions. Flood/furrow irrigation is the main application method for all irrigated crops on broadacre and horticulture farms in the Murrumbidgee region. Most of the length of supply and delivery canals in the Yanco and Mirrool irrigation areas is clay lined with the rest being either concrete lined or piped. Approximately 14 per cent of the total length of the delivery canals in the Yanco and Mirrool areas are rated as of poor condition.

From rainfall and irrigation water, a total of 97,000 ML per year is estimated to runoff from the Yanco and Mirrool irrigation areas. However, all this water is not lost to the MIA and Districts system as it contributes approximately 70,000 ML of irrigation supplies per year to the Wah Wah and Benerambah irrigation districts, while the balance drains to the Murrumbidgee river. The Barren Box Swamp acts as an on-line facility to store and then reuse runoff water from the Yanco and Mirrool areas. However, with further inflows into the Barren Box Swamp of 66,000 GL per year of

water escaped from delivery canals and some other inflows, discharges from the Swamp to the floodway have become a frequent occurrence. The volumes of water drained to the Murrumbidgee River and released to the floodway can be reduced by the use of more efficient water application methods on-farm, investment in additional capacity on- and off-farm to store and reuse water, and investment in canal refurbishment. Adoption of more efficient water application technologies and management practices on-farm can also reduce groundwater accession.

The potential of three options available for the Yanco and Mirrool irrigation areas to use water more efficiently are analysed both separately and simultaneously. These options are: (1) twin furrow application for wine grapes and drip application for Navel oranges; (2) on- and off-farm storage systems for reuse of runoff water; and (3) relining of earthen and dilapidated concrete delivery canals. The impacts of each of these options and combinations of them on land use, the system-wide water balance and farm financial performance are evaluated.

Each of the options resulted in a decrease in water lost from the system and for unchanged river diversion an increase in the availability of water within the system. The increased availability of water resulted in reduced river diversion in all of the options and increased consumptive use in all options except the twin furrow and drip irrigation option. Based on model simulations, river diversions of up to 123 GL (15 per cent) can potentially be avoided annually by the introduction of the water saving options considered, with the magnitude of the savings increasing with higher water prices at farm gate. In the options where reuse systems were included separately and simultaneously with the other options, the total irrigated broadacre area increased from the level in the base case, and some additional water was used on-farm. The volume of irrigation water runoff decreased for all options except the refurbishment option, while in the twin furrow and drip irrigation option the groundwater accession also decreased. All the options in which canal lining was introduced resulted in lower seepage losses. As seepage and deep percolated water contribute to groundwater accession, any reduction in these volumes may have some external costs as much of the groundwater accession in the MIA represents inflows to aquifers and some environmental benefits if the deep percolated water is saline.

The on- and off farm storages built in the reuse option stored the water which would otherwise have been lost through discharges to the floodway and the Murrumbidgee river in the base case. In this option, the reduction in the availability of water for the Wah Wah and Benerambah irrigation districts further downstream did not exceed 7 per cent and the cost to users of the reduced water availability is estimated at $0.2 million a year. However, if this option is combined with the canal relining option, then the availability of runoff water for the Wah Wah and Benerambah districts may be affected as canal escape losses are eliminated.

The simulated options are estimated to have only a small impact on farm incomes under the currently prevailing values of water and commodity market conditions. The annual aggregate return to land, water and family labour in the MIA is estimated to increase by just 1.0-2.0 per cent under the twin furrow and drip irrigation and reuse options. Under the canal refurbishment option, the annualised cost estimated at $4.0 million exceeded the incremental benefit of $2.3 million a year.

The economic benefits of increased irrigation efficiency should include the value of all environmental and other benefits as well as the increased benefits on-farm. The environmental benefits come from reduced river diversion in some cases, groundwater accession if it increases the salinity of groundwater and off-site pollution due to a reduction in the volume of contaminated runoff water discharged to the district drains and the river.

Increasing irrigation efficiency may need policy measures if public benefits including all environmental and other benefits exceed private benefits for greater adoption of water saving technologies. Possible measures include subsidies for investments in water saving technologies. Some incentives in this direction are already available through the NSW Rural Assistance Authority’s Special Conservation Scheme.

The external cost of irrigation runoff and groundwater accession and the potential of water saving technologies to reduce these costs means that cost effective solutions to increase water use efficiency and reduce external costs need to be sought simultaneously.

1. Introduction

Concern over the sustainability of natural resource use and the efficiency of water use and delivery prompted the Council of Australian Governments (COAG), in 1994, to agree upon a set of water reforms. The reforms provided new rules for the allocation and pricing of water, including rules for trade in water entitlements and the allocation of water to the environment.

These reforms, in particular the cap on the volume of irrigation diversions in the Murray Darling Basin, reduce the volume of water available to irrigators and other water users. There are two ways that water use can adjust to the lower availability. First, water use can be reduced on farm, through the adoption of water saving technologies and efficient water management practices and through a change in farm activities. Second, the efficiency of water delivery off farm can be improved by refurbishing the water delivery system to reduce conveyance losses and equipping the system to meet the specific delivery requirements such as pressurised water delivery and en-route storages for the on-farm adoption of efficient water application technologies.

Many environmental benefits are obtained from improved irrigation and water use efficiency. The rise in water tables that contributes to waterlogging and salinity in some areas can be restrained through reduced accessions to the groundwater tables as a result of higher water use efficiency. Improved water use efficiency can also lower the movement of pesticides, nutrients and salt downstream, reducing damage to aquatic ecosystems and other downstream water uses.

Government initiatives to increase water use efficiency

In response to COAG's water reforms the states have initiated various packages to assist the reform process. In 1998, as part of its Water Reform Structural Adjustment Program, the New South Wales Government launched the Water Use Efficiency Incentive Scheme. Irrigators can also obtain loans of up to $100 000 to upgrade their irrigation systems through the NSW Rural Assistance Authority's Special Conservation Scheme if these works will provide environmental benefits (NSW Agriculture 2000).

Commonwealth tax deductions are also available for capital expenditure on farm improvements that conserve water and prevent land degradation, under section 75D of the Taxation Act (Neeson, Glasson, Morgan, Macalpine and Darnley-Naylor 1995 p.251).

The Queensland Government has introduced the Rural Water Use Efficiency Initiative in 1999 in partnership with industry to improve the use and management of irrigation water. Over four years $41 million will be allocated to programs to improve water use efficiency on farms, reduce water losses from on farm water storage, reduce water losses in water delivery systems and to provide financial incentives to encourage adoption of best practice irrigation management (Queensland Department of Natural Resources 2000).

The Water for Agriculture program implemented by the Victorian Government aims to promote private sector investment in sustainable irrigation projects and to improve water use efficiency in Victoria. The program is administered and funded by the Victorian Department of Natural Resources and Environment. Regional coordinating groups, including representatives from government, industry groups and water authorities, are preparing a development plan that indicates the potential for expansion of sustainable irrigated agriculture in their region. Funding is provided to each group for feasibility and land suitability studies.

Both commonwealth and state government authorities have also been funding research into water use efficiency. LWRRDC is a statutory body whose primary aim is to identify and fund research and development that will help maintain Australia’s natural resource base. LWRRDC commissioned ABARE to explore the extent to which the potential benefits of improved water use efficiency can be realised by wider adoption of currently available water use technologies and management systems.

The objective of this project is to estimate the potential benefits of increasing the efficiency of irrigation and water use at various stages in the on- and off-farm irrigation systems. To undertake this analysis ABARE has developed a model that is used to estimate the benefits of improving irrigation and water use efficiency in part of the Murrumbidgee Irrigation Area (MIA). Such a model could also be used to simulate water use in other regions of the Murray Darling Basin.

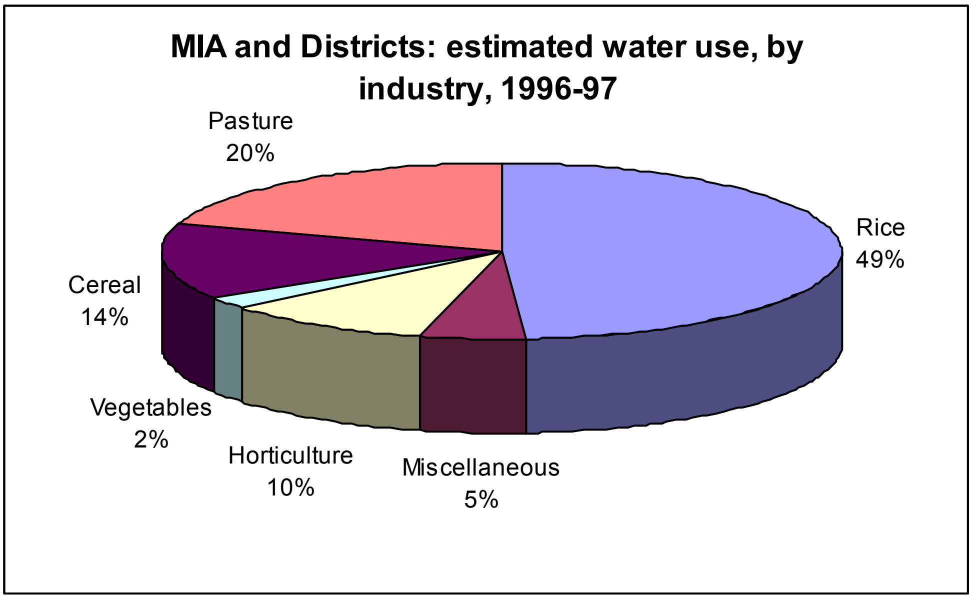
2. The Murrumbidgee Irrigation Area

The Murrumbidgee Irrigation Area and Districts are situated between the Lachlan and Murrumbidgee Rivers in south-western New South Wales, and consist of the Yanco and Mirrool Irrigation Areas, as well as the Benerembah, Tabbita and Wah Wah Irrigation Districts. Irrigated agriculture is an important contributor to regional revenue with the total irrigated output from this area estimated to be valued at around $325 million in 1997 (Hope and Wright 1999, p.48).

The Yanco Irrigation Area covers 1 173 farms in an area of around 89 000 hectares, two thirds of which is usually irrigated. There are over 1 200 farms in the Mirrool Irrigation Area, which covers an area of around 75 000 hectares, almost 80 per cent of which is usually irrigated. The main irrigated activities in the MIA are rice, coarse grains, pasture for livestock production and permanent horticulture principally citrus and wine grapes (Hope and Wright 1999, p.43).

Broadacre cropping is the predominant user of water for agricultural purposes, with rice using almost half of the water used by agriculture, followed by pasture at 20 per cent and cereals at 14 per cent (figure 1). Horticulture was estimated to use around 10 per cent of water used by agriculture. The MIA and District system also supplies a small proportion of total water use to rural towns and cities including Leeton and Griffith (Sinclair Knight Merz 1995, p.3).

Figure 1



The Yanco and Mirrool Irrigation Areas are run by Murrumbidgee Irrigation, with the Yanco Irrigation Area centred on the town of Leeton and the Mirrool Irrigation Area surrounding the city of Griffith. Water is supplied to farms via the Main Canal and connecting canal network after being diverted from the Murrumbidgee River at Narrandera. The volume of water that can be supplied through the system is dependant on the capacity of the canals, particularly at the choke points that restrict the volume of water that can be delivered, and the condition of the canals. Canal attendants control the distribution of water to farms, with each in charge of a division of 60 or more farms. Water flows to the farm boundary mostly by gravity, except for the Corbie/Merungle Hill Pumping Scheme. Regulating structures control the flows and levels in supply canals and Dethridge wheels measure the amount of water supplied to each farm. Irrigation supply canals in the MIA are of varying condition and the extent of losses from the system is partly influenced by the condition of the canals.

The main part of the MIA is drained by the Mirrool Creek, which eventually discharges into Barren Box Swamp, west of Griffith. The large surface area of the swamp contributes significantly to evaporation losses (Sinclair Knight Merz 1995, p.3). The Barren Box Swamp then supplies water to the Wah Wah Irrigation District (Neeson et. al 1995). The Barren Box Swamp acts as both a water storage, ensuring water is supplied downstream in periods of peak demands, and as flood protection. At times there can be an incompatibility between these different roles, as stored water may need to be released when there are flood concerns.

Adoption of water saving technologies and management practices

There has been limited uptake of alternative application technologies in the southern New South Wales regions. Flood/furrow irrigation is the main application method for all irrigated crops on broadacre and horticulture farms in the Murrumbidgee region. In 1996/97, for the average farm, 97 per cent of the area planted to pasture was irrigated by flood with the remainder being irrigated by either travelling irrigators or moveable sprays. Around 74 per cent of the horticultural area was irrigated by flood. The second most common irrigation system was drip irrigation system.

Most of the recent adoption of alternative irrigation systems, water use efficient cultural practices and efficient soil moisture management practices is occurring on horticultural farms (Sigred Tijs, CSIRO, personal communication, July 1999). Efficient soil moisture management practices and water use efficient cultural practices were seen as more applicable methods for large area farms to increase water use efficiency rather than changing the water application method. Water use efficient cultural practices such as laser levelling, beds, rows and square bays have been adopted on many broadacre farms (Hoare Cedric, Murrumbidgee Irrigation, personal communication, November 2000). A trend towards the use of efficient soil moisture management practices among the large area farms was reported (Sigred Tijs, CSIRO, personal communication, July 1999).

Nearly a half of the farms in the Murrumbidgee region in 1996-97 used some soil moisture monitoring tools. The runoff water from around 35 per cent of the total irrigated area in the Murrumbidgee region is fed into on-farm water reuse systems while the runoff water from the rest of the irrigated area is fed into to the Barren Box Swamp. The farms in the Wah Wah district reuse the runoff water collected and stored in the Barren Box Swamp.

For irrigated broadacre farms, most of the irrigated area has been landformed in some way, however only a small percentage was formed into beds and rows. Improvements in soil mapping through techniques such as EM31 and the use of laser levelling allows farmers to plan their farm layout to maximise water use efficiency. The farm layout is also important for the installation of water reuse systems to maximise water saving benefits.

Table 1 Length and condition of delivery channels within divisions of Yanco and Mirrool areas

	Division(s)	Earthen		Concrete		Piped		All	
		Length (km)	Condn 4-6 (%)	Length (km)	Condn 4-6 (%)	Length (km)	Condn 4-6 (%)	Length (km)	Condn 4-6 (%)
Yanco									
Main canal	2, 7-10,10a	228.9	7.7	38.6	21.7	7.0	0.0	274.4	9.4
Gogeldrie	4-6	95.3	14.6	4.0	39.4	0.8	0.0	100.1	15.4
South Gogeldrie	3	60.4	11.9	0.0	0.0	0.1	0.0	60.5	11.9
Total		384.6	10.0	42.5	23.4	7.9	0.0	435.0	11.2
Mirrool									
Main canal	4,10-12, 14-15	173.8	1.4	62.2	31.5	23.9	0.0	259.9	8.5
North Kooba	2	54.1	13.1	6.1	80.3	0.8	0.0	61.1	19.6
North Branch	3-5	36.1	6.6	22.3	33.7	5.0	0.0	63.4	15.6
Mirrool canal	6-9	129.5	27.4	19.7	43.6	4.0	0.5	153.3	28.8
Lake view	13	7.8	0.1	7.3	60.4	10.2	0.0	25.4	17.5
Total		401.4	11.8	117.7	38.3	44.0	0.0	563.1	16.4
MIA		786.0	10.9	160.3	34.3	51.9	0.0	998.1	14.1

There are 1000 kilometres of supply and delivery canals within divisions of the Yanco and Mirrool irrigation areas. The largest part (79 per cent by length) of the delivery canals found within divisions is clay lined (table 1). There are 86 kilometres of earthen canals (11 per cent) and 54 kilometres of concrete lined canals (34 per cent) rated as of poor condition (rated 4 to 6 inclusive). However, overall only 14 per cent of all the delivery canals found within divisions are rated as of poor condition.

Allocation of regulated water supplies

Water is delivered to irrigators in the MIA through a system of entitlements and allocations. There are seven types of water entitlements with two types namely high and normal security comprising the majority. Horticultural farms hold high security water entitlements to ensure that they are allocated 100 per cent of their entitlement in all years unless there is an extreme season. In each season, irrigators with normal security entitlements are allocated water equivalent to a percentage of their entitlement depending on the dam storage volumes in a year (McClintock, Van Hilst, Lim-Applegate and Gooday 1999).

In the past, the average annual allocations ranged from 78 per cent to 120 per cent, and averaged around 102 per cent (McClintock et. al 1999). However allocations are not to exceed 100 per cent under the cap on diversions for irrigated agriculture in the Murray Darling Basin, introduced in July 1997.

In the past, in addition to the water available to individual irrigators under their entitlements, they may have had access to ‘supplementary’ water supplies in a season when excess water was available. However, the availability of ‘off-allocation’ water is likely to be limited in the future following the introduction of environmental flows for rivers in the Murray Darling Basin (New South Wales Agriculture 1996).

In 1999 there were 345 GL of normal security entitlements for the Yanco Irrigation Area and 68 GL of high security entitlements. In the Mirrool Irrigation Area there were 278 GL of normal security entitlements and 175 GL of high security entitlements in the same year (Hope and Wright 1999 p.26). Water entitlements can be traded in the MIA on a permanent or temporary basis, although there are restrictions on certain types of trade and overall quantities (ABARE 1999).

Irrigators in the MIA pay both fixed and volumetric delivery charges. The variable charge for each irrigator is dependent on whether their water use is higher than their entitlement (such as when ‘off-allocation’ water is purchased). For example in 1995-96 the variable charge was $10.37 per megalitre, but for irrigators that used more water than their entitlement the variable charge rose to $13.12 per megalitre

(McClintock et al. 1999). Additionally, variable water charges change each year according to aggregate water use. If aggregate water use is lower in a particular season then the per unit charge for water is higher and vice versa (McClintock et al. 1999). The fixed component of water charges was estimated to be $480 per farm on average in 1995-96 (McClintock et al. 1999).

On farm water losses

The volume of water lost from farms through runoff and sub surface drainage can be highly variable depending on seasonal conditions. Water balance studies carried out for the NSW Land and Water Management Plan estimate that in a normal year a total of 97,000 ML of both irrigation and rain water is runoff from the farms in the Mirrool and Yanco irrigation areas (Morgan and Glasson 1995). Large area farms contributed 81 per cent of this runoff volume with the remainder being accounted for by the horticultural farms. Irrigation runoff contributes 71 per cent of the total runoff from large area farms compared to 82 per cent from horticultural farms. The total volume of irrigation water runoff from Mirrool and Yanco areas in an average year is estimated at 71,000 ML. The introduction of the cap, the environmental flow rules and a drainage-withholding period for rice paddocks may have reduced the volume of irrigation water runoff in recent years.

The runoff water from the southern part of the Yanco area is drained by the Yanco Main Southern Drain and the Gogeldrie Main Southern Drain in to the Murrumbidgee River. The total volume of runoff water discharged through these drains into the river averaged 28,000 ML a year over the 10 years to 1990-91 (Sinclair Knight Merz 1995).

The runoff water from the northern part of the Yanco irrigation area is drained by Little Mirrool Creek which later joins the Mirrool Creek while drainage water from the Mirrool irrigation area flows directly in to Mirrool Creek. Some water is then taken from Mirrool Creek to be supplied to farms in the Benerembah irrigation district, before the remainder is discharged into the Barren Box Swamp.

The Yanco and Mirrool irrigation areas also yield approximately 34,000 ML of net groundwater accession both from irrigation and rain fall (Morgan and Glasson 1995). Part of the sub surface drainage in horticultural farms is drained by tile drains, which also intercept some of the groundwater inflows occurring under these farms. The tile drains are estimated to discharge annually around 12,000 ML of water to the Barren Box Swamp.

Water losses from the delivery network

Off farm delivery losses occur through seepage, leakage, evaporation and escapes from delivery canals. Seepage losses occur mainly from earthen and dilapidated concrete lined canals. The rate of water loss through seepage depends on canal dimensions particularly water depth and wetted perimeter, groundwater level and the hydraulic conductivity of the soils. The water depth determines the hydraulic head and the groundwater level determines the hydraulic gradient between the canal bed and the groundwater table. If the groundwater level is high, the seepage losses may be negligible. Canal seepage losses from the MIA and District system are estimated to be around 18,000 ML a year (Sinclair Knight Merz 1995). Leakages result from overtopping of canal banks due to cracking of the banks, blowouts and yabby holes and when canals are filled at the start of the irrigation season and from around structures such as regulators. All leakage losses are estimated to add up to around 5,000 ML a year for the MIA (Sinclair Knight Merz 1995). The evaporation losses from canals are a function of temperature, relative humidity and the surface area of canals. Evaporation losses from canal surfaces can be substantial, particularly at high temperatures in the summer. The total canal evaporation losses are estimated to be around 13,000 ML a year (Sinclair Knight Merz 1995). Escapes from canals result when water is conveyed at flow rates in excess of supply system’s design capacity. Expansion in irrigated agriculture in the recent past in the MIA has resulted in demands for water in excess of the supply system capacity (Neeson et al. 1995). The unused capacity of the canals in times of peak demand has been progressively diminished resulting in an increase in the frequency of escapes from canals. The total volume of water lost through escapes is estimated at 66,000 ML a year (Neeson et al. 1995).

Reuse of drainage water

The Barren Box Swamp acts as an on-line storage for drainage water coming from the Mirrool and Yanco irrigation areas. The water stored in the Barren Box Swamp is reused as the Wah Wah irrigation district is supplied with regulated releases from the this swamp. The Benerambah irrigation district is supplied with irrigation water taken from the Sturt Canal with supplementation from Mirrool Creek. Based on the estimates discussed under on-farm losses, irrigation and rainfall runoff from Mirrool and Yanco Irrigation areas contribute approximately 70,000 ML a year to the irrigation supplies for the Wah Wah and Benerambah irrigation districts.

The Barren Box Swamp has a storage capacity of around 85,000 ML with overtopping occurring at 98,000 ML (Neeson et al. 1995). However, the Barren Box Swamp's licensed flood operation guidelines require discharges to commence at a storage level of 65,000 ML (Hoare Cedric, Murrumbidgee Irrigation, personal communication, December 2000). The main purpose of the Barren Box Swamp is to provide on-line storage for the Wah Wah irrigation district. In addition to the runoff water and canal escapes from the Yanco and Mirrool areas, the Barren Box Swamp also receives annually around 4,000 ML of water drained from urban areas.

Due to the expansion of irrigated agriculture in the MIA and improved on-farm drainage, the storage capacity of the Barren Box Swamp has fallen short of that required to store all the inflows. Consequently, releases to the Mirrool Creek Floodway have become a frequent occurrence with an estimated 43,000 ML of excess water released annually to the Mirrool Creek Floodway in recent years (Neeson et al. 1995). In an average year, the volume of water discharged to the floodway from the Barren Box Swamp is estimated to be 25,000 ML in excess of the capacity of the floodway. The cost of flooding of the land along the floodway is estimated at $473,000 a year in 1995. After netting out the benefits to some farms, which access the floodwater for irrigation, the net cost of flooding is estimated at $378,000 a year (Neeson et al. 1995). Most of the water spilled to the floodway is lost through seepage and evaporation while some water finds its way to the Lachlan River. The water lost through seepage may cause some environmental damage due to groundwater accession. Besides, being a relatively shallow storage with a large surface area the Barren Box Swamp contributes to significant evaporation losses estimated at 46,000 ML a year in 1995.

Potential water savings

All the water lost through seepage, groundwater accession, evaporation, discharges to the river and the floodway constitute water lost to the overall MIA and Districts system. The specific sources of these losses are: net groundwater accession from irrigation, seepage and evaporation from delivery canals, evaporation and releases from the Barren Box Swamp to the floodway and the water drained to the Murrumbidgee River from the southern part of Yanco irrigation area. The volumes of water drained to the Murrumbidgee River and released to the floodway (amounting to 71,000 ML a year) can be reduced by investing in additional storage capacities on- and off-farm for reuse of this water without an adverse impact on the supplies available to the districts. Adoption of efficient application technologies and management practices on-farm has the potential to reduce groundwater accession (which currently amounts to 34,000 ML a year) and the volumes of water released to the floodway and the Murrumbidgee river through reduced surface runoff from irrigation. The seepage and evaporation losses from the delivery canals (which currently amount to 21,000 ML a year) can be reduced by replacing earthen and dilapidated concrete canals with pipes. Refurbishment of delivery canals also has the potential to reduce escape losses (which currently amount to 66,000 ML a year) and thereby reduce the volume of water that needs to be released to the floodway.

Impediments to increasing water use efficiency

Physical, economic and institutional factors as well as risk affect the adoption of water saving technologies. Policies to influence the adoption of water saving technologies and other management practices need to focus on the institutional factors while considering the physical constraints.

The physical constraints relate primarily to the quantity and quality of the land in a particular region and access to different sources of water. The types of technology finally adopted will be heavily influenced by the soil type, and the suitability of farming activities to different water application technologies and practices and the form of delivery network in each region. For example, trickle/drip systems are more appropriate for heavier clay soils and micro sprays are more appropriate for lighter, sandier soils. The overall availability of water, both surface and groundwater relative to the availability of land can influence a farmer's decision to invest in water saving technologies. For instance, if the water market is not functioning well, a large farm with relatively less water available may find the adoption of water saving technologies more attractive than a small farm with relatively more water available. Further, wider availability of alternative sources of water (such as allocation, off-allocation, groundwater and reuse water) will lower the rate of adoption of water saving technologies. The availability and cost of labour is also important as some management practices (such as runoff monitoring and adjusting irrigation timing) may involve the substitution of labour for water in order to increase water use efficiency.

Once a farmer has invested in an expensive application technology such as an overhead spray or micro irrigation system and provided that crops are irrigated after closely monitoring the soil moisture levels, water will be saved every year whether the saved water is used or not. The stochastic nature of water supplies could influence the adoption of such water saving technologies.

Economic factors, such as commodity prices, the availability of finance, and changes in the costs of other inputs with the adoption of water saving technologies, will also have an influence. However, farmers or policy makers in an irrigation region are unlikely to be able to directly influence these factors.

Policy makers are able to have the most influence over institutional factors that can directly affect the adoption of water saving technologies and practices. The overall institutional setting faced by the irrigators affects their incentives to adopt water saving measures. These factors include the water charging policy, the lack of well functioning water markets and the type of irrigation delivery infrastructure and capacity constraints.

Higher water prices, combined with well functioning water markets, will improve the private benefits of adoption of water saving technologies within physical constraints on farms. Improved irrigation efficiency could allow irrigators to maintain existing areas of irrigated activities while releasing water for other purposes. However, if there are restrictions on the sale of water, except for large farms with low water supply the economic incentive for farms to adopt water saving technologies is reduced.

3 Options to improve irrigation and water use efficiency

A combination of both on- and off-farm water saving options can be considered for adoption as there are water savings to be made both on- and off-farm in the Yanco and Mirrool irrigation areas.

The following options are considered:
- changing the irrigation application technology to a more efficient system;
- reuse of both irrigation and rainfall runoff water by installing water reuse systems;
- adopting efficient soil moisture management practices for crops;
- investment in landforming, including laser levelling of paddocks, removing contour bays etc;
- refurbishment of off-farm delivery infrastructure.

Efficient application systems

On-farm water use efficiency can be improved by moving to a more efficient irrigation system. There are three main types of irrigation systems available: flood/furrow irrigation, overhead spray irrigation and micro irrigation (microjet and drip systems). The furrow irrigation system is the cheapest irrigation system available, in terms of capital cost but is generally considered to have the lowest water use efficiency. This type of irrigation on land with poor soil structure may cause increased surface runoff and excessive deep percolation. Overhead spray irrigation uses water more efficiently than flood irrigation. However, the performance of an overhead spray system is strongly influenced by wind conditions (Neeson et al. 1995, p.254). The application of water can be precisely controlled with an overhead spray system so that losses due to soil variations, slope and row length are reduced. Micro-irrigation (including both microjet and drip systems) is the most water use efficient irrigation system as it allows precise amounts of water to be applied to each row, or each plant. As it can aid in the adoption of precision irrigation techniques such as partial root zone drying (PRD), micro irrigation can also result in the improvement of the quality of fruits produced on horticultural farms. Micro-irrigation can achieve better water distribution in windy conditions. Other advantages of a micro-irrigation system are low energy requirements, reduced deep percolation, minimal surface runoff and potentially lower labour requirements as the system can be automated. The micro-irrigation system is also particularly useful on sandy soils, which have a low water holding capacity, as low volume but more frequent applications are possible (Neeson et al. 1995, p.60, 254, 255).

Alternative water sources

The two alternative water resources available are groundwater and irrigation and rainfall runoff collected in farm dams. Collection of rainwater is controlled in New South Wales under the Farm Dam Policy introduced in January 1999 (NSW Department of Land and Water Conservation 1999). Under this policy unlicensed dams can only collect 10 per cent of rainfall runoff from properties and the dams must be licensed if more rainwater is to be collected. However, the farms in the Western Division, which includes the Murrumbidgee Irrigation area, are exempted from this licensing requirement due to unique climatic conditions (NSW Department of Land and Water Conservation 1999, p.3). In the Murrumbidgee Valley it was estimated that only around 67 irrigators used groundwater in 1994. Even though groundwater use is regulated, the volume of groundwater used has traditionally been less than the volume allocated, but with usage increasing over time (Hope and Wright 1999, p.54 - 56). However, a sustainable yield policy operates in the MIA protecting groundwater from excessive draw down to avoid damage to the environment and other resources. Groundwater in the area is commonly used for livestock and domestic purposes, and all bores in the MIA must be licensed and have a volume entitlement (Hope and Wright 1999, p.53).

Efficient soil moisture management practices on-farm

Efficient soil moisture management practices include use of soil moisture monitoring tools and scheduling irrigation to avoid over watering and deficit irrigation in times of limited water availability.

Irrigation scheduling involves determining and maintaining a soil moisture range between which the crop will perform best including measuring soil moisture at different periods in time and predicting when the crop will need irrigating and with how much water. Irrigation scheduling is thus important to avoid over or under watering. Soybean yields can be reduced by as much as 30-50 per cent if there is moisture stress during the pod setting and filling stage (Neeson et al. 1995, p.3).

When the available water is limited, the trade off between its application to a crop during a critical growth or reproductive stage and other less critical growth stages can be considered in farm management decisions. In a multi crop situation, deficit irrigation schedules for each crop can be combined to develop a schedule for sequencing irrigation, where trade offs between applying different volumes of water during a particular growth stage of a crop are compared with those for another crop.

Land forming for flood irrigation

The three main landforming options used for flood irrigation by broadacre farms in the MIA are: non land formed contour bays, land formed contour bays and land formed border check.

- A non land formed contour bay is land that has not been laser levelled. This is the least water use efficient option as the non uniform slope of the land can result in both under and over irrigation of parts of the same crop.

- Moving to a land formed contour bay would improve on farm water use efficiency. Contour layouts involve a number of bays situated across the slope of the land, which are irrigated through the sequential ponding and draining of contour bays from the highest to the lowest bay. Obtaining high water use efficiency is generally difficult with the contour layout because of the slow filling and drainage from bays. However, drainage and irrigation times can be improved on the better-designed contour layouts. Given the constraints due to the physical set up, the highest efficiency achievable on this layout is 70 per cent (Neeson et al. 1995, p.134).

- Border check layouts incorporate bays that extend down the slope of the land. This layout is suitable for all crops, provided the slope is sufficient. If bays are set at an appropriate length and best management practises and irrigation scheduling are adopted then an irrigation efficiency of 80-85 per cent is achievable with a border check layout. The appropriate length depends on the type, structure, water holding capacity and permeability of the soil and the delivery rate of irrigation water (Neeson et al. 1995, p.135).

Canal refurbishment

Off-farm losses through seepage, leakage and escape can be lowered by refurbishment of canals through clay, concrete or plastic lining. Alternatively canals can be replaced with pipes to eliminate all of these losses. The remote monitoring of canal levels is another possible method to avoid escapes, although this is more applicable for larger capacity canals.

A combination of options

It should be noted that adoption of efficient application technologies and management practices on-farm can reduce irrigation runoff and thereby reduce the size of the storage capacity required to store and reuse both remaining irrigation and rain fall runoff water if these two options are to be adopted jointly. As refurbishment of canals can potentially eliminate escapes, the combination of this with other options may even lead to a reduction in supplies for the Wah Wah and Benerambah districts, that would necessitate Murrumbidgee Irrigation to increase canal deliveries to those districts. This may be both economically and environmentally attractive to these districts as they would then receive canal water instead of drainage water, that is contaminated with salt, herbicide residues and nutrients.

4. A model of the Murrumbidgee Irrigation Area

The model developed for a part of the Murrumbidgee Irrigation Area incorporates the Main canal and the major branch canals and represents 2400 farms grouped into 26 existing irrigation divisions of the MIA and District system covering most irrigated agriculture in the Yanco and Mirrool areas (figure 2). The model has three linked components: the farms in the area, an off farm water delivery system and a water authority. The price of water at farm gate represented in the model is the same for all divisions and is equal to the sum of the external price of water represented by the price of temporary water entitlement (TWE) outside the system and a uniform delivery charge. A uniform delivery charge means that charges to individual farms do not reflect the differences in conveyance losses between farms due to location. Model solutions provide, the allocation of water between divisions and, within each division, the optimal allocation of resources between alternative production activities and, for each cropping activity the optimal mix of water application technologies. This is achieved by maximising the sum over the whole irrigation system, the annual gross margin on all farms less the sum of the annual value of water purchased, rent to water, rent to canal capacity constraints and all annual rents plus the value of all evaporation, seepage and escape losses. An algebraic representation of the model is given in Appendix B

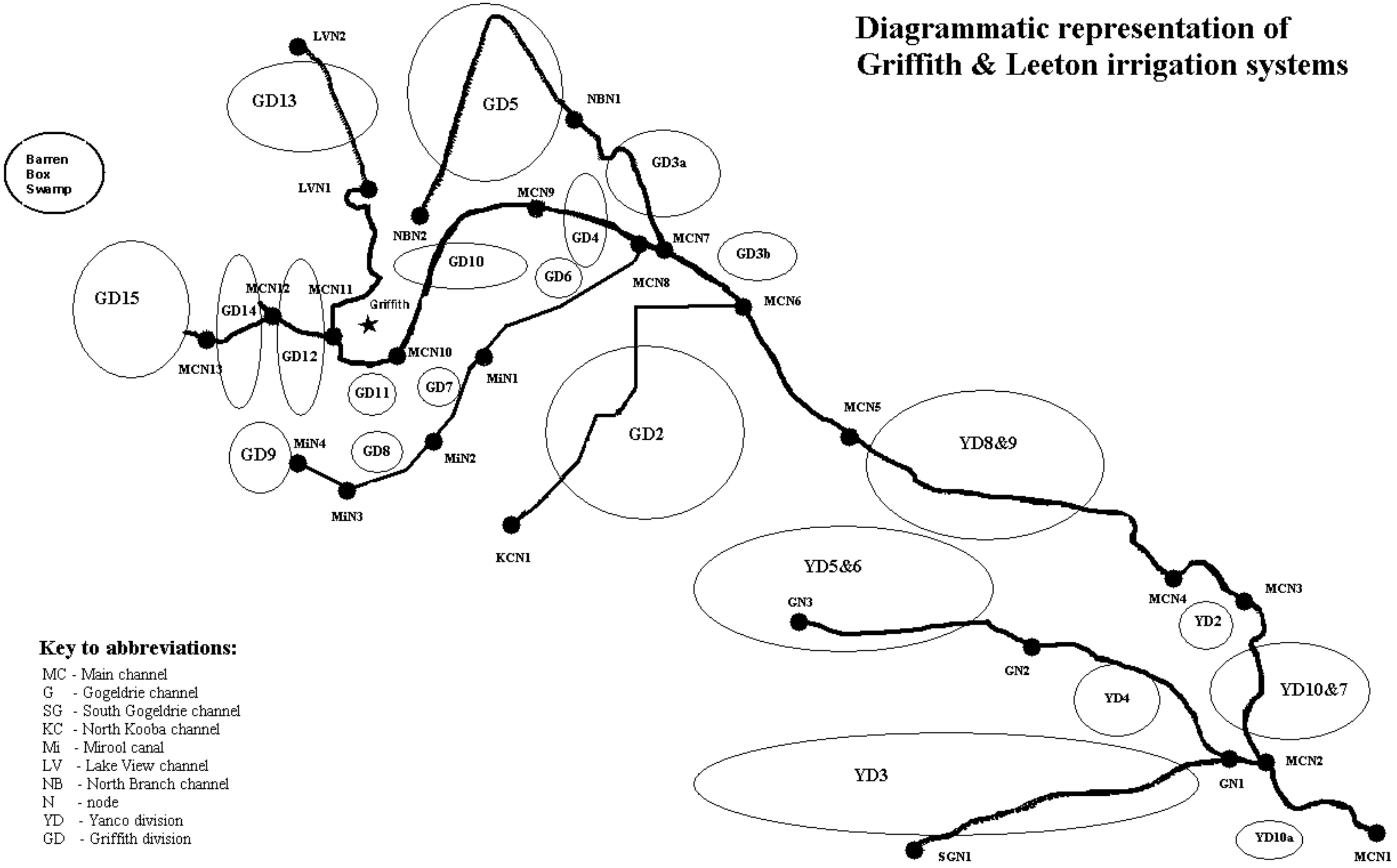
On-farm component

The on-farm component of the model chooses for each division and for a given set of technical and economic parameters the optimal combination and the levels of cropping and livestock activities and for each cropping activity the optimal mix of water application technologies subject to a set of constraints. For each division, the set of constraints specified includes constraints on the quantity and quality of land available, the quantities of family labour and alternative sources of water namely reuse and groundwater. The economic parameters in the on-farm component include, prices of crops and livestock commodities, variable input cost, annualised cost of water application technologies, annualised investment cost of storage built for the reuse system, cost of pumping to deliver water to the reuse storage and to pressurise water for drip irrigation. Technical parameters include irrigation requirements for a normal, a wet and a dry year for each crop derived by netting out rainfall and capillary rise from the potential evapotranspiration requirement. A set of runoff, deep percolation and capillary rise coefficients is used to calculate net water losses from irrigation. The reuse system when chosen stores both rain and irrigation runoff water to be reused on- or off- farm. The deficit in the potential evapotranspiration requirement after taking into account of rainfall, capillary rise and the runoff water that can be profitable reused is met by irrigation water from the off farm delivery system.

Off-farm delivery system

Water is diverted from the Murrumbidgee River at the Berembed Weir at Narrandera. The upstream part of the canal network that includes the Main canal and major branch canals up to the individual divisions is represented in the model in detail. The downstream delivery canals found within each division are represented simply by a conveyance loss rate that is estimated based on the type, condition, length and demand flow rate of each of the canal segments (table 2). The microcosm of the off-farm delivery network within each division, totalling 1000 kilometres in length, is not represented in the model in order to keep it to a manageable size. Parts of the MIA off-farm delivery network included in detail are the full length of the Main canal (120km) and the Gogeldrie, South Gogeldrie, North Kooba, Mirrool, Lake View and North Branch canals, all of which add to 275km. The canal network represented in the model keeps track of water flow after conveyance losses, and off takes from divisions at different nodes are accounted for. Refurbishment options are considered only for those canals found within divisions. Cost estimates of refurbishment options are used as well as estimates of the transmission loss rates after refurbishment.

Diagrammatic representation of Griffith & Leeton irrigation systems



Key to abbreviations:

MC - Main channel
G - Gogeldrie channel
SG - South Gogeldrie channel
KC - North Kooba channel
Mi - Mirool canal
LV - Lake View channel
NB - North Branch channel
N - node
YD - Yanco division
GD - Griffith division

Table 2 Specification of the Yanco and Mirrool irrigation systems included in the model

Primary Secondary Tertiary	Reach No	Division(s) included	Channel capacity (Ml/day)	Horticulture land (Ha)	Broadacre irrig. land (Ha)	Broadacre dry land (Ha)
Yanco						
Main canal	Reach 1	Yanco 10a	6500	144	153	147
Gogeldrie	Reach 1		1600	0	0	0
South Gogeldrie	Reach 1	Yanco 3	600	61	10904	5422
Gogeldrie	Reach 2	Yanco 4	900	735	1580	1144
Gogeldrie	Reach 3	Yanco 5 & 6	750	819	16991	8807
Main canal	Reach 2	Yanco 10 & 7	4700	1868	2873	2345
Main canal	Reach 3	Yanco 2	4600	337	1581	949
Main canal	Reach 4	Yanco 8 & 9	4500	400	20947	10556
Total			6500	4364	55029	29370
Mirrool						
Main canal	Reach 5		3000	0	0	0
North Kooba canal	Reach 1	Griffith 2	700	562	6707	3181
Main canal	Reach 6		3000	0	0	0
North branch canal	Reach 1	Griffith 3	400	1226	893	0
North branch canal	Reach 2	Griffith 5	309	1171	4732	2583
Main canal	Reach 7		3000	0	0	0
Mirrool canal	Reach 1	Griffith 6	1500	543	2884	1500
Mirrool canal	Reach2	Griffith 7	661	1453	677	932
Mirrool canal	Reach 3	Griffith 8	425	1546	674	811
Mirrool canal	Reach 4	Griffith 9	228	624	4769	2360
Main canal	Reach 8	Griffith 4	1500	1138	924	903
Main canal	Reach 9	Griffith 10	1500	1289	887	952
Main canal	Reach 10	Griffith 11	1500	659	305	0
Lake view canal	Reach 1		220	0	0	0
Lake view canal	Reach 2	Griffith 13	220	1079	5394	2833
Main canal	Reach 11	Griffith 12	1500	1326	715	893
Main canal	Reach 12	Griffith 14	1000	2088	1132	97
Main canal	Reach 13	Griffith 15	500	278	8315	3761
Total			3000	14982	39008	20806
System total			**6500**	**19346**	**94037**	**50176**

Water authority

The water authority delivers water and charges each farm a uniform price, that includes a component to cover average delivery costs for the system. Trading of water between farms within a division is implicit in the model and at the optimum each farm equates the marginal value product of water to the price of water which is uniform across all farms. The total availability of water to the Yanco and Mirrool areas is constrained at the average annual allocation adjusted for net sales outside the system. In general, supply can be constrained by total water availability and delivery constraints at the Berembed Weir where the water is diverted from the Murrumbidgee River. If the farmers in the Yanco and Mirrool areas are allowed to trade water with other systems the uniform price solved for farms within these areas is aligned with the external price of water represented by the price of temporary water entitlement (TWE). Even though conveyance losses differ between farms due to location, uniform pricing means that charges to individual farms do not reflect the differences.

5. Options simulated

The main options available to horticulture farms are, changing the irrigation application technology from broad furrow to twin furrow or a micro irrigation system and adopting efficient management practices. Whilst micro-irrigation systems are the most water use efficient, the current state of the delivery infrastructure in the MIA may limit the extent of their adoption. Micro irrigation systems require sufficiently high and flexible flow rates delivered with some pressure head at more frequent intervals. The adoption of micro irrigation systems could be hindered, when water is available on an inflexible roster system and with a supply system, which is stretched to more than its limits and inadequately equipped to handle pressurised water delivery. However, with an investment in a pump on-farm, the pressure head of the water delivered can be increased to a level required for the successful operation of micro irrigation systems. Many existing pipe and riser systems in the MIA can only deliver 1 L/second whereas micro irrigation systems require water to be delivered at flow rates up to 3 L/second per outlet.

Inclusion of a runoff reuse system on many existing horticultural farms farm may not be practicable due to the relatively small size of the farm and the small volume of runoff water produced. However, off-farm storage of runoff water from a number of horticultural farms can be considered.

For broadacre farms, the main options are adoption of efficient soil moisture management practices, installing a water reuse system and land forming. The impact of the adoption of efficient soil moisture management practices can not be properly evaluated as the model used in the analysis does not incorporate trade offs between alternative options for intra-seasonal allocation of water to individual crops. The model chooses between alternative options of landforming. However, an option where a given area of land is switched to a more efficient lay out is not considered in this analysis. Such a switch might be profitable if the markets for high value annual horticultural crops were to improve. The study assumed that the current environmental constraint on rice area, market situations for annual horticultural crops and relevant government policies remain unchanged in the simulated options. Therefore, for broadacre farms inclusion of a runoff reuse option only is evaluated in this study.

Investment in upgrading or relining canals is more likely to be required where canals are in poor condition or where canals run through very sandy soils where seepage losses are greater. Canal lining with clay is the cheapest option. However, the seepage reduction is not as great as with other forms of lining. While piping is the most expensive option, more water is saved as all forms of losses are eliminated. Furthermore, piping also offers benefits to the environment as accessions to the groundwater table and waterlogging alongside canals do not occur. The spread of pests such as waterweeds through the system is also inhibited (Sinclair Knight Merz 2000). The benefits of upgrading off-farm delivery infrastructure need to outweigh the costs for the upgrade. In many instances, given the existing value of water, major infrastructure refurbishment is unlikely to be cost effective to private investors (Sinclair Knight Merz 2000).

The benefits of these options can be evaluated by simulating them individually or jointly. The performance of each of these options needs to be measured against that of a base case in which existing conditions within the MIA are represented. In summary, the following options were analysed.

(i) A base case
(ii) Adoption of twin furrow irrigation for wine grapes and drip irrigation for Navel oranges by horticulture farms.
(iii) Investment in water reuse systems both on- and off-farm.
(iv) Relining of earthen and concrete delivery canals of poor condition
(v) Simultaneous adoption of twin furrow irrigation for wine grapes and drip irrigation for Navel oranges by horticulture farms and on- and off-farm reuse systems
(vi) All three water saving options introduced simultaneously

Base case

The base case represents existing conditions both on- and off farms within the Yanco and Mirrool irrigation areas. The existing pattern of allocation of land between different cropping enterprises is represented, while for each crop, the most prevalent water application technology is assumed. Furrow irrigation is the main application technology on horticultural farms whereas flood-furrow irrigation is being adopted for broadacre crops. Only a few farms have adopted reuse systems, consequently both irrigation and rainfall runoff water is discharged to the district drains. As the Benerambah and Wah Wah districts are not included in the model all runoff water is assumed to drain out from the Yanco and Mirrool irrigation areas that are included in the model. The existing conditions of the delivery network in different parts of the system are represented with corresponding rates of conveyance losses and canal capacity constraints, particularly at known choke points. In the model, the average annual allocation of water for the whole system is assumed to be equal to the average annual diversion at the Berembed weir plus net sales of water out of the system. The flow requirements of irrigation divisions not represented in the model but supplied by the tail reaches of the main and the Mirrool canals are incorporated in the model. A water delivery charge of $13.00 per ML and an average Temporary Water Entitlement (TWE) premium of $20.00 per ML are assumed. Trading of water between farms within the system is implicitly assumed while the water authority charges a uniform delivery cost per ML regardless of the location of the farm. More details of these assumptions and the model parameters are presented in Appendix C.

Adoption of twin furrow and drip irrigation by horticulture farms

The twin furrow irrigation system, which is recommended for wine grapes has a smaller wetted area compared to the common broad furrow system and consists of 2 narrow furrows close to the vine rows instead of a single broad furrow. Under experimental conditions, the twin furrow system was found to have reduced water application for wine grapes by 40 per cent without any loss of productivity (Neeson 1995). The twin furrow system requires investment in an on-farm piped delivery system with a low head (3 metre) pump to pressurise water. The water is delivered through a riser and then twin taps to the head of each row at a flow rate up to 1.5 litre/second.

The drip irrigation system is considered only for Navel oranges as it can also help the farmer obtain better quality fruits which are sold at a premium price in the fresh fruit markets. With a drip irrigation system installed for Navel oranges, the farmer can adopt partial rootzone drying (PRD) technique to improve the quality of fruits in addition to increasing irrigation efficiency. However, a better quality fruit is obtained in this manner at the expense of some yield losses. The drip irrigation system is not considered for Valencia oranges as the fruit is sold at a relatively lower price to be processed into juice and any quality improvement is unlikely to demand a premium price. The Navel oranges account for approximately 30 per cent of the total area planted to oranges in the MIA.

In this option, the twin furrow irrigation system is included for wine grapes and drip irrigation system for Navel oranges in addition to the broad furrow application method included for all horticultural crops in the base case.

Investment in water reuse systems both on- and off-farm

Reuse of runoff either on-farm or off-farm involves collecting and storing irrigation and rainfall runoff water for immediate or later reuse. Both on- and off-farm storage for reuse are considered as on-farm storage may not be feasible on many existing horticultural farms. It is assumed that in each division, a storage capacity large enough to store up to a third of the runoff produced in the division would be built. The storage capacity for a division may comprise of a number of small on- and off-farm storages. The on-farm reuse system recommended by NSW Agriculture consists of a pump installed at one location of the farm where a large area of the farm drains and storage built at the highest point on the farm. The runoff water is pumped to the storage while the flow from the storage for reuse is gravity fed. Off-farm storage for runoff water from horticultural farms may be constructed on- or off-line to existing district drains. Inclusion of a reuse system on-farm entails a capital cost from $20,000 to $43,000 per farm as well as costs of operating the pump and maintenance of the system and loss of some productive land (table 3).

Table 3 Cost of adopting on-farm reuse systems

Storage size (ML)	Storage area (Ha)	Capital cost ($)	Pumping cost ($/ML)	Maintenance cost ($/year)
5	0.24	20,091	2.03	683
10	0.74	29,000	2.25	683
26	1.61	33,560	3.15	833
48	2.40	42,980	3.26	833

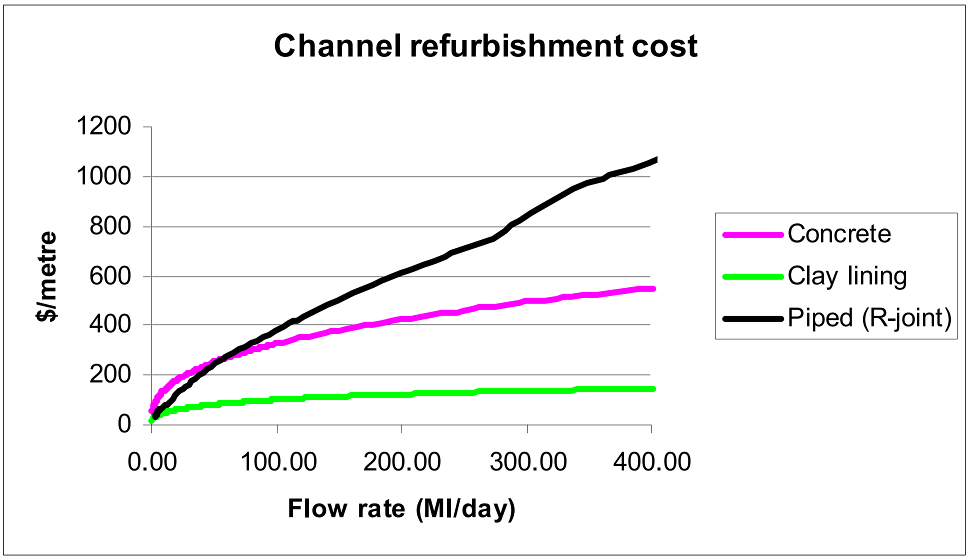
It is assumed that each storage built will be of 48 ML capacity. For each division, the model selects the optimal number of storages by taking into account the availability of runoff water and costs of investment given in table 3. The annual equivalent of the capital cost of $42,980 for a 48 ML storage calculated at a 7 per cent discount rate and a productive life of 30 years amounts to $3464. As few data are available on the cost of off-farm storage, the cost of supplying reuse water off-farm is assumed to be equal to that of on-farm.

Irrigation runoff coefficients for different crops given in Morgan and Glasson (1995) are used in calculating the volume of irrigation water runoff while rainfall runoff values for individual crops are derived as the difference between the total rainfall and the effective rainfall, which is used in crop evapotranspiration. The data on effective rainfall were obtained from New South Wales Agriculture (Austin Nicholas, New South Wales Agriculture, personal communication, February 2001). The model allows for evaporation losses of water stored with the evaporation rates increasing from 7 per cent in August to 17 per cent in January and December and then falling to 6 per cent in May. Seepage losses from the storages are assumed to be negligible, as they are likely to be located on land with low soil permeability. It is assumed that the volume of runoff water stored for reuse in the Yanco and Mirrool areas can not exceed a third of the total volume produced. In this manner adequate runoff water is made available for use by the districts while the runoff water lost to the system through releases to the flood way and the Murrumbidgee river is reduced. The impact of investment in reuse systems in the Yanco and Mirrool areas is assessed by comparing the system wide financial performance with that under the base case. A study undertaken in 1995 for the NSW Land and Water Management Plan found that the inclusion of on-farm reuse systems in the Yanco and Mirrool irrigation areas was not financially viable with a benefit cost ratio of less than 1. However, the same study found that the inclusion of reuse systems with storage capacities over 26ML was viable with rates of return of over 14 per cent when environmental benefits and costs were included (Neeson, et al. 1995). Another study (Hafi, Chapman and Van Hilst, 1998) found that the inclusion of reuse systems on dairy farms in the NSW Murray region was financially viable with a rate of return of around 10 per cent.

Relining of earthen and concrete delivery canals of poor condition

Only earthen and concrete canal reaches of poor conditions (rated 4 to 6 by the Murrumbidgee Irrigation) found within the divisions are considered for refurbishment. The canal reaches explicitly included in the model (table 2) are not considered for refurbishment as most of them are relatively large with design capacities of over 500ML/day. These primary canals in the system are more likely to be better maintained with regulated flow rates so that escape losses are kept to a minimum. Besides, the heavy capital expenditure needed to replace these largely earthen canals with concrete lining or pipe may not be justified as the total seepage and evaporation losses from the entire MIA system are just 3-4 per cent of the annual river diversion. The bulk of the 18,000 ML of seepage losses (estimated by Sinclair Knight Merz (1995)) could be assumed to occur from smaller canals located within divisions and not from the larger and deeper primary canals where the distance between the canal bed and the groundwater table (hydraulic gradient) is relatively small. On the other hand, the bulk of the evaporation losses could be assumed to occur from the larger primary canals, which are always filled with water and thus have a much larger surface area. Therefore, the smaller canals within divisions can reasonably be assumed to contribute to the bulk of the seepage, leakage and escape losses.

Figure 3



In choosing options for refurbishment of canals within divisions, in addition to their varying ability to reduce conveyance losses of different forms, the capital and annual maintenance costs also need to be considered. The capital cost of refurbishment of canals is estimated for different demand flow rates for each of the options considered (Appendix A). Concrete piping with rubber joints has the highest capital cost but requires very little maintenance, on the other hand clay and membrane lining of earthen canals have some of the lowest capital cost but relatively high maintenance cost (figure 3). As most of the concrete canals are located on lands with highly permeable soils, they would need to be refurbished with concrete lining or replaced with pipes. Given that the canals within divisions contribute to a small share of the annual 16,000 ML of evaporation losses from the entire MIA system, the option to replace them with rubber joint pipes was not considered because of its high capital cost. The option of relining earthen canals with clay was chosen largely for its low capital cost. In the process of refurbishment, these canals are also redesigned to meet the demand flow rates so as to reduce escape losses amounting to 66,000 ML a year.

6. The impact of increasing irrigation and water use efficiency

The impact of increased irrigation and water use efficiency is evaluated by comparing the simulated performance under each of the more water use efficient options with that of the base case. For each option simulated, the model produces results disaggregated by divisions. However, the results are presented for areas within the Yanco and Mirrool area by aggregating results of selected divisions. The areas identified and the canal reaches and divisions included are given in table 4.

Table 4 Grouping of divisions and canal reaches

Area	Reach No	Division(s) included
Yanco		
Main canal (up stream)	Reach 1-2	7, 10,10a
Gogeldrie	Reach 1-3	4-6
South Gogeldrie	Reach 1	3
Main canal (Down stream)	Reach 3-4	2,8-9
Mirrool		
Main canal (up stream)	Reach 5-8	4
North Kooba canal	Reach 1	2
North branch canal	Reach 1-2	3-5
Mirrool canal	Reach 1-4	6-9
Lake view canal	Reach 1-2	13
Main canal (Down stream)	Reach 9-13	10-11, 12-15

Base case

The base case is calibrated to represent as closely as possible the existing conditions both on- and off farm within the MIA system. The simulated allocation of land between different cropping enterprises given in table 5 reflects the constraints on land availability by layout categories, the annual allocation of water for the MIA, the canal capacity constraints at different reaches and the upper bounds on the area of individual crops. The simulated area under all irrigated broadacre crops was 85 per cent of the total irrigable broadacre area of 93,000 hectares, with the shortfall being accounted for by dry cropping. In both irrigation areas most of the irrigable land is used for broadacre cropping. However, the proportion of irrigable land under permanent tree crops is significantly greater in the Mirrool area (28 per cent) than in the Yanco area (7 per cent).

Table 5 Simulated area planted to crops under irrigation in the base case

	Rice (Ha)	Corase grains (Ha)	Oil seeds (Ha)	Veg (Ha)	Pasture (Ha	Broad-acre (Ha)	Citrus (Ha)	Vines (Ha)	Hort (Ha)
Yanco									
Main canal (Up)	784	1277	254	200	511	3026	1388	624	2012
Gogeldrie	4810	6572	2786	0	1659	15827	1072	482	1554
South Gogeldrie	2824	3729	1636	0	780	8969	42	19	61
Main canal (Down)	5835	7798	3379	0	1751	18763	509	228	737
Total	14253	19376	8055	200	4701	46584	3011	1353	4364
Griffith									
Main canal(Up)	268	456	166	0	34	924	364	774	1138
North Kooba	1945	2228	1057	150	562	5941	180	382	562
North Branch	1631	1882	1013	0	565	5091	767	1630	2397
Mirrool	2610	2874	1233	852	750	8319	1334	2832	4166
Lake view	0	1914	971	0	0	2885	345	734	1079
Main canal (Down)	3293	3949	2010	0	641	9893	1804	3836	5640
Total	9747	13303	6450	1002	2551	33053	4794	10188	14982
MIA	24000	32679	14505	1202	7252	79637	7805	11541	19346

The Yanco and Mirrool areas are estimated to use 77 per cent of river diversions to meet crop evapotranspiration with the balance being accounted for by conveyance losses (12 per cent), surface runoff (10 per cent) and net groundwater accession (2 per cent). However, these estimates do not take into account reuse of irrigation runoff and canal escapes coming from Yanco and Mirrool areas by the Benerambah and Wah Wah districts. The percentage of river diversions used consumptively could be higher for the overall system including these two districts. The Benerambah and Wah Wah districts are not included in the model and irrigation and rainfall runoff is assumed to drain out of the Yanco and Mirrool areas. The model tracks irrigation water entering the MIA system from the point of diversion by accounting for off takes by divisions and conveyance losses from successive canal reaches and delivery canals within divisions. For each canal reach represented in the model the simulated inflow, crop use, conveyance loss and outflow of irrigation water are presented in Appendix tables D1 and D2. In order to meet the flow requirements of divisions not represented in the model but supplied by the tail reaches of the main and Mirrool canals an additional 47 Gl of water is diverted annually increasing the total diversion to 832 Gl a year (table 6 and Appendix table D1). In December, the canal capacity at the Berembed Weir of the Main canal (6300 ML/day) was found to be binding.

Table 6 Simulated irrigation water balance in the base case

	Irrigation water GL/yr	Consumptive use (Gl/yr)	Surface runoff (Gl/yr)	Net accession (Gl/yr)	Conveyance loses (Gl/yr)	Application efficiency (%)	Convey-Efficiency (%)	System Efficiency (%)
Yanco								
Main canal (Up)	40	31	5	1	3	85	92	78
Gogeldrie	136	108	10	3	16	89	89	79
South Gogeldrie	62	50	4	1	7	91	88	80
Main canal (Down)	132	107	8	4	13	90	90	81
Total	370	296	27	8	39	89	90	80
Griffith								
Main canal (Up)	20	14	3	0	3	80	86	69
North Kooba	55	43	4	1	7	89	87	77
North Branch	67	49	8	2	8	83	89	74
Mirrool	109	81	13	2	13	85	88	74
Lake view	23	18	4	0	2	82	89	78
Main canal (Down)	141	102	18	2	18	84	87	72
Total	415	306	50	7	52	84	88	74
MIA	785	602	77	15	91	87	88	77

Crop and livestock production in the Yanco and Mirrool areas is estimated to return a profit of approximately $197 million a year to farmers. However, its distribution is skewed toward the Mirrool area with a total profit of 3 times that of the Yanco area (table 7). Despite a smaller share of the total farm profit (25 per cent), the Yanco area accounted for around 48 per cent of the annual volume of both river diversion and water applied to crops in the MIA. This is explained by the predominance of rice growing in the Yanco area, which accounts for around 59 per cent of the total rice area in the MIA. In contrast, broadacre cropping is less predominant in the Mirrool area with high value permanent horticultural crops accounting for a larger share of the available irrigable land (28 per cent compared to 7 per cent in the Yanco area). The above contrasting characteristics between the two irrigation areas explain the higher average returns per ML of water both diverted and applied to crops in the Mirrool area.

Table 7 Return to land and family labor in the base case

	Return to land and family Labour $m/yr	Average return to irrigation water[a] $/ML	Average return to water applied[b] $/ML
Yanco			
Main canal (Up)	12	267	291
Gogeldrie	17	116	131
South Gogeldrie	5	83	93
Main canal (Down)	14	100	111
Total	49	121	135
Griffith			
Main canal (Up)	10	469	546
North Kooba	9	156	181
North Branch	23	327	369
Mirrol	43	364	414
Lake view	10	403	451
Main canal (Down)	53	356	409
Total	149	335	383
MIA	197	234	265

a. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water diverted

b. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water applied

Benefits of increased irrigation efficiency

The overall benefits of increased irrigation efficiency are evaluated by comparing the simulated performance under each of the more water use efficient options with that of the base case. Apart from the returns to land and family labour, a number of other indicators can be used to compare performance under the various options. The volumes of river diversion, transmission losses and irrigation water deep percolated and runoff, but not reused after being applied to crops, and returns to water both diverted and applied to crops are the other measures reported in this study.

All of the more water use efficient options resulted in some increase in the availability of water within the system and a decrease in water losses to the system. A switch from broad furrow to more efficient twin furrow irrigation for wine grapes and drip irrigation for Navel oranges by horticulture farms (option 1) reduces the amount of water that need to be applied to meet crop consumptive demand with consequent reduction in runoff and deep percolation. Investments in on- and off-farm reuse systems (option 2) create an alternative source of water in addition to a reduction in the volume of runoff water discharged from the system. A reduction in transmission losses from canal refurbishment (option 3) means more water is available within the system and less water is lost through escapes, seepage and evaporation. When these three options are combined as in options 4 and 5, the overall impact on the system water balance will be determined by the interaction between the individual impacts of the first three more water use efficient options. If, in the base case, the availability of water after making allowance for transmission losses is less than the volume that need to be applied to crops to obtain the maximum profit from the system, then any of the other options will lead to more water being applied to crops.

Table 8 Irrigated cropping on broadacre land by options

	Base (Ha)	TF plus Drip (Ha)	Reuse (Ha)	Refurbish (Ha)	TF + Drip & reuse (Ha)	TF + Drip reuse & refurb (Ha)
Rice						
Yanco	14253	14253	14253	14253	14253	14253
Mirrool	9747	9747	9747	9747	9747	9747
Total	24000	24000	24000	24000	24000	24000
Coarse grains						
Yanco	19376	19376	19376	19376	19376	19376
Mirrool	13303	13303	13229	13217	13187	13187
Total	32679	32679	32605	32593	32563	32563
Oil seeds						
Yanco	8055	8055	8055	8247	8247	8247
Mirrool	6450	6450	6485	6538	6538	6538
Total	14505	14505	14540	14785	14785	14785
Vegetables						
Yanco	200	200	200	200	200	200
Mirrool	1002	1002	1002	1002	1002	1002
Total	1202	1202	1202	1202	1202	1202
Pasture						
Yanco	4701	4701	4755	4509	4565	4565
Mirrool	2551	2551	2583	2549	2583	2583
Total	7252	7252	7338	7058	7149	7149
Total						
Yanco	46584	46584	46639	46584	46641	46641
Mirrool	33053	33053	33046	33053	33058	33058
Total	79637	79637	79684	79637	79699	79699

The total irrigated broadacre area increased when reuse systems are introduced separately (Option 2) and simultaneously with other more water use efficient systems (Options 4 and 5) compared to the base case level largely due to the use of some of the saved water for irrigated cropping on those lands planted to dry crops in the base case (table 8). In these three options, despite an increase in the availability of water, total rice area remained unchanged at the base case level as the upper bound on the total rice area (24,000 ha) specified to represent the hydraulic loading (environmental) constraint had already been reached. In the reuse option, the sum of increases in the pasture and oilseed areas more than offset the decrease in coarse grain area. In the two options where reuse systems are introduced simultaneously with other more water use efficient systems the increase in oilseed area was more than offset by the sum of the decreases in coarse grain and pasture areas. In the refurbishment option, the total irrigated broadacre area remained unchanged at base case level as the sum of decreases in pasture and coarse grain areas offset the increase in oilseed area.

Table 9 Water balance by options for the Yanco and Mirrool areas

.

	Base (GL/yr)	TF plus Drip (GL/yr)	Reuse (GL/yr)	Refurbish (GL/yr)	TF + Drip & reuse (GL/yr)	TF + Drip reuse & refurb (GL/yr)
River diversions	785	782	732	764	715	662
Conveyance losses	0	0	0	0	0	0
Seepage	35	35	33	34	32	29
Escapes	55	55	51	0	50	0
Use of runoff water	0	0	0	0	0	0
Rain	0	0	46	0	46	46
Irrigation	0	0	36	0	31	31
Water applied to crops	694	692	730	731	710	710
Application losses	0	0	0	0	0	0
Runoff	77	65	41	83	46	46
Net accession	15	10	15	16	10	10
Evaporation from dam	0	0	6	0	5	5
Total loss	183	166	146	132	143	90
Savings in river diversions	0	3	53	21	70	123
Efficiency	0					
Conveyance (%)[a]	88	88	89	96	89	96
Application (%)[b]	87	89	91	86	91	91
System (%)[c]	77	79	80	83	80	86

a. percntage of water diverted which is finally applied to crops

b. percentage of water applied which is finally used to meet crop evapotranspiration

c. percentage of water diverted which is finally used to meet crop evapotranspiration

Table 10 Distribution of storage capacity for reuse of run off water

	Reuse		Reuse & TF + Drip		Reuse, TF + Drip & Refurb	
	Storage Capacity (GL)	Volume of water reused (GL/Yr)	Storage Capacity (GL)	Volume of water reused (GL/Yr)	Storage Capacity (GL)	Volume of water reused (GL/Yr)
Yanco						
Main canal (Up)	0.43	3.97	0.39	3.64	0.39	3.64
Gogeldrie	1.56	14.20	1.54	13.97	1.54	13.97
South Gogeldrie	0.85	7.67	0.84	7.66	0.84	7.66
Main canal (Down)	1.80	16.36	1.79	16.24	1.79	16.24
Total	4.64	42.19	4.56	41.51	4.56	41.51
Griffith						
Main canal (Up)	0.20	1.78	0.16	1.44	0.16	1.44
North Kooba	0.55	5.10	0.53	5.01	0.53	5.01
North Branch	0.64	5.87	0.55	5.17	0.55	5.17
Mirrool	1.10	10.10	0.96	9.04	0.96	9.04
Lake view	0.50	4.29	0.46	3.97	0.46	3.97
Main canal (Down)	1.39	12.64	1.18	11.01	1.18	11.01
Total	4.37	39.77	3.84	35.65	3.84	35.65
MIA	9.02	81.97	8.39	77.16	8.39	77.16

The volume of water diverted decreased in all more water use efficient options while the volume of water applied to crops increased in all of these except the twin furrow plus drip irrigation option compared to the base case levels (table 9 and Appendix tables D3 and D4). The volume of irrigation water runoff decreased in all except the refurbishment option. The increase in the volume of water applied to crops in each of the last two options where water saving technologies were introduced simultaneously was significantly less than the sum of the impacts of individual technologies when they were introduced separately. With much of the potential consumptive needs are met and both the total allocation of water and canal capacities becoming less binding the savings in river diversions increased significantly in the options where water saving technologies were introduced simultaneously. Reductions in the volume of water diverted and the losses both on- and off farm while maintaining or increasing the current level of consumptive use resulted in the increase in conveyance, application and system efficiencies (table 9).

In the reuse option, a total of 9 Gl of storage capacity is created to store an annual 82 Gl of runoff water for reuse within the MIA in addition to the existing 85 Gl capacity of the Barren Box Swamp located outside the MIA (tables 9 and 10). This is done after allowing 141 Gl of runoff water (41 Gl of irrigation and 100 Gl of rainfall) to leave the MIA to be stored in the Barren Box Swamp. The volume of runoff water stored within the Yanco and Mirrool areas in this option is only 15 per cent higher than the volume of water which would otherwise have been lost through discharges to the floodway and the Murrumbidgee river. In the reuse option, the availability of water for the Wah Wah and Benerambah irrigation districts further downstream is reduced by just 7 per cent or 10 GL a year. Using a TWE price of $20 per ML assumed in the model, the cost to water users in the Wah Wah and Benerambah districts of the reduced water availability is estimated at $0.2 million a year. The irrigation water escaped from canals constitutes a source of water for the two districts but the total volume of such escapes, which are eliminated in the refurbishment option, is less than the total volume of water discharged to the floodway and river. However, in the option where all three water saving options are combined, the elimination of canal escapes in addition to the reuse of run of water by the Yanco and Mirrool areas mean the availability of drainage water for the two districts may become insufficient to meet the requirement. In such an event, Murrumbidgee Irrigation may consider delivering some irrigation water to these districts.

In the reuse option, the storages were found to be emptied and refilled frequently as the inclusion of the reuse system had eased the canal capacity constraints in December leading to a decrease in the value of storing water over the spring months until December (table 10).

The sum of the seepage and evaporation losses from canals and the volume of water deep percolated from irrigation is estimated to decrease in all the options from the base case levels. As seepage and deep percolated water contribute to groundwater accession, any reduction in these volumes has external costs as much of these accessions represent inflows to aquifers storing useable water. In the Murrumbidgee Valley there were around 67 irrigators using groundwater in 1994 and the groundwater usage increased over time (Hope and Wright 1999).

The net economic benefits of increased irrigation efficiency should be estimated after taking into account the value of all such costs, other environmental benefits as well as the increased benefits on-farm. The environmental benefits come from reduced river diversion, groundwater accession if it is leading to increased salinity, off-site pollution due to a reduction in the volume of contaminated runoff water discharged to the district drains and river. In order to account for the environmental benefits and costs, an appropriate value for water, which reflects the value forgone by not using the water for the environment and all the costs of externalities including groundwater accession and off-site pollution should be used in the model.

A water price of $33/ML at farm gate assumed in the model is based primarily on the available data on traded values of water, which reflect the value of water mainly for agricultural uses while externality costs are assumed to be zero. For these reasons, in this study the financial benefits on-farm only are estimated with any savings of river diversions are valued at the assumed value of water. In the twin furrow plus drip irrigation and reuse options, the cost of technology is included in the analysis. However, in the refurbishment option, the estimated financial return also includes a return to investment in refurbishment of infrastructure, as the cost of this investment is not netted out from this measure. Therefore, an increase in this measure over the base case level does not necessarily mean that refurbishment of infrastructure results in increased net financial benefits. Given the large capital outlay involved and potential private and public benefits from refurbishment of infrastructure, a formula for recovering the cost of capital invested need to be developed. However, the cost of such capital and a mechanism for its recovery are not accounted for in the model.

The aggregate return to land, water entitlements and family labour in the MIA increased by $3.5 million in the twin furrow plus drip irrigation option from the base case level. In the reuse option, after netting out the cost to water users in the Wah Wah and Benerembah districts of reduced water availability, the aggregate return to land, water entitlements and family labour increased by $2.7 million per year. In the refurbishment option, the annualised cost of investment in canal lining estimated at $4.0 million exceeded the incremental benefits of $2.3 million a year. However, the incremental benefit (relative to the base case) in each of the last two options where water saving technologies were introduced simultaneously was less than the sum of the incremental benefits of individual technologies when they were introduced separately. With the introduction of water saving technologies existing canal capacity constraints became less binding and the value of these constraints decreased (table 11). The less binding are the canal capacity constraints, the smaller are the incremental benefit of a water saving option. Return to water diverted and applied to crops both increased in the twin furrow plus drip irrigation option as less water was diverted and water was applied to crops more efficiently. In the reuse option, return to irrigation water increased as less water was diverted but return to water applied to crops decreased as the area under marginally profitable crops increased with increased availability of water.

Table 11 Financial performance by options for the Yanco and Mirrool areas

	Base	**TF plus Drip**	**Reuse**	**Refurbish**	**TF+Drip & reuse**	**TF+Drip reuse & refurb**
	($m/yr)	**($m/yr)**	**($m/yr)**	**($m/yr)**	**($m/yr)**	**($m/yr)**
Profits before water and hired labour	206.52	208.31	209.02	209.15	209.61	209.61
Cost of upgrading land	0.12	0.12	0.12	0.19	0.19	0.19
Delivery charge on channel water	9.03	8.99	8.42	9.50	8.22	8.22
Cost of storing and pumping water	0.00	0.31	1.07	0.00	1.31	1.31
Cost of hired labour	0.00	0.00	0.00	0.00	0.00	0.00
Net farm profits	197.37	198.89	199.40	199.46	199.89	199.89
Off farm income	41.64	43.60	41.48	41.47	43.52	43.52
Return to land and family labour	239.01	242.49	240.89	240.94	243.41	243.41
Income from selling water outside	0.93	0.99	1.99	1.34	2.33	3.39
Return to land, family labour and water	239.94	243.48	242.88	242.28	245.74	246.80
Return to irrigation water ($/Ml)[a]	234.17	239.47	252.94	243.71	262.25	283.20
Return to water applied ($/Ml)[b]	264.70	270.69	253.66	254.90	264.11	264.11
Marginal value of channel constraints ($/Ml)	106.86	106.86	25.49	0.00	0.00	0.00

a. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water diverted

b. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water applied

7 Impact of higher water values

Due to past growth in diversions for irrigated agriculture, the lower reaches of the River Murray presently receive extremely low flows compared to pre development levels. The median annual flows in these reaches are now 20 per cent of the pre development levels and the frequency of drought-like flows occurring has increased to 60 per cent of years compared to 5 per cent of years prior to development. Reduced river flows have deprived the riverine environment of water. The range of environmental water use in the southern Murray-Darling basin includes the maintenance of river flow at some level and of seasonal flooding patterns needed by a number of native species.

The introduction of the cap and the environmental flow rules which are designed to maintain the river flow are expected to reduce the availability of water for irrigation resulting in the increase in the opportunity cost of water. In addition, if the costs of increased salinity in return flows and groundwater resources caused by irrigation are also internalised, the opportunity cost of water may increase further. Such an outcome is consistent with the COAG water reform process which promotes development of water pricing policies based on a more comprehensive estimate of total cost of delivery to encourage movement of water from low return and negative-environmental impact activities to high return activities.

In order to examine in detail the likely impacts of higher water values, the base case and all the other options were simulated again after increasing the farm gate price of water inclusive of delivery charge from \$33/ML to \$53/ML. In addition, in order to elicit the potential savings in river diversions at different water values, the base case and the combined twin furrow plus drip irrigation and reuse storage option were run at different TWE premiums ranging from \$0/ML to \$200/ML.

As expected, at higher water prices, consumptive use in the MIA decreased with the consequent reduction in diversions, as some cropping activities were no longer profitable. When the water value increased by \$20/ML with no water saving option introduced, the river diversion decreased by 44 GL/year (6 per cent) (tables 9 and 12). While the introduction of water saving options was able to reduce the negative impact of higher water values, it also reduced further the volume of water diverted. However, the potential reductions in diversion with the introduction of water saving options are lower at higher water values than at lower water values (tables 9 and 12). The highest possible savings in river diversion, which are obtained in the option where all three water saving options are introduced simultaneously decreased from 123GL/year to 119GL/year when the farm gate water price increased from $33/ML to $53/ML.

Table 12 Water balance by options at higher water values for the Yanco and Mirrool areas

	Base (GL/yr)	TF plus Drip (GL/yr)	Reuse (GL/yr)	Refurbish (GL/yr)	TF + Drip & reuse (GL/yr)	TF + Drip reuse & refurb (GL/yr)
River diversions	741	738	690	722	672	622
Conveyance losses	0	0	0	0	0	0
Seepage	33	33	31	32	30	28
Escapes	52	52	48	0	47	0
Use of runoff water	0	0	0	0	0	0
Rain	0	0	46	0	46	46
Irrigation	0	0	35	0	31	31
Water applied to crops	655	653	692	690	671	671
Application losses	0	0	0	0	0	0
Runoff	76	64	41	81	45	45
Net accession	10	6	11	11	5	5
Evaporation from dam	0	0	6	0	5	5
Total loss	171	154	137	124	133	83
Savings in river diversions	0	3	51	19	69	119
Efficiency	0					
Conveyance (%)[a]	88	88	88	96	88	96
Application (%)[b]	87	89	92	87	92	92
System (%)[c]	77	79	80	83	80	87

a. percntage of water diverted which is finally applied to crops

b. percentage of water applied which is finally used to meet crop evapotranspiration

c. percentage of water diverted which is finally used to meet crop evapotranspiration

At a water prices of $53/ML, with no water saving option introduced, the value of the reduced river diversion more than offsets the decrease in farm profits resulting in a slight increase in the aggregate return to land, water and family labour (table 13). The aggregate return to land, water and family labour increased with the introduction of water saving options with the estimated incremental benefits for all the more water use efficient options being higher than those at a farm gate water price of $33/ML.

Table 13 Financial performance by options at higher value for the Yanco and Mirrool areas

	Base ($m/yr)	TF plus Drip ($m/yr)	Reuse ($m/yr)	Refurbish ($m/yr)	TF+Drip & reuse ($m/yr)	TF+Drip reuse & refurb ($m/yr)
Profits before water and hired labour	204.68	206.47	207.23	207.17	207.71	207.71
Cost of upgrading land	0.12	0.12	0.12	0.12	0.12	0.12
Delivery charge on channel water	8.52	8.48	7.93	8.97	7.72	7.72
Cost of storing and pumping water	0.00	0.31	1.12	0.00	1.36	1.36
Cost of hired labour	0.00	0.00	0.00	0.00	0.00	0.00
Net farm profits	196.04	197.56	198.05	198.08	198.50	198.50
Off farm income	41.93	43.89	41.77	41.77	43.81	43.81
Return to land and family labour	237.97	241.45	239.82	239.85	242.31	242.31
Income from selling water outside	3.64	3.75	5.67	4.38	6.39	8.38
Return to land, family labour and water	241.61	245.21	245.49	244.23	248.70	250.69
Return to irrigation water ($/Ml)[a]	247.20	252.87	267.22	256.83	277.78	299.98
Return to water applied ($/Ml)[b]	279.41	285.82	266.30	268.71	278.03	278.03
Marginal value of channel constraints ($/Ml)	106.86	106.86	25.49	0.00	0.00	0.00

a. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water diverted

b. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water applied

The savings in river diversion to the MIA at different TWE premiums with and without water saving options are presented in figure 4. An outward shift in the supply schedule of saved water with the introduction of water saving technologies means it costs less to bid water away from the MIA if water saving technologies are introduced. However, the actual cost of bidding water away from the MIA could be higher if there are institutional restrictions on selling water to other regions and if the existing market situations for high value vegetable crops were to be improved – for example – if new markets could be found. Savings in diversion arise at higher water values through reduction in consumptive use because irrigated cropping activities are becoming increasingly unprofitable (figure 5). It should be noted that for each irrigated crop, the production technology specified in the model assumes that once the planting decision has been made the farmer strives to obtain the maximum yield by irrigating to meet to the potential evapotranspiration requirement. However, in reality when irrigation water is in short supply or the value of water is sufficiently high, more water use efficient management practices such as deficit irrigation and irrigation sequencing can be practiced in the short term instead of completely abandoning the crop. If such intra-seasonal water management options were introduced in to the model, much smoother supply schedules of saved water compared to those presented in figure 4 would be obtained. However, this was not done due to budget and time constraints.

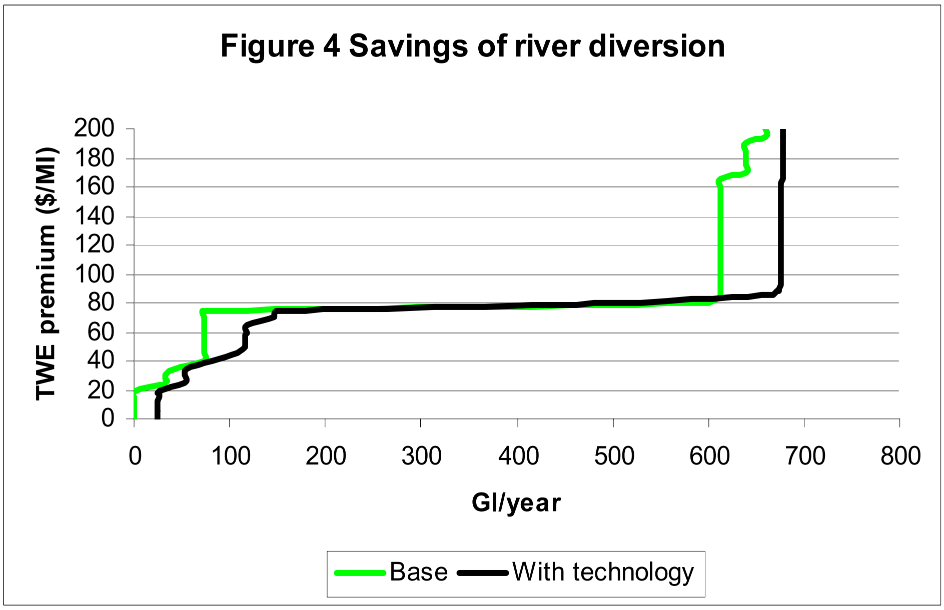


Figure 4 Savings of river diversion

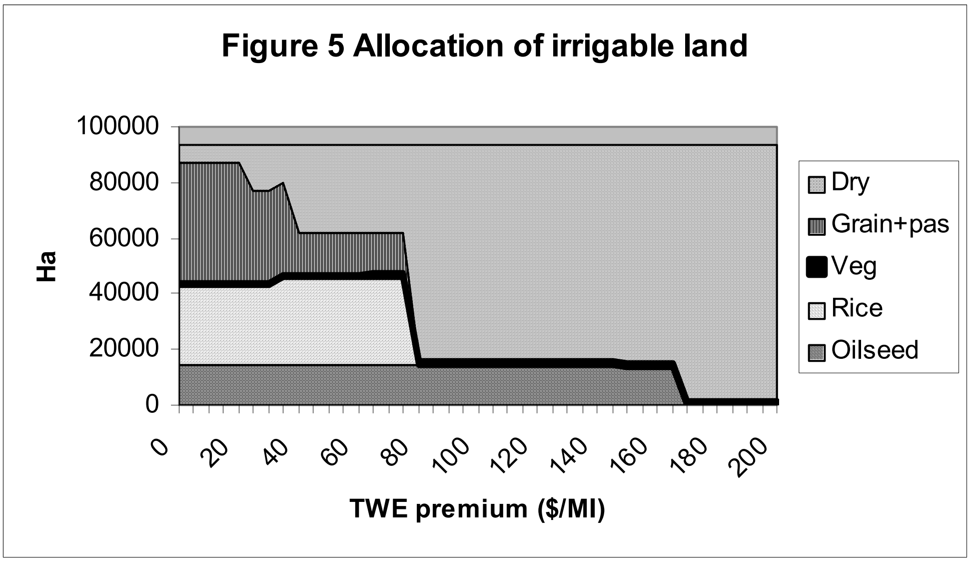


Figure 5 Allocation of irrigable land

8 Conclusions

The adoption of a range of on-farm options to improve irrigation and water use efficiency can result in higher farm incomes through the use of saved water on-farm. In addition there are potential environmental benefits from reduced river diversions, groundwater accessions if the deep percolated water is saline and off-site pollution due to a reduction in the runoff of contaminated water.

Therefore, when considering the economic benefits of increased irrigation efficiency the value of all environmental and other benefits as well as the increased on-farm benefits should be included. The introduction of the cap and the environmental flow rules and measures, if implemented in the future, designed to internalise the external cost of increased salinity in return flows and groundwater resources are expected to increase the opportunity cost of water with consequent greater benefits from increasing irrigation efficiency.

Currently there are no clearly defined and enforceable water rights for the environmental uses and the existing water entitlements are almost exclusively for consumptive or out of stream uses. However, there are implicit environmental rights enforced through the cap on diversions, environmental flow rules and other regulations. The enforcement of some form of environmental rights is important as allocations based on the consumptive market alone may not produce an efficient outcome if the reduced river flow between the point of diversion and the point the return flow enters the river has opportunity costs. In order to strengthen the existing measures, some initiatives, including the creation of market based environmental water entitlements are proposed in the White Paper on water recently released by the NSW DLWC for public comment. If such rights are allowed and there are no legal restrictions of water transfers between irrigation areas and states, environmental users could probably purchase and retire consumptive rights.

However, in the absence of market based environmental water entitlements, increasing irrigation efficiency may need policy changes if public benefits exceed private benefits for greater adoption of water saving technologies – for example- subsidies for investments in water saving technologies. Some incentives in this direction are already available through the NSW Rural Assistance Authority’s Special Conservation Scheme which offers loans of up to $100 000 to upgrade on-farm irrigation systems and tax deductions for capital expenditure for farm improvements that have some environmental benefits.

The external costs of irrigation runoff and groundwater accession and the potential of water saving technologies to reduce these pollutants at source add another impetus to improving water use efficiency. In some cases, there may be external benefits of irrigation runoff and groundwater accession if they represent inflows to other water resources downstream. Therefore cost effective solutions to increase irrigation efficiency and externality problems need to be sought simultaneously. Even though the relevant environmental and externality issues can be analysed to some extent with the existing model, the static nature of the model may limit the use of some of the results. As waterlogging, accession to groundwater and salinisation are environmental processes that evolve over time, a dynamic optimisation model is required to adequately address these issues. Such a model should incorporate increases in groundwater tables and salinity levels and its influence on crop yields and optimal choice of crops/crop rotations and investment in water saving technologies over time.

Appendix A: Estimation of cost of refurbishment

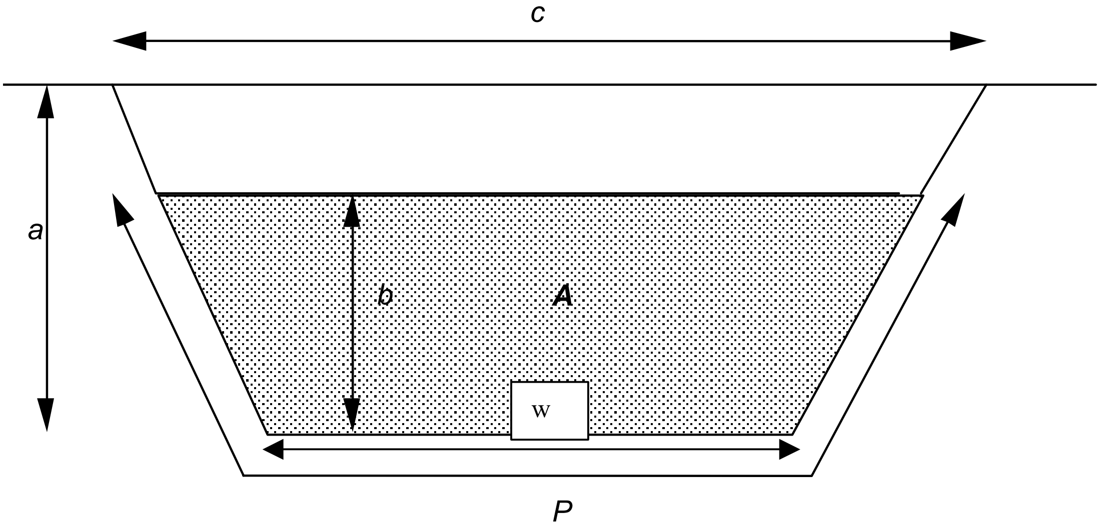
There is little information available on the relationship between the actual cost of irrigation infrastructure refurbishment and the design flow rate for the MIA. As a result an engineering approach was used to estimate the relationship between the cost of refurbishment per lineal metre and the design flow rate for each option.

Cost of refurbishment of an irrigation canal reach depends on the option chosen, the length of the reach and the flow rate required in the reach. The required flow rate in a given reach depends on the rate of withdrawal of water by the farms assigned to the reach and the downstream reaches and the rate of loss of water due to seepage, evaporation and escapes in downstream reaches.

The general approach to estimate a relationship between cost of refurbishment and design flow rate involves three steps. First, the hydraulic functional relationships between the flow rate and the canal or pipe geometry were derived for a range of plausible design flow rates. Second, the specifications of canal or pipe geometry were used to derive quantities of materials and labour required for refurbishment for a range of flow rates. Labour and machinery are required for breaking up and removing existing lined canals or pipes, and for earth works for reshaping or excavation. Material inputs include concrete, clay and plastic membrane for lining and new pipes. Third, using prevailing prices of materials and hired labour, the cost of refurbishment per lineal metre was estimated for a range of flow rates for each of the options.

Open canals

Figure 3 Water flow in a trapezoidal open canal



The functional relationship between the rate of flow in an open trapezoidal canal and its geometry is given by the Manning's equation (equation 1).

$$Q = \frac{A.R^{2/3}.S^{1/2}}{n} \qquad (1)$$

Where $R = A/P$

Q	rate of flow (m^3/second)
A	cross sectional area of water flow (m^2)
R	hydraulic radius (m)
P	wetted perimeter (m)
S	slope of canal
n	friction coefficient

The estimated flow rates and the corresponding specifications were checked against that of some of the canals in the MIA. In the case of concrete and clay lining, the volume of material required for lining 1 lineal metre of canal to a thickness of 10 cm was then estimated. The total cost of refurbishment of 1 lineal metre of canal including the cost of breaking up and removing existing linings, reshaping and excavation was estimated for the range of flow rates estimated.

Gravity pipes

The rate of flow in a gravity fed pipe is a function of the diameter of the pipe and the friction head loss per metre. The Hazen-Williams formula provides for a practical way of relating flow rate to pipe diameter in gravity fed pipes.

$$V = 0.355Cd^{0.63}\left(\frac{H}{L}\right)^{0.54} \qquad (2)$$

Where		
	V	velocity of flow (m/s)
	d	diameter (m)
	H	friction head loss (m)
	L	length of canal (m)
	C	a coefficient

The velocity V can also be defined in terms of flow rate Q, which is measured in m^3/s.

$$V = \frac{Q}{\pi(d/2)^2}$$

Substituting the value of V in equation 2 yields.

$$Q = 0.08875\pi C\left(\frac{H}{L}\right)^{0.54} d^{2.63} \qquad (3)$$

The flow rates were estimated for a range of diameters of pipes available from CSR Humes. It is assumed that pipes will be used only in those reaches with demand flow rates less than 150 ML/day. The prices per lineal metre of pipes with different diameters were obtained from CSR Humes (personnel communication John Bower, CSR Humes, Tamworth, 2000).

The relationship between flow rates and cost was found to be non-linear for both trapezoidal canals and gravity pipes. A series of non-linear relationships between the cost of refurbishment per lineal metre and the flow rate covering different ranges of flow rates were estimated for each option (equation 4).

$$C_{fk} = \beta_{fk} Q_{fk}^{(1+\alpha_{fk})} \qquad (4)$$

Where C_{fk} = cost of refurbishment with option k for the flow rate range *f* (\$/m)

Q_{fk} = flow rate with refurbishment option *k* within the flow rate range *f* (ML/day); and

α_{fk} and β_{fk} are coefficients

The coefficients of equation 3 were estimated by minimising the sum of squared deviations between the actual and the predicted values of C_{rk} using the solver routine in Excel 97. The coefficients estimated in this manner are given in table A1. The total cost of refurbsihment of canals within a division is then estimated for different canal refurbsihment options as given in equation 5.

$$TC_{rs} = \sum_{f,k} C_{fk} L_{rsk} \tag{5}$$

Where TC_{rs} = total cost of refurbishment for division *r* in Refurbishment option *s*

L_{rsk} = total length of canals in demand flow rate range *f* in division *r* to be refurbished with option *k* in refurbishment option *s*

Table A1 The coefficients of the non-linear relationship between cost of refurbishment and flow rate

Flow rate range	Earth		Membrane		Concrete		Pipe- flush joints		Pipe- rubber joints	
(Ml/day)	Beta	Alpha	Beta	Alpha	Beta	Alpha	Beta	Alpha	Beta	Alpha
1-10	21.24942	-0.64185	28.18537	-0.64190	**58.09158**	**-0.62500**	13.36431	-0.34220	16.38365	-0.33661
11-20	21.96932	-0.65910	29.14406	-0.65921	**58.09158**	**-0.62500**	13.36431	-0.34220	16.38365	-0.33661
21-30	22.55639	-0.66808	29.92457	-0.66820	**58.09158**	**-0.62500**	13.31562	-0.33290	12.12801	-0.23404
31-40	23.09322	-0.67504	30.63706	-0.67517	**58.09158**	**-0.62500**	13.31562	-0.33290	12.12801	-0.23404
41-50	23.61109	-0.68106	31.32657	-0.68121	**58.09158**	**-0.62500**	12.68943	-0.32268	16.84078	-0.31831
51-60	24.08680	-0.68615	31.98083	-0.68648	**58.09158**	**-0.62500**	12.68943	-0.32268	16.84078	-0.31831
61-70	24.66473	-0.69192	32.74105	-0.69219	**58.09158**	**-0.62500**	13.86944	-0.34508	18.55014	-0.34276
71-80	27.78198	-0.71948	36.87459	-0.71973	**58.09158**	**-0.62500**	13.86944	-0.34508	18.55014	-0.34276
81-90	27.78257	-0.71888	36.87534	-0.71913	**58.09158**	**-0.62500**	14.39032	-0.35383	18.00647	-0.33722
91-100	27.78258	-0.71847	36.87535	-0.71872	**58.09158**	**-0.62500**	14.39032	-0.35383	18.00647	-0.33722
101-140	**27.78258**	**-0.71798**	**36.87535**	**-0.71823**	**58.09158**	**-0.62500**	12.98789	-0.33214	17.35376	-0.32979
141-200	**27.78258**	**-0.71798**	**36.87535**	**-0.71823**	**58.09158**	**-0.62500**	12.79913	-0.32801	16.34337	-0.31695
201-300	32.43196	-0.74739	43.16326	-0.74814	**58.09158**	**-0.62500**	na	na	na	na
301-400	37.06654	-0.77085	49.42656	-0.77192	**58.09158**	**-0.62500**	na	na	na	na

Appendix B: An algebraic representation of the Yanco and Mirrool area model

The model developed for the Yanco and Mirrool areas was used to simulate the behaviour of farmers and regional water authorities toward the adoption of both on-farm and off-farm irrigation technologies within the limits set by the existing physical, economic and institutional environment. There are three inter linked components in the model: the farms in the area, an off farm water delivery system and a water authority. It incorporates the Main canal and the major branch canals and represents 2400 farms grouped into 26 existing irrigation divisions of the MIA and district system covering the majority of irrigated agriculture in the MIA. The upstream part of the canal network that includes the Main canal and major branch canals up to the individual divisions is represented in the model in detail. The up stream canal network is structured in terms of 26 sequential reaches separated by nodes for ease of tracking the flow of water with each reach is assigned to a division (figure 3 and table 3). Water is diverted from the Murrumbidgee River at the Berembed Weir at Narrandera (at node 1) to reach 1. The downstream delivery canals located within each division are represented simply by a conveyance loss rate estimated based on the type, condition, length, demand flow rate of each of the canals segments.

The model is formulated on an annual basis. However, with water balancing is being done on an average per day basis for each month within a year while labour supply and use are expressed on a seasonal basis within a year. For each division, a number of resource constraints are specified which include constraints on the quantity and quality of land available, the quantities of family labour and alternative sources of water namely reuse and groundwater. The economic parameters used in the model include, prices of crops and livestock commodities, variable input cost, annualised cost of water application technologies, annualised investment cost of storage built for the reuse system, cost of pumping to deliver water to the reuse storage and to pressurise water for drip irrigation.

Model solutions provide the optimal price of water, the allocation of water between divisions and within each division the optimal allocation of resources between alternative production activities and for each cropping activity the optimal mix of water application technologies. The model also solves for prices of resources, which are measured in annual rent equivalents.

Two versions of the model were developed to represent the incentives faced by farmers in the MIA in their use of land and water resources. The first version represents the conditions for optimal behaviour by farmers as well as the water authority within a well functioning water market. In particular, water authorities in the first model are assumed to charge a price that reflects the cost of delivering water, including conveyance losses, to each farm. The second model also represents conditions for optimal behaviour by farmers as well as the water authority, but subject to a uniform water price prevailing regardless of the difference between farms in costs of conveyance losses. Uniform pricing of irrigation water entails some economic losses and consequently this form of pricing is not economically efficient (Hafi, Klijn and Toyne, 1999). The second version of the model, which represents the uniform pricing currently practised by water authorities, is used in this analysis. However, the details of both of the models are given below as the uniform pricing (second) model is formulated by trading off some efficiency elements in the criteria of the first model to achieve equity in the form of uniform pricing.

Only a generalised form of the model developed for the MIA is reported here. The full MIA model includes more detail of the diverse land use options, resource constraints, sources of water for irrigation and institutional constraints. However, the general form of the model presented here retains the key features that are required to address the issues associated with the adoption of both on- and off-farm irrigation technologies.

Model 1

Efficient water and land use and the corresponding efficient prices of water are obtained in model 1 as the solution to the problem of maximising the objective function (1) subject to the inequality constraints on volumes (2) – (4) and prices (5) – (7).

$$\begin{aligned}&\sum_{r,n,t'} A_{rnt} P_{nt}^{GM} + \sum_{m} WS_m \left(VTWE_m - P_m^W\right) - \sum_{m} WB_m VTWE_m - \sum_{m} Q_m^{11} P_m^W - \sum_{r,m} RW_{rm} DWCST \\ &- \sum_{r,m} DAMNUM_{rm} DAMCOST - \sum_{r} \Phi_r V_r^2 - \sum_{m} \Omega_m V_m^3 - \sum_{r,m} \chi_r V_{rm}^4\end{aligned} \qquad (1)$$

The objective function represents, for the whole irrigation system, the annual gross margin on all farms less the sum of the annual value of water 'purchased' externally at each off-take, rent to water at source (river), rents to canal capacity constraints and all annual land rents. The decision variables are the volume of water diverted from river and, for each division, the area used for each crop and irrigation technology, and on the price side, the annual land rents, the rent of water at source (river) and the prices of water along the canals. In the optimum, the value of the objective function must be zero.

$$\sum_{nt} A_{rnt} + 2.5 * DAMNUM_r \leq \Phi_r \text{ and } V_r^2 \left(\sum_{nt} A_{rnt} + 2.5 * DAMNUM_r - \Phi_r \right) = 0, \text{ for } \forall\ r \qquad (2)$$

In each region *r*, the sum of the areas used for all crops *n* with all application technologies *t* plus the area taken up by reuse storage cannot exceed the given area of land, Φ_r. If the sum of the areas of land used for crop production is less than the available area then the value of land in this region is zero.

$$\sum_m 30 * Q_m^{11} + WS - WB \leq \Omega \text{ and } V^3 \left[\left(\sum_m 30 * Q_m^{11} + WS - WB \right) - \Omega \right] = 0 \qquad (3)$$

The sum over the year of the water flows in month *m* from the source through node 1 to reach 1 plus water sold to other water authorities cannot exceed the annual allocations from the river to the irrigation area, Ω plus water purchased from other authorities. If the annual flow to this reach plus outside sales is less than the allocation plus water purchased outside then the value of water associated with this allocation constraint is zero.

$$Q_m^{ir} \leq \chi_r \text{ and, } V_{rm}^4 \left(Q_m^{ir} - \chi_r \right) = 0 \text{ for } \forall\ i, r \text{ and } m \qquad (4)$$

For each node *i* and each reach *r* the daily water flow should be no greater than the peak design daily flow. If the daily water flow is less than the design daily flow, then the value of this capacity constraint is zero.

$$\sum_{n.t} \frac{\xi_{nm} - \eta_{rm} - \delta_{nm}}{\left(1 + \vartheta_n + \kappa_n\right)} A_{rnt} - RW_{rm} \leq CW_{rm} \quad \text{and}$$

$$V_{rm}^5 \left[\sum_{n.t} \frac{\xi_{nm} - \eta_{rm} - \delta_{nm}}{\left(1 + \vartheta_n + \kappa_n\right)} A_{rnt} - RW_{rm} - CW_{rm} \right] = 0,$$

for $\forall\ r$ and m

(5)

For all the irrigated land in division *r*, in each month *m*, the sum of average daily water flows at individual division off takes within the region cannot be less than the daily net (after rainfall and capillary rise) evapotranspiration requirement of all crop activities on the irrigated land adjusted for both surface runoff and deep percolation losses less the volume of reuse water used. If the total net water requirement from the off farm delivery system within the region is less than the sum of flow rates at the individual farm off takes then the value of water for the individual farms in the region is zero.

$$\frac{CW_{rm}}{(1-\beta_r)} + \sum_{j\in j_i, r'\in r'_i} Q_m^{jr'} + \varepsilon_r \mu_r Q_m^{ir} \le Q_m^{ir} \quad \text{and}$$

$$V_{irm}^{6}\left(\frac{CW_{rm}}{(1-\beta_r)} + \sum_{j\in j_i, r'\in r'_i} Q_m^{jr'} + \varepsilon_r \mu_r Q_m^{ir} - Q_m^{ir} \right) = 0, \text{ for } \forall\ i,\ r \text{ and } m \qquad (6)$$

For division *r* located at reach *r*, in each month *m*, the daily water flow from the supplying node *i* to that reach cannot be less than the flow to the division adjusted for daily seepage, escape and evaporation loss in canals within division plus water flows from the next downstream node plus daily seepage, escape and evaporation loss in reach *r*. If the flow from node *i* exceeds flow requirements then the value of water at that reach is zero. Note that for simplicity there is assumed to be one division at each reach. Hence, the escape, seepage and evaporation losses within division stand for losses in local delivery systems to all farms in the division.

$$30 * RW_{rm} \le DAMNUM_r * 48, \text{ and, } V_{rm}^{7}\left(30 * RW_{rm} - DAMNUM_r * 48\right) = 0, \text{ for } \forall\ r \text{ and } m \qquad (7)$$

In each division *r* and in each month *m*, the volume of reuse water used cannot exceed the total capacity of the storage which is equal to the number of storage built times the capacity of each storage (48 ML per month). If the monthly volume of reuse water drawn from the dam is less than total storage capacity, the value of this limit is zero.

$$RW_{rm} \le \sum_{n,t} A_{rnt}(\xi_{nm} - \eta_{rm})\vartheta_{nt} + RRW_{rm} + \theta_m DT_{rm-1} - DT_{rm},$$

$$\text{and, } V_{rm}^{8}\left\{ RW_{rm} - \left[\sum_{n,t} A_{rnt}(\xi_{nm} - \eta_{rm})\vartheta_{nt} + RRW_{rm} + \theta_m DT_{rm-1} - DT_{rm} \right] \right\} = 0, \text{ for } \forall\ r \text{ and } m \qquad (8)$$

In each division *r* and in each month *m* the volume of reuse water used cannot exceed the total volume of irrigation runoff water produced plus the maximum rainwater harvested plus the volume of water carried over from the previous month adjusted for the evaporation and seepage losses less the volume of water carried forward to the next month. If the volume of runoff water used is less than the volume of runoff water available, then the value of this limit is zero.

$$V_r^2 + \sum_m \frac{\xi_{nm} - \eta_{rm}}{\left(1 + \vartheta_{nt} + \kappa_{nt}\right)} V_{rm}^5 - \sum_m \left(\xi_{nm} - \eta_{rm}\right) \vartheta_{nt} V_{rm}^8 \geq P_{nt}^{GM} \quad \text{and}$$

$$A_{rnt}\left(V_r^2 + \sum_m \frac{\xi_{nm} - \eta_{rm}}{\left(1 + \vartheta_{nt} + \kappa_{nt}\right)} V_{rm}^5 - \sum_m \left(\xi_{nm} - \eta_{rm}\right) \vartheta_{nt} V_{rm}^8 - P_{nt}^{GM} \right) = 0, \text{ for } \forall\ r,w,l \text{ and } f' \tag{9}$$

In each division *r*, for each crop *n*, for each application technology *t*, on a per hectare basis, the value of land plus the value of water in all months of the year less the value of runoff water produced in all months in the year cannot be less than the given gross margin for that crop managed with that water application method, P_{nt}^{GM}. If the sum of these values is greater than the gross margin, then the land is not used for growing crop *n* with application technology *t*.

$$V_{rm}^5 - V_{rm}^8 \leq DWCST + V_{rm}^7 \text{ and } RW_{rm}\left[V_{rm}^5 - V_{rm}^8 - \left(DWCST + V_{rm}^7\right)\right] = 0 \tag{10}$$

In each division *r* and in each month *m* the difference between the value of water used in the division and the value of water stored in the dam for reuse cannot exceed the cost of pumping runoff water to the storage plus the value of the capacity of the storage in that month. If the difference between the values of water used in the division and stored in the dam is less than the cost of storing then no water will be stored in the dam.

$$\sum_m 48 * V_{rm}^7 / 30 + 2.5 * V_r^2 \leq DAMCOST \quad \text{and}$$

$$DAMNUM_r\left[\sum_m 48 * V_{rm}^7 / 30 + 2.5 * V_r^2 - DAMCOST\right] = 0, \text{ for } \forall r \tag{11}$$

In each division *r*, the annual value of the capacity of a storage unit plus the value of land taken up by this storage unit cannot exceed the annualised cost of a storage unit.

If the annual value of the capacity plus the land taken up by a storage unit is less than the annualised cost, then no storage will be built in this division.

$$V^{8}_{rm} \geq \theta_m V^{8}_{rm+1} \text{ and } DT_{rm}\left(V^{8}_{rm} - \theta_m V^{8}_{rm+1}\right) = 0 \qquad (12)$$

In each division *r* and in each month *m*, the value of water stored in the dam cannot be less than the value of water stored in the dam the following month adjusted for seepage and evaporation losses and if this value exceeds the value of water in the following month no dam water will be carried forward to the following month.

$$V^{3}_{m} \geq VTWE - P^{W} \text{ and } WS_m\left[V^{3}_{m} - \left(VTWE - P^{W}\right)\right] \qquad (13)$$

The value of water at source cannot be less than the value of water outside the system less the cost of delivering water to outside systems and if the value of water at source is greater than the net external value of water, no water will be sold.

$$V^{3}_{m} \leq VTWE \text{ and } WB_m\left(V^{3}_{m} - VTWE\right) \qquad (14)$$

The value of water at source cannot exceed the value of water outside the system and if the value of water at source is less than the external value of water no water will be purchased.

$$\begin{aligned}&(1-\varepsilon_1\mu_1)V^{6}_{11m} \leq V^{3}_{m} + V^{4}_{11m} + P^{W}_{m} \text{ and },\\&Q^{11}_{km}\left((1-\varepsilon_1\mu_1)V^{6}_{11m} - \left[V^{3}_{m} + V^{4}_{11m} + P^{W}_{m}\right]\right) = 0 \text{ for } \forall \text{ and } m\end{aligned} \qquad (15)$$

In each month *m*, the value of water at node 1 reach 1 - net of evaporation, seepage and escape losses at that reach - cannot exceed the value of water at source plus the value of the capacity constraint at the weir and the external price paid for water at source, P_m, and if the value at node 1 reach 1 is less than the total value at source then no allocation water flows to reach 1.

$$V^{6}_{irm} \geq (1-\varepsilon_{r'}\mu_{r'})V^{6}_{jr'm} \text{ and } Q^{jr'}_{m}\left(V^{6}_{imr} - (1-\varepsilon_{r'}\mu_{r'})V^{6}_{jmr'}\right) = 0 \quad \text{for } \forall\ j \in j_i, r' \in r'_i, m \qquad (16)$$

In each month *m*, the value of water at node *i* and reach *r* cannot be less than the value of water - net of evaporation and seepage losses - at the next downstream node for any of the subsequent reaches, and if for any downstream reach the value is less than the value - net of losses - at the reach just upstream from it then no water flows to this downstream reach. Note that if water flows through adjacent nodes and reaches, then the value of water increases the further downstream it is used.

Note that (14) and (15) imply that if water is used at some downstream reach *r*, then the value of water at source, V_s, is related to the value of water at this reach by $V_s = V_m^3 + V_{11m}^4 + P_m^W = V_{imr}^6 \prod_{r' \in R'} \left(1 - \varepsilon_{r'} \mu_{r'}\right)$, where *R'* is the set of all upstream reaches direct from reach *r* to the source.

$$V_{rm}^6 \geq \left(1 - \beta_r\right) V_{rm}^5 \text{ and } CW_{rm}\left(V_{rm}^6 - \left(1 - \beta_r\right) V_{rm}^5\right) = 0 \text{ for } \forall r \text{ and } m \qquad (17)$$

At each reach *r* and each month *m*, the value of water cannot be less than the value of water at the division assigned to this reach adjusted for escape, seepage and evaporation losses occurring in the local delivery system and if this value exceeds the value of water used in the division then no canal water will be flowing to that division.

The model conditions imply that at the optimum, in the presence of conveyance losses the value of water increases with distance from source until water flows cease. The difference in the value of water between any two adjoining nodes cannot exceed the value of water lost in conveyance between these nodes.

Model 2

The volume conditions for model 2 are identical to those of model 1.

However, the price/cost conditions (15), (16) and (17) are replaced by (18), (19) and (20) respectively.

$$V_{11m}^6 \leq V_m^3 + V_{11m}^4 + P_m^w \text{ and } Q_m^{11}\left[V_{11m}^6 - \left(V_m^3 + V_{11m}^4 + P_m^w\right)\right] = 0 \text{, for } \forall\ m \qquad (18)$$

In each month *m*, the value of water at node 1 reach 1 cannot exceed the value of water at source plus the external price paid for water at source, P_m^W, and if the value at node 1 reach 1 is less than the total value at the source then no water flows to reach 1.

$$V_{irmr}^6 \geq V_{jr'mr}^6 \text{ and } Q_{km}^{jr'}\left(V_{irmr}^6 \geq V_{jr'mr}^6\right) = 0 \text{, for } \forall\ j \in j_i, r' \in r'_i, m \qquad (19)$$

In each month *m*, the value of water at node *i* and reach *r* cannot be less than the value of water at the next downstream node for any of the subsequent reaches and if the value at a subsequent reach is less than the value at the upstream reach then no water flows to the downstream reach.

$$V^{6}_{rm} \geq V^{5}_{rm} \text{ and } CW_{rm}\left(V^{6}_{rm} - V^{5}_{rm}\right) = 0 \text{ for } \forall r \text{ and } m \tag{20}$$

At each reach *r* and each month *m*, the value of water cannot be less than the value of water at the division assigned to this reach and if this value exceeds the value of water used in the division then no canal water will be flowing to that division.

Note that conditions (17), (18) and (19) differ from conditions (14), (15) and (16), respectively only in that seepage, escapes and evaporation losses are ignored, and thus if there is water used at a downstream reach *r*, then the value of water at that reach is the same as the value at all direct upstream reaches, *r'*, all the way to the source, $V_s = V^3_m + V^4_{11m} + P^w_m = V^6_{irm} = V^6_{i'r'mr}$.

Solution of uniform pricing problem of model 2

Optimal values for the farmers' and water authorities' decisions subject to uniform water prices prevailing are obtained as the solution to the conditions (1)-(14), (18), (19) and (20). Again, the solution is fully defined by these conditions and can be obtained in a number of ways. Here, the solution is obtained by maximising

$$\begin{aligned}
&\sum_{r,n,t'} A_{rnt} P^{GM}_{nt} + \sum_{m} WS_{m}\left(VTWE_{m} - P^{W}_{m}\right) - \sum_{m} WB_{m} VTWE_{m} - \sum_{m} Q^{11}_{m} P^{W}_{m} - \sum_{r,m} RW_{rm} DWCST \\
&- \sum_{r,m} DAMNUM_{rm} DAMCOST - \sum_{r} \Phi_{r} V^{2}_{r} - \sum_{m} \Omega_{m} V^{3}_{m} - \sum_{r,m} \chi_{r} V^{4}_{rm} \\
&+ \sum_{i,m,r} Q^{ir}_{m}\left(\varepsilon_{r} \mu_{r} V^{6}_{irm}\right) + \sum_{r,m} CW_{rm} \beta_{r} V^{6}_{rm}
\end{aligned} \tag{21}$$

with respect to nonnegative price and volume variables subject to the inequality constraints for conditions (1)-(13), (17), (18), (19). The criterion (20) has the same interpretation as the criterion (1) above except for two additional (the last two) terms. These terms are the sum over all nodes, months and reaches of the value of all evaporation, seepage and escape losses evaluated at the optimum uniform water price. The term can also be interpreted as the sum - over months *m*, nodes *i* and reaches (or farms) *r* - of the value of the *ad valorem* subsidy to a water user *r* at the rate $(\varepsilon_r \mu_r + \beta_r)$ that is implicit in water charges set at a second best uniform price. Second best, in the sense that within the set of all possible uniform prices the optimal uniform price is obtained. Note: the implicit subsidy is expressed in terms of this second best optimum price not in terms of the price to the user that would prevail in the unrestricted optimum of model 1. Again in optimum, the value of the criterion must be zero.

Notation

Subscripts, superscripts and ranges

i and j	node	i,j =1, ..., 67
r and r'	reach, division assigned	r,r' =1, ..., 67
m	month	m =1, 2, ..., 12
n	crop	c =wheat, canola, soybean rice, lucerne and annual pasture, onions, tomatoes carrots, citrus and vines
t	irrigation technology for horticulture crops	a = broad furrow, twin furrow and drip

W	Water
GM	Gross margin

Variables

V^e	value, or shadow price, associated with volume constraint (e)
Q_m^{ir}	rate of water flow from node i to reach r in month m (ML/day)
A_{rnt}	area planted to crop n with application technology t in division r (Ha)
HA_{rstk}	area of application technology k adopted on tree crop t on soil
WS_m	Volume of TWE sold out of the system in month m (ML/day)
WB_m	Volume of TWE purchased from outside the system in month m (ML/day)
RW_{rm}	Volume of dam water used in region farm r in month m (ML/day)
CW_{rm}	Volume of diverted water used in region farm r in month m (ML/day)
DT_{rm}	Volume of dam water carried over from month m to month $m+1$ in region farm r (ML/day)
$DAMNUM_r$	The number storage units built in division r.

Parameters

P_m^W	delivery charge of water at source in month m (\$/ML)
$VTWE_m$	Value of temporary water entitlements outside the system in month m (\$/ML)
$DWCST$	Cost of pumping runoff water to storage (\$/ML)
$DAMCOST$	Annualised cost of storage (\$/48 ML capacity unit)
P_{nt}^{GM}	gross margin of crop n planted with application technology t (\$/ha)
P_a^{GM}	gross margin of production from animal type a (\$/head)
μ_r	length of reach r (metres)

ε_r	proportion of the flow rate lost due to evaporation and seepage along reach r per metre
β_r	proportion of the flow rate lost due to evaporation and seepage from the canals within a region farm
ξ_{nm}	evapotranspiration requirement of crop n in month m (ML/ha/day)
ϑ_{nt}	proportion of irrigation water runoff from crop n planted with application technology t
κ_{nt}	proportion of irrigation water percolated down to shallow acquifers from crop n planted with application technology t
η_{rm}	rainfall in region farm r in month m (ML/ha/day)
Ω_m	flow of water diverted at the source in month m by the water authority (ML/day)
χ_r	Canal capacity constraint in reach r (ha)
$DAMCAP_{rm}$	limit on drawing water from the dam in region farm r (ML/day)
RRW_{rm}	harvesting rights of rainfall runoff water in month m on region farm r (ML/day)
Φ_r	area of land available on farm r (ha)
β_{nm}	Capillary rise under crop n in month m (ML/day)
θ_m	Proportion of water stored lost due to seepage and evaporation in month m (ha)

Appendix C: Assumptions used in the model

Table C1 Net irrigation requirements of broadacre crops – in an average (1962-1996) year

Layout/crop	Aug (Ml/ha)	Sep (Ml/ha)	Oct (Ml/ha)	Nov (Ml/ha)	Dec (Ml/ha)	Jan (Ml/ha)	Feb (Ml/ha)	Mar (Ml/ha)	Apr (Ml/ha)	May (Ml/ha)	Total (Ml/ha)
LFBC											
Wheat	0.5	0.7	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.7	2.7
Rice	0.0	0.0	2.9	2.5	4.2	2.8	1.5	0.0	0.0	0.0	13.9
Canola	0.3	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6	2.1
Soybean	0.0	0.0	0.0	1.2	1.5	2.0	1.8	1.0	0.0	0.0	7.5
Lucerne (grazing)	0.3	0.5	1.2	2.1	3.0	2.9	2.3	1.7	0.7	0.2	14.9
Lucerne (established)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	2.6
Lucerne (maintained)	0.4	0.5	1.3	2.2	2.9	2.9	2.3	1.7	0.7	0.2	15.1
Annual pasture (established)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	1.8
Annual pasture	0.6	0.5	1.0	0.0	0.0	0.0	0.0	0.0	3.5	0.3	5.9
LFCB											
Wheat	0.5	0.7	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.6	2.6
Rice	0.0	0.0	2.9	2.5	4.2	2.8	1.5	0.0	0.0	0.0	13.9
Annual pasture (established)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	1.8
Annual pasture	0.6	0.5	1.0	0.0	0.0	0.0	0.0	0.0	3.5	0.3	5.9
NLCB											
Wheat	0.3	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6	2.1
Rice	0.0	0.0	2.9	2.5	4.2	2.8	1.5	0.0	0.0	0.0	13.9
Annual pasture (established)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5
Annual pasture	0.4	0.5	0.9	0.0	0.0	0.0	0.0	0.0	3.2	0.2	5.2

a evapotranspiration requirement after netting out

Table C2 Evapotraspiration requirements of horticultural crops

Horticultural crop	Age of trees	MONTHS												Total
		Jul (Ml/ha)	Aug (Ml/ha)	Sep (Ml/ha)	Oct (Ml/ha)	Nov (Ml/ha)	Dec (Ml/ha)	Jan (Ml/ha)	Feb (Ml/ha)	Mar (Ml/ha)	Apr (Ml/ha)	May (Ml/ha)	Jun (Ml/ha)	
Citrus	1	0.02	0.01	0.26	0.46	0.57	0.84	0.89	0.87	0.66	0.28	0.10	0.02	5.00
	2	0.03	0.01	0.29	0.52	0.65	0.95	1.00	0.98	0.74	0.32	0.12	0.03	5.62
	3 to 5	0.03	0.02	0.36	0.65	0.81	1.18	1.25	1.23	0.93	0.39	0.15	0.03	7.03
	6 to 30	0.04	0.02	0.42	0.76	0.94	1.38	1.46	1.43	1.08	0.46	0.17	0.04	8.20
Vines	1	0.00	0.02	0.15	0.26	0.38	0.98	1.00	0.49	0.35	0.19	0.01	0.00	3.82
	2	0.00	0.03	0.21	0.35	0.52	1.35	1.37	0.67	0.48	0.26	0.02	0.00	5.25
	3 to 30	0.00	0.04	0.28	0.48	0.71	1.84	1.87	0.91	0.66	0.35	0.02	0.00	7.16

Table C3 Application efficiency measures for horticultural crops

Application technology	Vines		Citrus	
	Yanco (%)	Mirrol (%)	Yanco (%)	Mirrol (%)
Furrow	76	85	81	85
Twin furrow	83	90	-	-
Drip	95	95	95	95

Table C4 Diversions from Marandera regulator

Year	Jul (Ml)	Aug (Ml)	Sep (Ml)	Oct (Ml)	Nov (Ml)	Dec (Ml)	Jan (Ml)	Feb (Ml)	Mar (Ml)	Apr (Ml)	May (Ml)	Jun (Ml)	Total (Ml)
1986/87	0	0	17,287	48,559	111,314	126,492	161,637	141,403	148,365	78,164	36,579	0	869,800
1987/88	0	0	37,745	102,840	145,675	164,255	171,262	161,336	158,263	50,839	31,929	0	1,024,144
1988/89	0	0	26,150	111,435	121,534	130,247	167,115	161,440	86,500	1,387	5,138	0	810,946
1989/90	0	0	12,762	98,248	117,203	158,257	165,403	130,887	134,321	49,708	19,185	0	885,974
1990/91	0	0	13,889	101,791	122,959	141,745	144,852	134,978	147,892	79,175	67,218	0	954,499
1991/92	0	12,855	40,408	161,170	138,102	144,504	168,366	124,835	154,650	70,337	36,346	0	1,051,573
1992/93	600	22,979	39,608	54,852	76,978	59,934	143,022	123,919	89,984	64,175	58,790	0	734,841
1993/94	0	5,744	24,684	58,144	103,562	125,930	175,004	137,936	81,200	69,772	64,591	0	846,567
1994/95	25,361	77,613	97,425	160,334	127,590	167,377	126,682	116,395	128,517	60,397	18,245	0	1,105,936
1995/96	0	13,824	72,287	109,619	73,721	150,755	127,488	138,769	69,080	63,274	48,987	0	867,804
1996/97	0	7,636	58,831	133,837	119,532	166,200	191,045	138,890	108,040	77,954	42,831	929	1,045,725
Average	2,360	12,786	40,098	103,712	114,379	139,609	158,352	137,344	118,801	60,471	39,076	84	927,074

Appendix D: Detailed results

Table D1 Tracking the annual river diversion through the Yanco and Mirrool areas in the base case

Primary	Secondary	Tertiary	Reach No	Division(s) included	Inflow (Gl/yr)	Applied to crops (Gl/yr)	Conveyance losses (Gl/yr)	Outflow (Gl/yr)
Main canal			Reach 1	Yanco 10a	832	2	3	826
	Gogeldrie		Reach 1		197	0	0	197
		South Gogeldrie	Reach 1	Yanco 3	62	55	7	0
	Gogeldrie		Reach 2	Yanco 4	136	15	2	119
	Gogeldrie		Reach 3	Yanco 5 & 6	119	106	13	0
Main canal			Reach 2	Yanco 10 & 7	629	34	6	589
Main canal			Reach 3	Yanco 2	589	11	2	576
Main canal			Reach 4	Yanco 8 & 9	576	108	13	455
Main canal			Reach 5		455	0	1	454
	North Kooba canal		Reach 1	Griffith 2	55	48	7	0
Main canal			Reach 6		400	0	1	399
	North branch canal		Reach 1	Griffith 3	65	17	2	47
	North branch canal		Reach 2	Griffith 5	47	42	5	0
Main canal			Reach 7		334	0	0	333
	Mirrool canal		Reach 1	Griffith 6	122	23	3	96
	Mirrool canal		Reach2	Griffith 7	96	19	2	75
	Mirrool canal		Reach 3	Griffith 8	75	20	2	52
	Mirrool canal		Reach 4	Griffith 9	52	33	3	16
Main canal			Reach 8	Griffith 4	211	17	3	191
Main canal			Reach 9	Griffith 10	191	17	2	171
Main canal			Reach 10	Griffith 11	171	8	1	162
	Lake view canal		Reach 1		23	0	0	23
	Lake view canal		Reach 2	Griffith 13	23	21	2	0
Main canal			Reach 11	Griffith 12	140	17	1	121
Main canal			Reach 12	Griffith 14	121	26	2	93
Main canal			Reach 13	Griffith 15	93	54	8	31
System total					**832**	**694**	**90**	**47**

Table D2 Rates of water flow, applied to crops lost in conveyance in December in the Yanco and Mirrool areas in the base case

Primary	Secondary	Tertiary	Reach No	Division(s) included	Inflow (Ml/da	Applied to crops (Ml/day)	Conveyance losses (Ml/day)	Outflow (Ml/day)
Main canal			Reach 1	Yanco 10a	6300	14	24	6262
	Gogeldrie		Reach 1		1493	0	1	1491
		South Gogeldrie	Reach 1	Yanco 3	472	419	53	0
	Gogeldrie		Reach 2	Yanco 4	1019	99	13	907
	Gogeldrie		Reach 3	Yanco 5 & 6	907	806	101	0
Main canal			Reach 2	Yanco 10 & 7	4769	236	40	4494
Main canal			Reach 3	Yanco 2	4494	78	17	4398
Main canal			Reach 4	Yanco 8 & 9	4398	821	96	3481
Main canal			Reach 5		3481	0	5	3476
	North Kooba canal		Reach 1	Griffith 2	432	381	52	0
Main canal			Reach 6		3043	0	5	3038
	North branch canal		Reach 1	Griffith 3	493	128	13	352
	North branch canal		Reach 2	Griffith 5	352	317	34	0
Main canal			Reach 7		2545	0	2	2543
	Mirrool canal		Reach 1	Griffith 6	981	174	24	783
	Mirrool canal		Reach2	Griffith 7	783	164	16	602
	Mirrool canal		Reach 3	Griffith 8	602	173	21	408
	Mirrool canal		Reach 4	Griffith 9	408	253	24	130
Main canal			Reach 8	Griffith 4	1562	128	22	1412
Main canal			Reach 9	Griffith 10	1412	129	16	1267
Main canal			Reach 10	Griffith 11	1267	59	6	1202
	Lake view canal		Reach 1		123	0	0	123
	Lake view canal		Reach 2	Griffith 13	123	113	10	0
Main canal			Reach 11	Griffith 12	1079	124	11	944
Main canal			Reach 12	Griffith 14	944	195	18	731
Main canal			Reach 13	Griffith 15	731	422	60	250
System total					**6300**	**5235**	**685**	**380**

Table D3 Water balance by options for the Yanco irrigation areas

	Base (GL/yr)	TF plus Drip (GL/yr)	Reuse (GL/yr)	Refurbish (GL/yr)	TF + Drip & reuse (GL/yr)	TF + Drip reuse & refurb (GL/yr)
River diversions	370	387	355	373	353	327
Conveyance losses	0	0	0	0	0	0
Seepage	13	13	12	12	12	11
Escapes	26	27	25	0	25	0
Use of runoff water	0	0	0	0	0	0
Rain	0	0	27	0	27	27
Irrigation	0	0	15	0	15	15
Water applied to crops	331	346	360	361	358	358
Application losses	0	0	0	0	0	0
Runoff	27	28	12	32	12	12
Net accession	8	8	8	9	7	7
Evaporation from dam	0	0	3	0	3	3
Total loss	74	76	60	53	59	33
Savings in river diversions	0	-17	15	-3	17	43
Efficiency	0	0	0	0	0	0
Conveyance (%)[a]	90	89	90	97	90	97
Application (%)[b]	89	90	94	89	94	94
System (%)[c]	80	80	83	86	83	90

a. percntage of water diverted which is finally applied to crops

b. percentage of water applied which is finally used to meet crop evapotranspiration

c. percentage of water diverted which is finally used to meet crop evapotranspiration

Table D4 Water balance by options for the Mirrool irrigation area

	Base (GL/yr)	TF plus Drip (GL/yr)	Reuse (GL/yr)	Refurbish (GL/yr)	TF + Drip & reuse (GL/yr)	TF + Drip reuse & refurb (GL/yr)
River diversions	462	442	424	438	409	382
Conveyance losses	0	0	0	0	0	0
Seepage	23	22	21	21	20	18
Escapes	29	28	26	0	25	0
Use of runoff water	0	0	0	0	0	0
Rain	0	0	19	0	19	19
Irrigation	0	0	20	0	16	16
Water applied to crops	363	345	370	370	352	352
Application losses	0	0	0	0	0	0
Runoff	50	38	30	51	34	34
Net accession	7	2	7	7	2	2
Evaporation from dam	0	0	3	0	3	3
Total loss	109	89	87	79	84	58
Savings in river diversions	0	20	38	24	53	80
Efficiency						
Conveyance (%)[a]	89	89	89	95	89	95
Application (%)[b]	84	88	89	84	89	89
System (%)[c]	77	80	79	82	79	85

a. percntage of water diverted which is finally applied to crops

b. percentage of water applied which is finally used to meet crop evapotranspiration

c. percentage of water diverted which is finally used to meet crop evapotranspiration

Table D5 Financial performance by options for the Yanco irrigation area

	Base ($m/yr)	TF plus Drip ($m/yr)	Reuse ($m/yr)	Refurbish ($m/yr)	TF+Drip & reuse ($m/yr)	TF+Drip reuse & refurb ($m/yr)
Profits before water and hired labour	53.06	54.76	55.11	55.21	55.58	55.58
Cost of upgrading land	0.00	0.00	0.00	0.05	0.05	0.05
Delivery charge on channel water	4.30	4.50	4.13	4.69	4.11	4.11
Cost of storing and pumping water	0.00	0.12	0.55	0.00	0.66	0.66
Cost of hired labour	0.00	0.00	0.00	0.00	0.00	0.00
Net farm profits	48.76	50.14	50.43	50.47	50.76	50.76
Off farm income	23.50	23.91	23.38	23.37	23.86	23.86
Return to land, family labour and water	72.26	74.05	73.80	73.84	74.62	74.62
Return to irrigation water ($/Ml)[a]	121.00	120.76	130.01	125.29	133.01	143.56
Return to water applied ($/Ml)[b]	135.19	134.94	128.16	129.62	131.29	131.29

a. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water diverted

b. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water applied

Table D6 Financial performance by options for the Mirrool irrigation area

	Base ($m/yr)	TF plus Drip ($m/yr)	Reuse ($m/yr)	Refurbish ($m/yr)	TF+Drip & reuse ($m/yr)	TF+Drip reuse & refurb ($m/yr)
Profits before water and hired labour	153.46	153.55	153.91	153.94	154.03	154.03
Cost of upgrading land	0.12	0.12	0.12	0.14	0.14	0.14
Delivery charge on channel water	4.72	4.49	4.29	4.81	4.11	4.11
Cost of storing and pumping water	0.00	0.19	0.52	0.00	0.65	0.65
Cost of hired labour	0.00	0.00	0.00	0.00	0.00	0.00
Net farm profits	148.61	148.75	148.98	148.99	149.13	149.13
Off farm income	18.14	19.69	18.11	18.11	19.66	19.66
Return to land, family labour and water	166.75	168.44	167.08	167.10	168.79	168.79
Return to irrigation water ($/Ml)[a]	335.05	355.89	368.66	356.71	388.36	419.60
Return to water applied ($/Ml)[b]	382.74	406.90	375.84	377.01	398.98	398.98

a. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water diverted

b. farm profits plus total cost of water delivered less the imputed cost of family labour divided by the total volume of water applied

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