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Efficient pricing and allocation of irrigation water

A model of the Murrumbidgee Irrigation Area

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Abstract

A model of the Murrumbidgee Irrigation Area with two linked components: the farms in the area and the off farm water delivery system is developed. Two versions of the model are formulated. The first version represents the practice of uniform pricing by water authorities where the differences in conveyance losses between farms are ignored while in the second version water authorities are assumed to charge an efficient price that reflects the cost of delivering water, including the conveyance loss to each farm. Each model version simultaneously yields optimal prices (uniform or efficient) of water delivered to farms and the allocation of water between farms and, for each farm the optimal allocation of resources over production activities and for each cropping activity the optimal mix of water use technologies.

Uniform pricing of irrigation water entails some economic losses and consequently it is not economically efficient. In contrast, assuming negligible transaction costs there are no economic losses under efficient pricing. Preliminary results for the Murrumbidgee Irrigation Area show that a change to efficient pricing leads to improvements in farm financial performance and both irrigation and water use efficiency. It is also shown that investment in refurbishment of infrastructure is more profitable under efficient pricing than under uniform pricing.

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Introduction

The limited availability of water resources in Australia combined with growing demand for water have resulted in an increased emphasis on better management of existing water resources. Establishing competitive markets in water rights was identified by the Council of Australian Governments (1994) as the most appropriate instrument for allocating water resources. In general, holders of rights to water in the Murray Darling Basin are now able to trade water on both a permanent and temporary basis, although various constraints and limits on transfers apply (Topp and McClintock 1998).

Many irrigation systems supplying water to farms in the Murray Darling Basin suffer from conveyance losses. For instance, water is lost through seepage from clay channels and through the broken linings of many concrete channels. In the early 1990s, for example, approximately 12 per cent of water entering supply channels in the Murrumbidgee Irrigation Area (MIA) and Districts was estimated to have been lost through seepage, leakage, evaporation and escapes (Sinclair and Knight Merz, 1995, New South Wales Agriculture. 1996). Refurbishment work in the MIA was recently undertaken to reduce these losses. If irrigation channels are in a poor state, there may be large conveyance losses in transporting water to farms near the tail reaches of an irrigation system compared with losses to farms near the head reaches. This results in differences in the cost of delivering water to individual farms, however, currently no irrigation authorities in Australia use marginal delivery cost pricing for charging for water. Currently, Victorian bulk water providers are required to account for transmission losses in their bulk entitlements, although this is not the case in New South Wales (Productivity Commission 1999). However, the differences in delivery costs between farms are generally not taken into account when trading water entitlements. Irrigators face prices that exclude delivery costs, while delivery charges are uniform and do not reflect the marginal delivery costs to individual irrigators. As a result, some irrigators pay a delivery charge per megalitre in excess of the marginal delivery costs to them, while others pay less.

As conveyance losses in many irrigation systems are significant, the current trading arrangements will not result in efficient water use unless the differences in conveyance losses between farms are taken into account to the extent that the benefits of doing so exceed the administration costs.

A model developed by ABARE for the Murrumbidgee Irrigation Area (MIA) can be used to illustrate the potential size of the costs of ignoring differences in conveyance losses between farms. In this study, the model is used to compare water and land prices, resource rents, water use and farm incomes under uniform water pricing with those under an efficient pricing system in which actual conveyance losses are charged to individual users. Provided transaction costs in water rights trading are negligible, the uniform water pricing case is consistent with the existing system of trade in water rights and delivery charges that are equalised across all users. And, again, assuming negligible transaction costs, the efficient pricing case is consistent with trading in water rights and charging marginal delivery costs to each user.

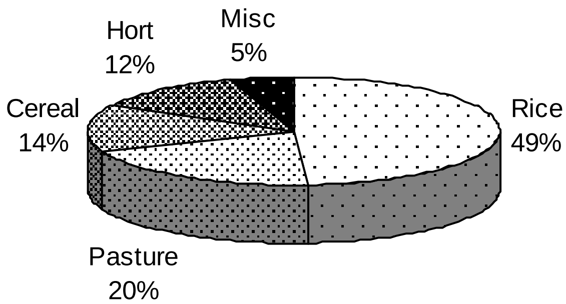
The Murrumbidgee Irrigation Area

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 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 1999, p.43).

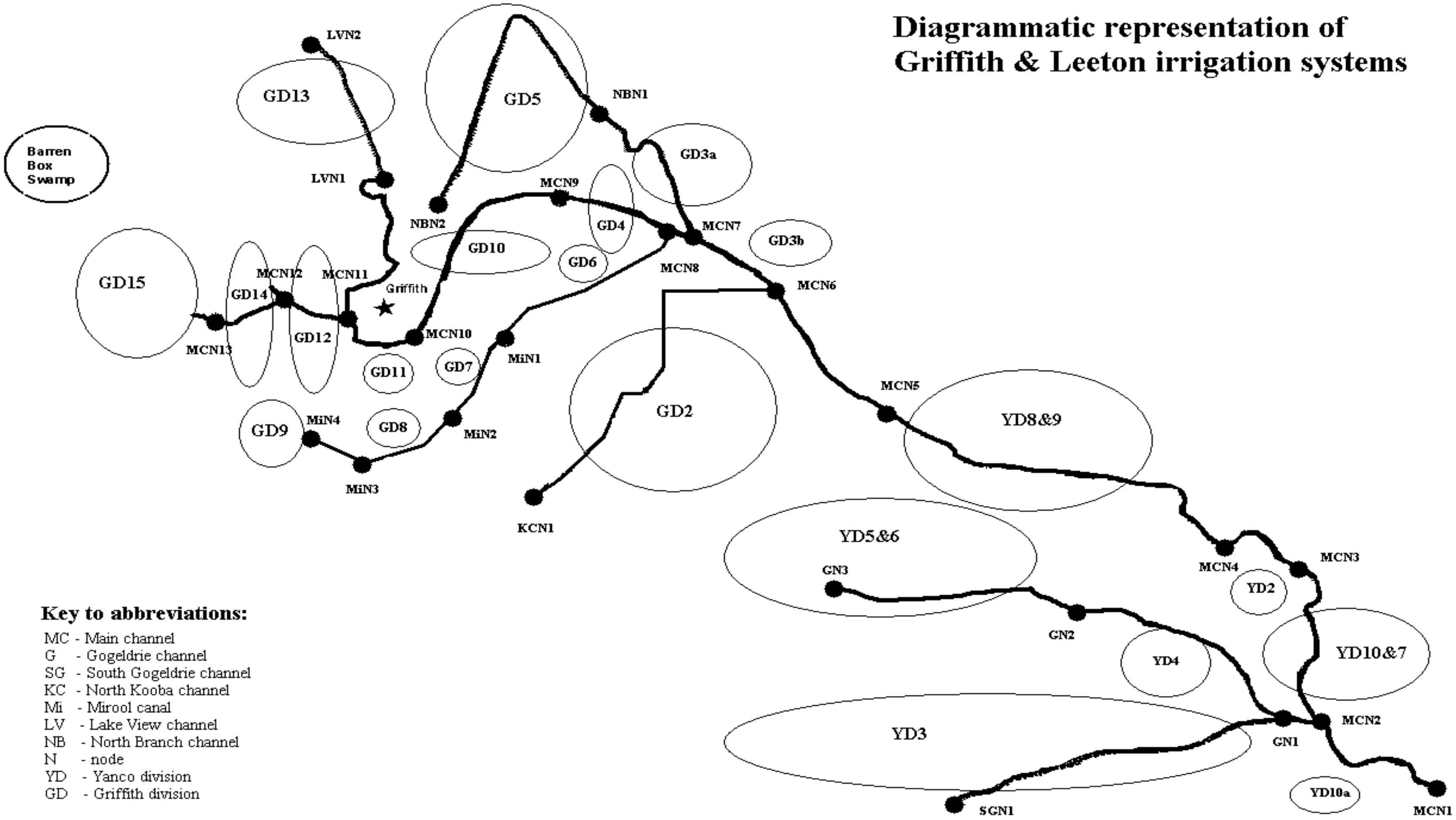
Broadacre cropping is the predominant user of water for agricultural purposes, with rice using almost half of the water used by agriculture, followed by pasture, at 20 per cent and cereals at 14 per cent (Figure 1). Horticulture was estimated to use around 12 per cent of water used by agriculture. The MIA and District system also supplies a small proportion of total water use to rural towns and cities including Leeton and Griffith (Sinclair Knight Mertz 1995).

Figure 1 MIA and Districts: water use by industry, 1996-97



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 channel network after being diverted from the Murrumbidgee River at Narrandera. Irrigation supply channels in the MIA are of varying condition and the extent of losses from the system is influenced by the condition of the channels.

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

The model representation of the MIA

The model includes the Yanco and Mirrool irrigation areas and represents 2400 farms grouped into 26 existing irrigation divisions covering the majority of agriculture in the MIA (figure 2 and appendix table A1). The model has two linked components: the farms in the area and an off farm water delivery system. 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 Main canal and major branch canal reaches conveying water to individual divisions are only represented in the model while the channel network within each division is represented simply by a conveyance loss rate estimate based on the type, condition, length and demand flow rate for each channel segment (appendix table A2). The model is formulated on an annual basis. However, water balancing is done on an average per day basis for each month within a year.

Efficient water pricing and allocation in the presence of transmission losses

In the model, the canal network is represented by 26 sequential reaches separated by nodes with divisions located along the channel reaches. However, for simplicity there is assumed to be one division at each reach. The optimum allocation of water resources within a system occurs when all irrigators equate the local price of received water to their marginal value product (Chakravorty and Roumasset 1991).

Efficient pricing and allocation of water between divisions in the presence of transmission losses can be investigated using volume conditions 1–4 which track water use, losses and flows through the system and the associated price conditions (5–7). The model representation of the MIA has *r* divisions and *r* reaches of variable length, μ_r, each separated by a node $i \neq j$. Water is diverted from the Murrumbidgee River (source) at the Berembid Weir at Narrandera (node *i*=1) to reach *r*=1. A detailed description of all notations used is given in appendix B.

$$\sum_m 30 * Q_m^{11} + WS - WB \leq \Omega \text{ and } V^1 \left[\left(\sum_m 30 * Q_m^{11} + WS - WB \right) - \Omega \right] = 0 \text{, for} \quad (1)$$

The sum over a year of the water flows in month *m* from the Murrumbidgee River through node 1 to reach 1, Q_m^{11}, plus water sold in a year to other water authorities, *WS*, cannot exceed the annual allocations from the river to the irrigation area, Ω, plus water purchased in a year from other authorities, *WB*. 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, V^1, is zero.

$$Q_m^{ir} \le \chi_r \text{ and, } V_{rm}^2\left(Q_m^{ir} - \chi_r\right) = 0 \text{ for } \forall\ i, r \text{ and } m \qquad (2)$$

For each node *i* and each reach *r* the daily water flow, Q_m^{ir}, should be no greater than the peak design daily flow, χ_r. If the daily water flow is less than the design daily flow, then the value of this capacity constraint, V_{rm}^2 is zero.

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

$$V_{irm}^3\left(\frac{CW_{rm}}{(1-\beta_r)} + \sum_{j \in j_i, r' \in r'_i} Q_m^{jr'} + \varepsilon_r \mu_r Q_m^{ir} - Q_m^{ir}\right) = 0, \text{ for } \forall\ i, r \text{ and } m \qquad (3)$$

For division *r* located at reach *r*, in each month *m*, the daily water flow from the supplying node *i* to that reach, Q_m^{ir}, cannot be less than the flow to the division, CW_{rm}, adjusted for daily seepage, escape and evaporation loss in channels within the division occurring at rate, β_r, plus the sum of water flows to the next downstream nodes $\sum_{j \in j_i, r' \in r'_i} Q_m^{jr'}$, plus daily seepage, escape and evaporation losses occuring at rate $\varepsilon_r \mu_r$ in reach *r*. If the flow from node *i* exceeds flow demanded then the value of water at that reach, V_{irm}^3, is zero. As the farms are grouped in to divisions, the escape, seepage and evaporation losses occurring at rate, β_r, within division *r* stand for average losses in local delivery systems in that division.

$$\sum_{n,t} \frac{\xi_{nm} - \eta_{rm} - \delta_{nm}}{(1 + \vartheta_n + \kappa_n)} A_{rnt} \le CW_{rm} \text{ and } V_{rm}^4\left[\sum_{n,t} \frac{\xi_{nm} - \eta_{rm} - \delta_{nm}}{(1 + \vartheta_n + \kappa_n)} A_{rnt} - CW_{rm}\right] = 0 \text{ for } \forall\ r \text{ and } m \qquad (4)$$

In each month *m*, the sum over crops *n* and application technologies *t* of daily water flow requirements at individual farm off takes within division *r* cannot be less than the daily net (after rainfall, η_{rm} and capillary rise, δ_{nm}) evapotranspiration requirement, ξ_{nm}, of all crop activities on the irrigated land adjusted for both surface run off, ϑ_n, and deep percolation losses, κ_n. 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, V^4_{rm}, in the region is zero.

$$(1-\varepsilon_1\mu_1)V^3_{11m} \le V^1 + V^2_{1m} + P^W \text{ and },$$
$$Q^{11}_{km}\left((1-\varepsilon_1\mu_1)V^3_{11m} - \left[V^1 + V^2_{1m} + P^W\right]\right) = 0 \text{ for } \forall \text{ and } m \qquad (5)$$

The price conditions associated with the volume conditions 1–3 state that in each month *m*, the value of water at node 1 reach 1, V^3_{11m},— net of evaporation, seepage and escape losses at that reach — cannot exceed the value of the annual allocation constraint for water at source, V^1, plus the value of the capacity constraint at the Berembid weir , V^2_{1m}, and the delivery charge paid for water at source, P^w, 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. As the MIA is assumed to trade water with other authorities, the value of the allocation constraint in equation 1, V^1 can move between the Value of Temporary Water Entitlements (*VTWE*) net of the delivery charge if water is sold to other authorities and the *VTWE* if water is purchased from other authorities (equations B1 and B2 in appendix B).

$$V^3_{irm} \ge (1-\varepsilon_{r'}\mu_{r'})V^3_{jr'm} \text{ and } \quad Q^{jr'}_m\left(V^3_{imr} - (1-\varepsilon_{r'}\mu_{r'})V^3_{jr'm}\right) = 0 \quad \text{for } \forall\ j \in j_i, r' \in r'_i, m \qquad (6)$$

In each month *m*, the value of water at node *i* and reach *r*, V^3_{irm}, cannot be less than the value of water — net of evaporation, seepage and escape losses — at the next downstream node, j, for any of the subsequent reaches, r', 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 (5) and (6) 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 $V_s = V_m^1 + V_{11m}^2 + P^W = V_{irm}^3 \prod_{r' \in R'} \left(1 - \varepsilon_{r'} \mu_{r'}\right)$, where *R'* is the set of all upstream reaches direct from reach *r* to the source.

$V_{irm}^3 \geq (1-\beta_r)V_{rm}^4$, and $CW_{rm}\left[V_{irm}^3 - (1-\beta_r)V_{rm}^4\right] = 0$ for $\forall$ *r and m* (7)

At each reach *r* and each month *m*, the value of water, V_{irm}^3, cannot be less than the value of water at the division assigned to this reach, V_{rm}^4, 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 in the solution, in the presence of conveyance losses the value of water increases with distance from source (equations 5 and 6) and the rate of conveyance losses occurring within the division (equation 7) until water flow ceases. The difference in the value of water between any two adjoining nodes cannot exceed the value of water lost in conveyance between these nodes. Similarly, the difference in the value of water between a node and an associated division cannot exceed the value of water lost in conveyance between these two points.

The volume and price conditions associated with efficient land use are given in appendix B. These conditions state that in each region *r*, the sum of the areas used for all crops *n* with all application technologies *t*, A_{rnt}, cannot exceed the given area of land, Φ_r (equation B3 in appendix B), and on each division *r*, for each crop *n*, for each application technology *t*, on a per hectare basis, the value of land, V_r^{B3} plus the value of water in all months of the year cannot be less than the given gross margin for that crop managed with that water application method, P_{nt}^{GM} (equation B4 in appendix B).

Efficient water and land use and the corresponding efficient prices of water are obtained as the solution to the problem of maximising the objective function (8) subject to the inequality constraints on volumes (1) – (4) and B3 and prices (5) – (7), B1–B2 and B4.

$$\sum_{r,n,t'} A_{rnt} P_{nt}^{GM} + WS\left(VTWE - P^{W}\right) - WB\ VTWE - P^{W} \sum_{m} 30 * Q_{m}^{11} - \Omega\ V^{1} - \sum_{r,m} \chi_{r} V_{rm}^{2} - \sum_{r} \Phi_{r} V_{r}^{B3} \qquad (8)$$

The objective function represents, for the whole irrigation system, the annual gross margin on all farms plus the annual value of TWE sold outside less the annual value of TWE ‘purchased’ externally, less the total delivery charge on the water entering the system at source, rent to water at source (river), rents to channel 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 channels. In the optimum, the value of the objective function must be zero.

Uniform pricing of water

Some price conditions of the above model are reformulated to represents conditions for optimal behavior 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. The uniform pricing model is formulated by trading off some efficiency elements in the criteria of the efficient pricing model to achieve equity in the form of uniform pricing.

The volume conditions for the uniform pricing model are identical to those of the efficient pricing model. However, the price/cost conditions (5), (6) and (7) are replaced by (9), (10) and (11) respectively.

$$V_{11m}^{3} \le V^{1} + V_{1m}^{2} + P^{W} \text{ and } Q_{m}^{11}\left[V_{11m}^{3} - \left(V^{1} + V_{1m}^{2} + P^{W}\right)\right] = 0, \text{ for } \forall\ m \qquad (9)$$

$$V_{irm}^{3} \ge V_{jr'm}^{3} \text{ and } Q_{km}^{jr'}\left(V_{irm}^{3} - V_{jr'm}^{3}\right) = 0, \text{ for } \forall\ j \in j_{i}, r' \in r'_{i}, m \qquad (10)$$

$$V_{irm}^{3} \ge V_{rm}^{4} \text{ and } CW_{rm}\left[V_{irm}^{3} - \left(V_{rm}^{4}\right)\right] = 0 \text{ for } \forall r \text{ and } m \qquad (11)$$

Note that conditions (9), (10) and (11) differ from conditions (5), (6) and (7), respectively in that seepage, escapes and evaporation losses are ignored. Therefore, if there is water used at a downstream reach *r*, then the value of water at that reach is the same for all direct upstream reaches, *r'*, all the way to the source, $V_s = V^1 + V_{1m}^2 = V_{irm}^3 = V_{i'r'm}^3 = V_{rm}^4 - P^W$.

Values for the farmers' and water authorities' decisions subject to uniform water prices prevailing are obtained as the solution to the conditions (1)–(4), (9)–(11) and B1–B4. 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

$$\sum_{r,n,t'} A_{rnt} P_{nt}^{GM} + WS\left(VTWE - P^W\right) - WB\ VTWE - P^W \sum_m 30 * Q_m^{11}$$
$$- \Omega\ V^1 - \sum_{r,m} \chi_r V_{rm}^2 - \sum_r \Phi_r V_r^{B3} + \sum_{i,m,r} Q_m^{ir}\left(\varepsilon_r \mu_r V_{irm}^3\right) + \sum_{r,m} CW_{rm} \beta_r V_{irm}^3$$

(12)

with respect to nonnegative price and volume variables subject to the inequality constraints for conditions (1)–(4), (9)–(11) and B1–B4. The criterion (12) has the same interpretation as the criterion (8) 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 the efficient pricing model. Again in optimum, the value of the criterion must be zero.

Impact of efficient pricing

The introduction of efficient pricing results in some divisions paying a higher price for water than other divisions, as the cost of water lost in conveyance is fully charged to the individual farmer. The effective price of water increases with the exchange rate from diverted to received water (table 1 and appendix table C1) and as a result, the capital value of irrigable land decreases (equation B4). Thus, the introduction of efficient pricing creates a distributional issue as the value of land and water property rights change. The demand for irrigation water is at its highest in December and exceeds the design flow capacity of the Berembid Weir, creating a positive price for this constraint (equation 2). However, the price of this constraint at source is lower under the efficient pricing option, than under the uniform pricing option as the overall demand for diversion is reduced due to an increase in the average price of water.

Table 1 Estimated efficient price of water at different points in the MIA

Division	Ratio of water diverted to received	Uniform pricing[a]			Efficient pricing[a]		
		Land rent (LFBC) ($/ha.yr)	Price of water ($/ML)	Price of water & infra[b] ($/ML)	Land rent (LFBC) ($/ha.yr)	Price of water ($/ML)	Price of water & infra[b] ($/ML)
Yanco 10a	1.09	216.7	38.4	191.4	240.2	37.2	184.1
Yanco 3	1.13	216.7	38.4	191.4	216.6	38.5	190.5
Griffith 6	1.15	216.7	38.4	191.4	215.9	39.0	193.0
Griffith 4	1.16	216.7	38.4	191.4	215.0	39.5	195.8
Griffith 15	1.17	216.7	38.4	191.4	214.4	39.9	197.7

a. assuming a VTWE of $34/ML and a delivery charge of $14/ML at

b: includes the value of the capacity constraint at the Berembid weir in December when this constraint becomes binding

The administration of the uniform pricing regime entails a subsidy, which is equal to the economic value of water lost in conveyance, and this subsidy enhances the total capital value of irrigation infrastructure and water entitlements. The uniform pricing case is economically inefficient as the estimated total annual profit of $243 million a year by farmers in the MIA is achieved with a total annual cost of $6.9 million to the society (table 2). For each division, the implicit subsidy is estimated by multiplying the volume of water lost in conveyance up to the division by the price of water at the corresponding reach (equation 12). In the uniform pricing option, the price of water remains the same at all reaches and equals the price of the allocation constraint at source plus the price of the infrastructure capacity constraint. With higher prices for land and lower prices for water at downstream reaches compared to efficient pricing, uniform pricing may have encouraged over-expansion of the irrigation area thereby creating additional demands on the existing delivery infrastructure. With efficient pricing, the total annual capital value of irrigation infrastructure fell by 12 per cent as the price of the infrastructure capacity constraint decreased due to a decrease in the demand for diversion water (table 3).

Table 2 Return to resources and financial performance - MIA

	Uniform pricing ($m/yr)	Efficient pricing ($m/yr)	Reduced conveyance losses with uniform pricing ($m/yr)	Reduced conveyance losses with efficient pricing ($m/yr)
Return to resources				
Return to land	142.26	142.66	142.26	143.05
Return to water entitlements	19.85	17.57	19.85	17.57
Return to irrigation infrastructure	29.83	26.20	29.83	30.01
Return to family labour	58.31	58.31	58.31	58.31
Total return to resources	250.25	244.74	250.25	248.94
Less implicit subsidy in average pricing	6.87	0.00	2.48	0.00
Total net return to resources	243.38	244.74	247.77	248.94
Financial performance				
Farm profits	199.98	201.48	204.16	205.76
Off farm income	41.42	41.45	41.33	41.32
Income from selling water outside	1.99	1.81	2.27	1.86
Total	243.38	244.74	247.77	248.94
Return to irrigation water ($/Ml)[a]	247.52	248.29	256.48	254.34
Return to water applied ($/Ml)[b]	279.31	279.44	267.60	265.21

a. Farm profits plus total cost of water delivered less the imputed cost of family labor divided by the total volume of water diverted.
b. Farm profits plus total cost of water delivered less the imputed cost of family labor divided by the total volume of water applied.

The introduction of efficient pricing is estimated to increase total profit by around 1 per cent, or $570 per farm. This is due to more water being used by upstream farms, with a consequent reduction in transmission losses and an elimination of the implicit subsidy as conveyance losses are fully charged to the individual farms. Although farm income is higher on average, efficient pricing results in higher incomes on upstream farms, while incomes on downstream farms are slightly lower than under uniform pricing. Another distributional issue created by efficient pricing is that the values of land and water property rights change whereas uniform pricing results in the equalisation of these values by way of averaging between farms (table 1).

Table 3 Water balance for the MIA

	Uniform pricing (GL/yr)	Efficient pricing (GL/yr)	Reduced conveyance losses with uniform pricing (GL/yr)	Reduced conveyance losses with efficient pricing (GL/yr)
River diversion	790.2	788.0	777.8	785.4
Conveyance losses	89.9	87.8	32.3	32.2
Water applied to crops	700.2	700.2	745.5	753.2
Application losses				
Runoff	66.9	65.8	68.7	68.4
Deep drainage	61.6	62.3	66.1	67.2
Total losses	218.4	215.9	167.1	167.8
Savings in river diversions[a]	0.0	2.2	12.4	4.7

a. Reduction in river diversion from the uniform pricing level.

With efficient pricing, the returns to a unit of water diverted and applied to crops increased while the annual volumes of water diverted decreased from the uniform pricing levels (tables 2 and 3). In addition to an annual saving of 2 GL of diversion, efficient pricing also resulted in a reduction in conveyance and run off losses. The evaluation of the economic impacts of efficient pricing should also include the value of all environmental and other benefits and costs as well as the impact on the farms and irrigation region. The environmental benefits come mainly from reduced river diversion.

Implication for refurbishment of infrastructure

The local price of water and the rate of flow of water at each location influence the profitability of investment in refurbishing irrigation infrastructure. This is because the greater the aggregate value of water flowing through each location, the greater the benefit from preventing its loss. In both efficient and uniform pricing options the annual volume of water flowing declines with the distance from source as the divisions located at different points along the reaches draw water from it, and as water is lost in conveyance. The declining volume of water flowing as distance from source increases tends to decrease the profitability of refurbishment investment further downstream under both uniform and efficient pricing (appendix table C2). However, the increasing marginal value of water with distance from source and/or at higher ratios of diverted to received water under efficient pricing tend(s) to increase the profitability of investment compared with uniform pricing (appendix C1). Overall, the value of water flow declines with distance from source and/or at higher ratios of diverted to received water under both the uniform and efficient pricing options. However, efficient pricing results in refurbishment investment at downstream locations, particularly in divisions with a large ratio of diverted to received water being relatively more profitable, because at these locations the value of water flow is higher than under uniform pricing.

Options for channel refurbishment

Approximately 86 kilometres (11 per cent) of earthen and 53 kilometres (33 per cent) of concrete lined channels found within MIA divisions are rated as in a poor condition (rated as condition 4–6 by the Murrumbidgee Irrigation) (appendix table A2). These channel reaches appear to contribute to the bulk of the seepage, leakage and escape losses in the MIA. In choosing options for refurbishment of channels in poor condition 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. Hafi, Kemp and Alexander (2000) have estimated the capital cost of channel refurbishment for a number of options. Concrete piping with rubber joints has the highest capital cost but requires very little maintenance while clay and membrane lining of earthen channels have some of the lowest capital cost but relatively high maintenance cost. As most of the concrete channels are located on land with highly permeable soils, they need to be refurbished with concrete lining or replaced with pipes. Relining of earthen and concrete channels in conditions 4–6 with clay and concrete respectively is considered to be the most appropriate option largely due to its low capital cost and the ability to significantly reduce seepage losses and fully eliminate leakage and escape losses. The channels within divisions contribute to a large share of the annual seepage, leakage and escape losses from the entire MIA system but to a small share of the evaporation losses (Hafi, Kemp and Alexander, 2000). The option to replace channels within divisions with rubber joint pipes, which would have eliminated all losses including evaporation was not considered because of its high capital cost and the small evaporation losses from the existing channels.

Benefits of reducing conveyance losses with alternative water pricing

In order to estimate the net benefits of investment in channel refurbishment with alternative pricing regimes, a formula for recovering the cost of capital invested need to be developed as refurbishment of infrastructure involves large capital outlay and potential private and public benefits. This is not done in this study due to a time constraint, however, the model was re run separately with efficient and uniform pricing assumptions after reducing the conveyance loss rates (β_r) to reflect the improvement in conveyance efficiency resulting from relining of earthen and concrete channels in conditions 4–6.

In the case of reduced conveyance losses under alternative pricing options, the estimated total profit also includes a return to investment in refurbishment of infrastructure, as the cost of this investment is not netted out from this measure (table 2). Therefore, an increase in this measure over the base level (uniform pricing with high conveyance losses) does not necessarily mean that investment in channel refurbishment results in increased profits. The improvement in conveyance efficiency is estimated to yield greater incremental benefits with efficient pricing ($5.6 million a year) compared to uniform pricing ($4.4 million a year). Reduced conveyance losses with efficient pricing resulted in an increase in the total capital value of land and irrigation infrastructure and a decrease in the capital value of water entitlement. In addition, the basin wide environmental benefits from reduced river diversion estimated at 5 GL a year and ground water accession due to reduced seepage losses also need to be considered.

Conclusions

Charging a uniform price for delivery of water to farmers in an area where the marginal cost of delivering water differs between farms leads to inefficient water delivery and use, and a lower aggregate farm income compared with the outcomes under efficient pricing. In fact, the introduction of trade in water rights without charging users the marginal cost of conveying water (including losses) to them might not have led to more efficient water use. An efficient approach to pricing — one that takes into account differences in conveyance losses between farms — would increase the farm income derived from irrigated agriculture and the profitability of investment in channel refurbishment. However, these income and efficiency gains would come at some administrative cost and there can be both winners and losers, depending on how the losses are accounted for.

Appendix A: Specification of the model representation of the MIA

Table A1 Specification of the Yanco and Mirrool irrigation systems included in the model

Primary / Secondary / Tertiary	Reach No	Division(s) included	Channel capacity (ML/day)	Horticul-ture 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**

Table A2 Length and condition of delivery channels within divisions of the MIA

Primary / Secondary / Tertiary	Division(s) included	Earth length (km)	Earth Condn 4-6 (%)	Concrete length (km)	Concrete Condn 4-6 (%)	Piped length (km)	Piped Condn 4-6 (%)
Main canal-R	Yanco 10a	11.9	37.0	0.0	0.0	0.0	0.0
Gogeldrie -R1							
South Gogeldrie	Yanco 3	60.4	12.0	0.0	0.0	0.1	0.0
Gogeldrie-R2	Yanco 4	29.5	2.0	0.5	0.0	0.3	0.0
Gogeldrie-R3	Yanco 5 & 6	65.8	20.0	3.5	45.0	0.5	0.0
Main canal-R3	Yanco 10 & 7	42.8	8.0	25.0	19.0	3.2	0.0
Main canal-R4	Yanco 2	40.5	5.0	10.7	29.0	2.6	0.0
Main canal-R4	Yanco 8 & 9	133.7	6.0	2.9	21.0	1.2	0.0
Main canal-R5							
North Kooba canal	Griffith 2	54.1	13.0	6.1	80.0	0.8	0.0
Main canal-R6		0.0	0.0	0.0	0.0	0.0	0.0
North branch canal-R1	Griffith 3	15.7	7.0	9.5	33.0	3.6	0.0
North branch canal-R2	Griffith 5	20.4	6.0	12.9	34.0	1.4	0.0
Main canal-R7							
Mirrool canal-R1	Griffith 6	59.8	32.0	0.0	0.0	0.8	0.0
Mirrool canal-R2	Griffith 7	18.6	18.0	15.3	33.0	1.6	1.0
Mirrool canal-R3	Griffith 8	18.4	60.0	4.5	79.0	1.2	0.0
Mirrool canal-R4	Griffith 9	32.8	6.0	0.0	0.0	0.4	0.0
Main canal-R8	Griffith 4	30.2	3.0	12.7	18.0	0.9	0.0
Main canal-R9	Griffith 10	30.9	1.0	2.0	0.0	0.7	0.0
Main canal-R10	Griffith 11	0.5	0.0	20.1	54.0	3.9	0.0
Lake view canal-R1							
Lake view canal-R2	Griffith 13	7.8	7.0	7.3	33.0	10.2	0.0
Main canal-R11	Griffith 12	5.7	0.0	17.4	29.0	7.0	0.0
Main canal-R12	Griffith 14	13.1	0.0	9.7	14.0	10.1	0.0
Main canal-R13	Griffith 15	93.4	1.0	0.2	0.0	1.3	0.0
System total		**786.0**	**11.0**	**160.3**	**33.0**	**51.9**	**0.0**

Appendix B: Other conditions and notations used in the model

$$V^1 \geq VTWE - P^W \text{ and } WS\left[V^1 - \left(VTWE - P^W\right)\right] \quad \text{(B1)}$$

$$V^1 \leq VTWE \text{ and } WB\left(V^1 - VTWE\right) \quad \text{(B2)}$$

$$\sum_{nt} A_{rnt} \leq \Phi_r \text{ and } V_r^{B3}\left(\sum_{nt} A_{rnt} - \Phi_r\right) = 0, \text{ for } \forall r \quad \text{(B3)}$$

$$V_r^{B3} + \sum_m \frac{\xi_{nm} - \eta_{rm}}{\left(1 + \vartheta_{nt} + \kappa_{nt}\right)} V_{rm}^4 \geq P_{nt}^{GM} \quad \text{and} \quad A_{rnt}\left(V_r^{B3} + \sum_m \frac{\xi_{nm} - \eta_{rm}}{\left(1 + \vartheta_{nt} + \kappa_{nt}\right)} V_{rm}^4 - P_{nt}^{GM}\right) = 0,$$

for $\forall r,w,l$ *and* f' (B4)

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	*n* =wheat, canola, soybean rice, lucerne and annual pasture, onions, tomatoes carrots, citrus and vines
t	irrigation technology for horticultural crops	*t* = broad furrow, twin furrow and drip

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)
WS	volume of TWE sold out of the system (ML/year)
WB	volume of TWE purchased from outside the system (ML/year)
CW_{rm}	aggregate rate of water flow to farms in division *r* in month *m* (ML/day)

Parameters

P^{W}	delivery charge of water at source ($/ML)
$VTWE$	Value of temporary water entitlements outside the system ($/ML)
P_{nt}^{GM}	gross margin of crop *n* planted with application technology *t* ($/ha)
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 channels 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	annual volume of water diverted at the source by the water authority (ML/year)
χ_r	Channel capacity constraint in reach *r* (ha)
Φ_r	area of land available on farm *r* (ha)
δ_{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: Detailed results

Table C1 Land rents and the price of water and access to infrastructure with efficient pricing

Primary Secondary Tertiary	Division(s) included	Land rent (LFBC) ($/ha/yr)	Price of water ($/ML)	Price of water & infrastructure ($/ML)	Ratio of water recived to diverted
Main canal-R	Yanco 10a	240.2	37.2	184.1	1.09
Gogeldrie -R1					
South Gogeldrie	Yanco 3	216.6	38.5	190.5	1.13
Gogeldrie-R2	Yanco 4	218.6	37.2	184.1	1.09
Gogeldrie-R3	Yanco 5 & 6	216.5	38.6	191.0	1.13
Main canal-R3	Yanco 10 & 7	242.1	37.0	183.3	1.09
Main canal-R4	Yanco 2	218.5	37.3	184.7	1.10
Main canal-R4	Yanco 8 & 9	217.9	37.7	186.5	1.11
Main canal-R5					
North Kooba canal	Griffith 2	215.4	39.3	194.5	1.15
Main canal-R6					
North branch canal-R1	Griffith 3	217.6	37.8	187.4	1.11
North branch canal-R2	Griffith 5	216.6	38.5	190.8	1.13
Main canal-R7					
Mirrool canal-R1	Griffith 6	215.9	39.0	193.0	1.15
Mirrool canal-R2	Griffith 9	217.1	38.2	189.1	1.12
Main canal-R8	Griffith 4	215.0	39.5	195.8	1.16
Main canal-R9	Griffith 10	229.4	38.0	188.4	1.12
Main canal-R10	Griffith 11	218.0	37.6	186.0	1.10
Lake view canal-R1					
Lake view canal-R2	Griffith 13	217.3	38.1	188.4	1.12
Main canal-R11	Griffith 12	233.9	37.7	186.6	1.11
Main canal-R12	Griffith 14	217.6	37.8	187.3	1.11
Main canal-R13	Griffith 15	214.4	39.9	197.7	1.17

Table C2 Tracking the annual river diversion through the MIA with efficient pricing

Primary Secondary Tertiary	Division(s) included	Inflow (GL/yr)	Applied to crops (GL/yr)	Conveyance losses (GL/yr)	Outflow (GL/yr)
Main canal-R	Yanco 10a	788	2	3	783
Gogeldrie -R1		190	0	0	190
South Gogeldrie	Yanco 3	84	74	9	0
Gogeldrie-R2	Yanco 4	106	16	2	88
Gogeldrie-R3	Yanco 5 & 6	88	78	10	0
Main canal-R3	Yanco 10 & 7	593	33	5	555
Main canal-R4	Yanco 2	555	13	2	539
Main canal-R4	Yanco 8 & 9	539	145	16	379
Main canal-R5		379	0	1	378
North Kooba canal	Griffith 2	47	41	6	0
Main canal-R6		331	0	1	331
North branch canal-R1	Griffith 3	61	14	1	45
North branch canal-R2	Griffith 5	45	41	4	0
Main canal-R7		270	0	0	270
Mirrool canal-R1	Griffith 6	92	20	3	69
Mirrool canal-R2	Griffith 7	69	13	1	55
Mirrool canal-R3	Griffith 8	55	14	2	40
Mirrool canal-R4	Griffith 9	40	36	3	0
Main canal-R8	Griffith 4	178	11	2	164
Main canal-R9	Griffith 10	164	15	2	148
Main canal-R10	Griffith 11	148	7	1	141
Lake view canal-R1		48	0	0	48
Lake view canal-R2	Griffith 13	48	44	4	0
Main canal-R11	Griffith 12	92	13	1	78
Main canal-R12	Griffith 14	78	22	2	54
Main canal-R13	Griffith 15	54	47	7	0
System total		**788**	**700**	**88**	**0**

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