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Management of irrigation water storages: carryover rights and capacity sharing

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The intertemporal management of irrigation water involves a consumption-storage decision, where the benefits of using water today are evaluated against the uncertain benefits of storing water for future use. Traditionally in Australia, state governments have centrally managed the major water storages: making decisions on water allocations given prevailing storage levels. However, in practice there are a number of factors which may prevent a centralised approach from achieving an optimal allocation of water. This paper considers in detail two decentralised approaches to storage management: carryover rights and capacity sharing. This paper also presents a quantitative analysis of storage management, involving the application of a stochastic dynamic programming model.

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1 Introduction

Water storages (reservoirs) serve to reduce the variability of the supply of irrigation water. The management of these storages involves an inter-temporal consumption-storage decision, where the benefits of consuming water today need to be evaluated against the uncertain benefits of storing water for future use. In Australia, state governments have traditionally centrally managed the major water storages: making decisions on water allocations (water released for consumption today) given prevailing storage levels. Adopted storage policies can be thought to vary along a yield-reliability spectrum: ranging from conservative (low yield-high reliability) to aggressive (high yield-low reliability).

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In practice there are a number of factors which could prevent a centralised storage management policy from achieving an optimal allocation of water, including the presence of asymmetric information between the central manager and irrigators. Where a central manager adopts a sub-optimal storage management policy, this may result in reductions in mean irrigator incomes and potential increases in income variability. In this paper, the potential effects of sub-optimal storage policy on irrigators are demonstrated quantitatively, via a stochastic dynamic programming model applied to a representative region.

An alternative to central control of water storages is to decentralise the process by providing water users with some form of storage or inter-temporal transfer property right. This paper considers two property rights systems, carryover rights and capacity sharing. Carryover rights allow water users to hold over a proportion of their seasonal water allocation for use in future seasons. Carryover rights have, in various forms, been widely adopted within the Murray-Darling Basin. However, carryover rights are subject to a number of limitations.

Capacity sharing is a system of property rights to water from shared storages proposed by Dudley (Dudley and Musgrave 1988, Dudley and Alaouze 1989, Dudley 1990a, Dudley 1992). Rather than allocating users a share of total releases, each user is allocated a share of total storage capacity, as well as a share of inflows into and losses from the storage. Capacity sharing has been adopted successfully by SunWater at the St George irrigation region in southern Queensland and more recently in the nearby MacIntyre-Brook region. Capacity sharing has a number of potential advantages over standard carryover rights systems; however it remains largely untried outside Queensland.

The first section of this paper describes the storage management problem in detail and considers how a centralised approach can potentially lead to an inefficient allocation of water. The second section of the paper presents the results of a quantitative analysis of irrigation storage management, in which a stochastic dynamic optimisation model is applied to a representative irrigation region. The third section of the paper considers two alternatives to centralised storage management: carryover rights and capacity sharing.

2 The water storage problem

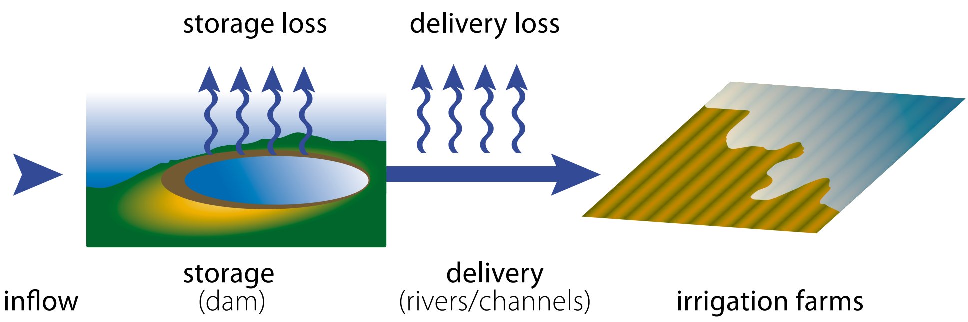
The water storage problem involves a comparison of the marginal benefit of consuming water now with the expected marginal benefit of storing water for consumption in the future such that the expected net present value of welfare is maximised in the long run. While this type of consumption-storage problem is common in economics, the water storage problem has a number of unique features.

One of these unique features is the extreme variability of the supply of water. The primary source of this variability is climate variability: inflows into storages are the product of variable rainfall (particularly in Australia) and associated catchment run-off. Further, the demand for water tends to be inversely related to inflows and this acts to exacerbate the variability in the marginal value of water. For example, in dry periods, when inflows are low, farm rainfall and soil moisture are likely to be lower and crop water requirements higher. Another relatively unique feature of the water storage problem is the presence of centralised storage. While private on-farm storage of water is possible, it is often costly and inefficient relative to collective water storage in central dams.

An optimisation problem

This section defines the water storage problem more precisely as a stochastic dynamic optimisation problem. A number of economists have modelled the irrigation water storage problem in this way (Dudley 1998, Dudley and Hearn 1993, Beare et al. 1998, Brennan 2008, Alouze 1992 and Howitt et al. 2002). For a detailed review of the relevant economic literature see Brennan (2007). An applied example of the model is presented later in the paper. The model focuses on the storage problem facing a simple representative irrigation system as shown in figure a.

a A simple irrigation system



It is assumed the irrigation system contains a single water storage, which receives stochastic inflows. A single storage model can be interpreted as an aggregated representation of a multiple storage system (see for example Perera and Codner 1988). The model also assumes there is no on-farm water storage and that there are no instream or tributary flows downstream of the storage. Irrigation water is released from the storage and transported to farms (via natural water courses and irrigation channels), and losses occur both in storage and in the delivery of water.

In practice, an irrigator's demand function for water will be the result of a comprehensive production decision, in which the optimal use of a range of inputs (for example land, water and labour) is determined given prevailing input and output prices. For the purposes of this model, a simple exogenous demand curve for water is assumed. In the long run, irrigators also face capital investment decisions. Again, for simplicity, it is assumed the capital stock and the land developed for irrigation is fixed. Irrigators' capital investment decisions are considered in more detail in Hafi et al. (2001), Hafi et al. (2006) and Brennan (2006).

The model is formulated in discrete time. The model time periods can be thought of as water years (for example financial years), although theoretically the unit of time could equally be months or days. Later in the paper we consider some of the practical differences between inter-seasonal (between year) and intra-seasonal (within year) water storage decisions.

Demand for irrigation water

From equation 1, demand for irrigation water Q, by water user i, at time t, is a function of the price of water p and the local water state R (local rainfall and/or prevailing soil moisture).

The local water availability state, R, is assumed to be determined by an exogenous stochastic process. Water users, i, are intended to represent individual irrigators (as the owners of water entitlements), however this could easily be generalised to include other types of water users.

1 Where: $Q_{i,t} = d_i(p_t, R_t)$

Q = Water demand

p = the market price of water

R = local rainfall/soil moisture

d = demand function

Supply of irrigation water

The model assumes there is a single class of water entitlement. Each irrigator has a nominal entitlement V and in each period the social planner announces a percentage allocation A. The allocation specifies the proportion of the entitlement available for consumption in the current period. It is also assumed that allocations can not exceed 100 per cent of entitlements. Equation 2 is the market clearing condition which states that total allocated water (supply) must equal total water demand. For each irrigator, net trade can be calculated as the difference between final demand Q and the initial allocation in period t (equation 3).

2

$$A_t \sum_i v_i = \sum_i Q_{i,t}$$

$$A_t \leq 1$$

3

$$T_{i,t} = Q_{i,t} - A_t V_i$$

Where:

A = allocation proportion

V = nominal water entitlement

T = net trade in water

The total volume of water available in any time period, W_t, is equal to the starting water storage level, S_{t-1}, plus inflows, IN_t, less storage evaporation losses, EL_t (equation 4). Inflows are assumed to be generated by an exogenous stochastic process. Evaporation losses (equation 5) are assumed to be some increasing function of the storage level. Storage evaporation losses may in practice depend on a range of factors, including prevailing weather conditions.

In each period t, system outflows, Out, must be less than total water availability as in equation 6. Outflows include allocated irrigation water plus delivery losses, plus any fixed water requirements (equation 7). For simplicity, transmission losses are assumed equal for all irrigators.

4 $$W_t = S_{t-1} + IN_t - EL_t$$

5 $$EL_t = f(S_{t-1})$$

6 $$Out_t \leq W_t$$

7 $$Out_t = A_t\left(\sum_i V_i\right)(1 + tl) + fw$$

Where:

W = total water availability

S = volume of water in storage

IN = inflows into storage

Out = total water outflow

tl = transmission loss parameter

fw = fixed water requirements (minimum river flows, essential town water etc)

EL = evaporation losses

Equation 8 specifies the evolution of the water storage level over time. The volume of water held in storage at the end of each time period t, equals start of period storage volume plus inflows, less storage losses and outflows. The storage volume is constrained by the maximum storage capacity, S_{MAX}, and the minimum storage level, S_{MIN} (equation 9).

8 $$S_t = S_{t-1} + IN_t - Out_t - EL_t$$

9 $$S_{MIN} \leq S \leq S_{MAX}$$

Where:

S_{MAX} = total storage capacity

S_{MIN} = minimum storage level (dead storage)

An implicit assumption in the model is that inflows and outflows occur simultaneously within each period. This assumption is reasonable for certain time scales; however it may become less realistic for longer time periods. For example, in a model with an annual time scale a large proportion of inflows may occur early in the period before outflows are released, potentially resulting in dam spills.

The objective function

The optimisation problem involves choosing the allocation A, for each point in time and each state of the world, which maximises the objective function given the water availability constraints. The objective function is shown in equation 10 and is equal to the expected discounted sum of water surplus (the area under the water demand curve less the marginal cost of suppling water). Implicit in the objective function is the assumption that water users are risk neutral.

$$\max_{A_t}\left\{E\left(\sum_{t=1}^{\infty}\beta^t\sum_i\left(\int_0^{Q_{i,t}}d^{-1}(Q_{i,t},R_t)dQ_{i,t}-Q_{i,t}mc\right)\right)\right\} \quad (10)$$

Where:

β = discount factor

mc = the short run marginal cost of supplying irrigation water

The model can be solved as a discrete stochastic dynamic programming problem with one policy variable, A, and two state variables, W and R. An applied example of the model is presented later in the paper.

Unused allocations

The model above implicitly assumes all allocated water is used within the period it is allocated, yet in practice this may not be the case. Unused allocations may occur if there are constraints in the delivery (or trade) of water or where the marginal benefit of water use is less than the marginal cost. Unused allocations are more likely to arise in wet years when the marginal value of water is low, and where there are restrictions on intra- or inter-regional water trade and/or restrictions on inter-temporal water management. Unused allocations are returned to the common pool and result in an increase in storage levels and an improvement in the reliability of water entitlements. It has been noted by Brennan (2008) that the removal of institutional constraints on trade may result in an increase in the utilisation of allocations, which may inadvertently have a detrimental effect on the reliability of water entitlements.

Centralised storage management

In Australia, the storage management decision tends to be centrally controlled. This occurs through an announced allocation system, where in each season the dam manager announces a percentage allocation: the percentage of the nominal entitlement volume available for use within that season.

Consider the simplified example of an irrigation system outlined above: a single storage, stochastic inflows, multiple irrigators with unrestricted intra-regional trade in allocations. In order for a centralised storage management policy to achieve an efficient allocation of water a number of conditions must be met.

First we need to assume the dam manager has perfect information. Specifically, that the dam manager has information on the (current and future expected) aggregate demand curve for water. Effectively, the dam manager needs to know the marginal value of water for each point in time and each water state of the world. Given this information, the dam manager would be in a position to develop an optimal release rule, which would specify the optimal aggregate amount of water to be released from the storage (the optimal allocation A_t) for each point in time and for each water state.

Secondly, we need to assume that water (allocation) trade within the region is efficient and costless, that is, there are zero transaction costs. Under these assumptions, the optimal aggregate amount of water would be released each period and this water would then be efficiently allocated across irrigators via trade in water allocations. Under these conditions, the allocation of water across time and space would be efficient. In practice there may be a number of reasons why these conditions may not be met and why a centralised storage management policy may lead to a sub-optimal allocation of water, including asymmetric information between the storage manager and irrigators and the presence of transaction costs associated with water trade.

Asymmetric Information

In practice, it is unlikely dam managers will have complete information on irrigator water preferences. Dam managers may obtain approximations of aggregate water demand (current and expected) through observing traded prices and through discussions with representative irrigators. However, it is unlikely dam managers will obtain full information on aggregate water demand without knowing individual water demands. Irrigators are likely to have information on their water demands that is not available to dam managers. Further, the costs of acquiring this information from individual irrigators are likely to be prohibitive, particularly given significant heterogeneity and variability in irrigator preferences.

Irrigators may display highly heterogeneous water preferences as a result of differing crop water requirements (for example perennials and annuals), spatial variation (differences in soil type and local climate), and variation in risk preferences. Irrigators' water preferences may change over time in response to changes in relative prices of commodities, which could alter the mix of irrigated activities, or they could change if irrigators' attitudes to risk change.

With asymmetric information, a central manager may implement a sub-optimal release (allocation) policy. For example, a central manager with incomplete information may choose to adopt a simple aggressive release policy, releasing all available irrigation water in each period. In practice, asymmetric information may affect both inter-seasonal (between years) and intra-seasonal (within water years) storage decisions. This distinction is discussed briefly below.

Intra- and inter-seasonal storage decisions

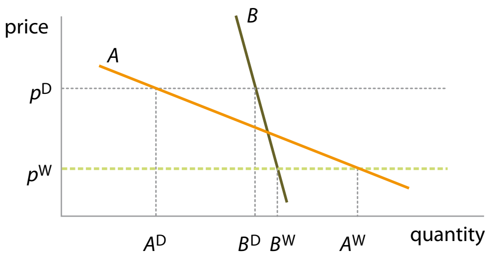
Water allocation occurs on a 'water year' or irrigation season cycle. In each season, the announced allocation specifies the volume of water available for use. Allocations are announced incrementally within the season: typically the initial allocation is relatively low, before allocations are increased as additional inflows arrive. In the absence of any carryover rights, the dam manager maintains control over the inter-seasonal water storage decision. Irrigators do have a degree of flexibility over intra-seasonal water use/storage, since they can delay the use of announced allocations within the season. However, irrigators can not bring forward later season allocations. This can be a problem where the intra-seasonal allocation is overly conservative, that is, where early season allocations are low and there is unallocated water available in storage. This may occur in practice for a number of reasons.

Under the current entitlement system, dam managers have to ensure enough water is available to deliver all allocation volumes and to cover all losses. In order to avoid reducing announced allocations, dam managers may hold excess water in storage early in the season to insure against the risk of higher than anticipated losses. Where the dam manager has imperfect information on water demands (especially the timing of water use within the season), uncertainty over expected season losses will be higher. In the short run, the intra-seasonal allocation of water may also be delayed by lag times in allocation announcements.

Transaction costs

There is evidence to suggest irrigators face significant transaction costs when trading water allocations in the Murray-Darling Basin (see Allen Consulting 2006). Transaction costs in water allocation trade can include both direct financial costs, such as fees paid to water brokers and exchanges and application fees paid to governments, as well as non-financial costs such as time costs incurred by irrigators. As noted by Freebairn and Quiggin (2006), while transaction costs may be expected to decline as water markets 'mature' (and as improvements are made to property rights systems and associated institutions) the fundamental complexity of water rights (and of water as a commodity) would suggest transaction costs are likely to remain significant for the foreseeable future. In addition to transaction costs there also exist a range institutional constraints on water trade, although these less commonly apply to intra-regional temporary trade (trade in allocations within a region), see (Goesch et al. 2006, Goesch et al. 2008 or Peterson et al. 2004).

b Water requirements of two irrigators under variable supply



Under a simple announced allocation system (with a single class of entitlement), substantial temporary trade in water allocations may be required to achieve an efficient allocation of available water across irrigators (Freebairn and Quiggin 2006). This can be illustrated with a simple example as shown in figure b. In this example there are two irrigators; irrigator A has an elastic demand curve for water (for example annual crops) while irrigator B has an inelastic demand curve (for example perennial crops). P^W represents the market price of water in a 'wet' year while P^D is the higher market price of water during a 'dry' year. For simplicity it is assumed the demand curves are the same in both states.

From the diagram it can be seen that irrigator B demands a similar amount of water in each state, irrigator A's demand varies significantly between states. Under a simple announced allocation system, substantial temporary trade will need to occur to generate an efficient allocation of water. If both irrigators have identical water entitlements, irrigator B will buy water from irrigator A in a dry year, while in a wet year irrigator A will buy water from irrigator B. Any system of water property rights which better aligns entitlement reliability levels with irrigator reliability preferences will tend to reduce the need for temporary water trade and reduce irrigators' exposure to associated transaction costs. One approach is to define different classes of water entitlements with distinct reliability levels (that is, high and low reliability entitlements).

High and low reliability entitlements

High and low reliability entitlement systems are relatively common in the Murray-Darling Basin. High and low reliability entitlement systems have the potential to reduce temporary water trade requirements by providing water rights which more closely match the reliability preferences of individual irrigators (see Freebairn and Quiggin 2006). However, a two reliability level approach has a number of limitations. Under this system, irrigators will need to hold a mix of the two entitlement classes in order achieve a specific reliability level. This may involve some additional cost for irrigators, particularly where there are transaction costs associated with permanent trade. Such a system also places an artificial upper and lower bound on available reliability levels.

Under a high and low reliability system there is a need to ensure the mix of high and low reliability entitlements in the system at any point in time is appropriate. Freebairn and Quiggin (2006) consider a system where the water authority takes an active role in the market for water entitlements to ensure the optimal mix of high and low reliability entitlements is achieved. Such a system would use market preferences for high and low reliability entitlements to reveal information about the aggregate reliability preference in a region. There are, however, obvious costs associated with a water authority taking such an active role, including the transaction costs of engaging in the market as well as additional administrative effort and regulatory requirements. In addition, there are likely to be difficulties in determining the appropriate conversion ratios between high and low entitlements.

Implications for investment

In the model and discussion above it has been assumed the irrigation capital stock is fixed. In the model we have assumed irrigators can not make any additional investments to increase the area set up for irrigation or to change irrigation activities. In practice, it is likely there will be significant interdependence between storage management polices and irrigator investment decisions. For example, Dudley (1988) develops a model where total area irrigated and storage policies are jointly determined by a single decision maker. Brennan (2006) presents a model where the proportion of available irrigation land devoted to three activities (horticulture, dairy and broadacre) is a function of the yield and reliability of water entitlements.

In the long run, a fixed centralised storage policy may act as a constraint on irrigator investment, for example preventing an optimal distribution of low and high flexibility irrigation activities. Where a fixed aggressive storage policy is adopted this may constrain investment in more intensive forms of agriculture which require more reliable water supply. A potential example of this would be the significantly greater proportion of horticultural activity in Victorian irrigation systems relative to NSW systems where the storage policy is significantly more aggressive.

3 Model case study

In this section the optimisation model developed earlier is applied to a case study region to demonstrate the potential benefits of improvements in storage policy. The case study is based on the Murrumbidgee region in NSW. The choice of the Murrumbidgee region is one of convenience and it is intended that the results be sufficiently general.

The Murrumbidgee region is a relatively complicated water supply system with two major storages, the Blowering and Burrinjuck dams, and a connection to the Snowy Mountains hydroelectric scheme. The modelling in this study abstracts from these complexities and makes the simplifying assumption of a single storage. For a detailed representation of the Murrumbidgee system, with multiple storages and constraints in delivery capacity, see the model of Beare et al. (1998). A detailed discussion of model assumptions and solution procedures is contained in appendix A. Model parameters have been estimated econometrically using empirical data or drawn from econometric literature where possible.

Results

Two distinct storage policies are evaluated in this case study: a base case policy representative of a sub-optimal 'aggressive' storage policy, and an optimal storage policy. The base case storage policy assumes all available irrigation water (water in excess of basic environmental and town water requirements) is allocated up to a maximum allocation of 100 per cent in any given water year. With such a rule, inter-year storage reserves occur only when water availability exceeds 100 per cent of entitlement volumes. This rule implicitly assumes there are no unused allocations and no reserves are held for high security entitlements. This rule can be considered a reasonable approximation of the typical centralised policy adopted in NSW irrigation systems, see Hughes et al. (2009).

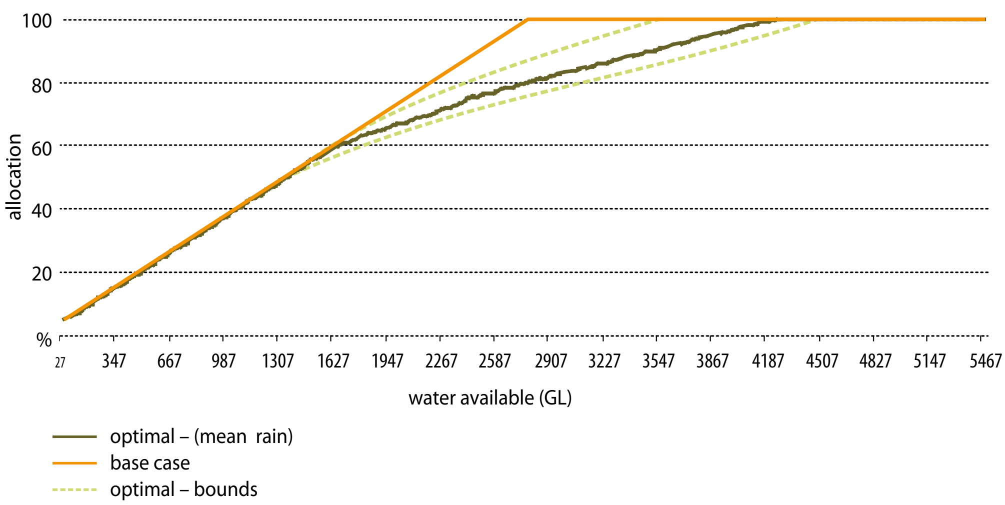
The optimal policy represents the release policy that would be adopted by a central planner with full information. The optimal policy can also be interpreted as the aggregate release policy that would result under an effective decentralised system of storage management, such as carryover rights or capacity sharing (discussed in detail later in the paper). The difference in welfare (as measured by mean water surplus) between the two polices represents the potential gains from improving storage management policy in the presence of information asymmetry. However, the model excludes a number of other potential benefits of improved storage management, such as a reduction in reliance on temporary trade (and associated transaction costs) and removal of constraints on investment.

It is important to note the estimated optimal release policy should not be interpreted literally as the optimal policy to be applied in the Murrumbidgee region. Clearly if there is an information problem preventing the dam manager from estimating the optimal policy (as we propose), the same information problem would prevent any researchers from estimating it.

Policy functions

The base case policy function and the estimated optimal policy function (the allocation or release rule) are shown in figure c.

C Estimated optimal release rule



These policy functions specify the allocation of water as a function of the state of the world: the level of water availability and local rainfall. For very high and very low levels of water availability, the optimal policy and the base case policy converge. In between these extremes, the optimal policy allocates less water and holds more water in storage.

Simulation results

Given the estimated policy function, Monte Carlo simulations can be performed and probability distributions over key variables generated. Tables 1, 2 and 3 contain the simulation results for key model variables, including the mean value, standard deviation (S.D.) and coefficient of variation (C.V.). The model assumes there are two irrigators, with irrigator 1 being representative of broadacre / general security entitlement holders and irrigator 2 being representative horticulture / high security entitlement holders.

The optimal storage policy results in a small reduction in mean water allocations (–0.6%) and mean water use (irrigator 1: –0.8%, irrigator 2: +0.2%) relative to the base case policy, and a substantial increase in the mean (end of year) storage level (from 14 per cent to 33 per cent). Overall, the optimal policy results in an 11.8 per cent increase in mean irrigator water surplus relative to the base case.

The optimal policy has an even greater effect on the variability of water use and water prices. The variability of water use (as measured by the coefficient of variation) is reduced by 26.5% for irrigator 1 and by 28.7% for irrigator 2, while the variability in the objective value is reduced 63.6 per cent. A key feature of the optimal policy is its ability to use storage to reduce the variability of water supply. While the model doesn't explicitly account for the risk preferences of irrigators, if irrigators are risk averse they will value a reduction in the variability of water supply.

1 Simulation results, base policy rule

	units	mean	S.D.	C.V
Allocation, A	%	82.8	20.86	0.25
Price, P	$ / ML	65.7	257.0	3.91
Storage level, S	%	14.0	21.8	1.55
Evaporation Loss, EL	GL	66.9	16.4	0.24
Water Demand/Use, Q_i				
– Irrigator $i = 1$	GL	1 662.4	444.3	0.27
– Irrigator $i = 2$	GL	250.0	37.5	0.15
Objective Value	$ Million	353.8	132.9	0.38

2 Simulation results, optimal policy rule

	units	mean	S.D.	C.V
Allocation, A	%	82.3	15.2	0.18
Price, P	$ / ML	55.1	114.0	2.07
Storage level, S	%	33.0	25.0	0.76
Evaporation Loss, EL	GL	74.8	16.6	0.22
Water Demand/Use, Q_i				
– Irrigator $i = 1$	GL	1 649.7	324.1	0.20
– Irrigator $i = 2$	GL	250.4	26.8	0.11
Objective Value	$ Million	395.5	54.6	0.14

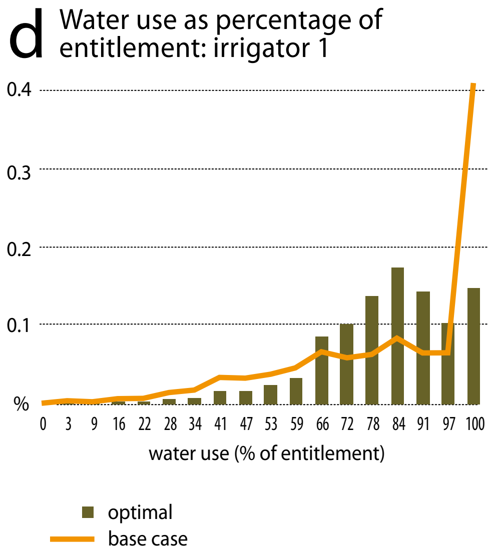
3 Simulation results, deviation from base

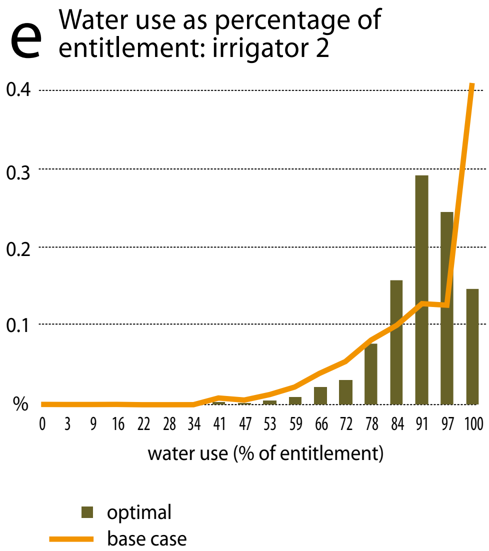
	units	mean	S.D.	C.V.
Allocation, A	%	–0.6	–27.2	–26.7
Price, P	%	–16.3	–55.6	–47.0
Storage level, S	%	134.8	14.7	–51.2
Evaporation Loss, EL	%	11.8	1.6	–9.2
Water Demand/Use, Q_i				
– Irrigator $i = 1$	%	–0.8	–27.1	–26.5
– Irrigator $i = 2$	%	0.2	–28.6	–28.7
Objective Value	%	11.8	–58.9	–63.3

Overall, the modelling results here are consistent with similar studies undertaken by Brennan (2008) and Dudley (1988) in that a sub-optimal release policy results in a relatively small reduction in mean incomes and a substantial increase in the variability of incomes.

Figures d and e display histograms for water demand/use for the two representative irrigators under the base case and optimal policies.

These figures demonstrate how the differences in water preferences between the two irrigators result in different water use patterns given variability in water supply. Irrigator 1 (broadacre) displays relatively variable water use relative to irrigator 2 (horticulture). Figures d and e also demonstrate the effect of the optimal release policy on the variability of water use. For both irrigators, the optimal policy results in a lower probability of a 100 per cent allocation, in exchange for a lower probability of low allocations relative to the base case.





It should be noted that the model assumes the existence of a single class of water entitlement and that any differences in the reliability of water use between irrigator 1 and irrigator 2 occur as a result of temporary water trade. When water allocations are reduced, irrigator 2 offsets the reduction by purchasing water from irrigator 1. In theory, an equivalent outcome could be achieved if the dam manager, knowing the preferences of individual irrigators, constructed separate water entitlements with appropriate reliability levels, or alternatively, where each irrigator owned a capacity share and managed releases according to their reliability preferences.

Sensitivity analysis

The inflow and rainfall distribution used in this model was estimated based on historical data. As such, it may overestimate future water availability levels given the potential effects of climate change. Further, the Murrumbidgee irrigation region has tended to receive reasonably reliable inflows (relative to many other irrigation systems in the Murray-Darling Basin). For these reasons it is useful to consider how the model results change when water availability is reduced. A sensitivity analysis was performed to estimate the effect of reduced rainfall and inflows on model results. In each of the scenarios the joint rainfall and inflow probability distribution is altered such that mean inflows and rainfall are reduced in a fixed ratio of 3:1 (3 per cent reduction in inflows for every 1 per cent reduction in rainfall), to capture the fact that reductions in rainfall are expected to be associated with more than proportional reductions in run-off (see Adamson et al. 2007).

The scenarios therefore assume both an increasing probability of low rainfall conditions and lower mean inflows associated with each rainfall state. Each scenario captures both a reduction in irrigation water availability and an increase in irrigation water demand because of a reduction in local rainfall. The results of this sensitivity analysis are shown in tables 4 and 5.

As expected, reductions in mean rainfall and inflows result in reductions in mean objective values and increases in mean water prices for both the optimal and base case simulations. The important point to note here is that the benefits of adopting the optimal storage policy over the base case policy increase as water availability is reduced. That is, as water availability is reduced

4 Sensitivity analysis, reduction in inflow/rainfall, mean effects

	units	scenario			
Rainfall Mean	% change	Basecase	–5	–10	–15
	mm	406.6	386.3	365.9	345.6
Inflow Mean	% change	0	–15	–30	–45
	GL	2 704	2 301	1 898	1 491
Base Case					
– Mean Price	$/ML	65.7	115.3	243.0	555.4
– Mean Objective	$ Million	354	315	273	206
Optimal Policy					
– Mean Price	$/ML	55.1	69.3	89.1	128.1
– Mean Objective	$ Million	395	382	362	332
Deviation					
– Mean Price	% change	–16.3	–39.9	–63.3	–76.9
– Mean Objective	% change	11.8	21.2	32.6	61.8

5 Sensitivity analysis reduction in inflow/rainfall, variance effects

	units	scenario			
Rainfall Mean	% change	Basecase	–5	–10	–15
	mm	406.6	386.3	365.9	345.6
Inflow Mean	% change	0	–15	–30	–45
	GL	2 704	2 301	1 898	1 491
Base Case					
– S.D. Price	$/ML	257.0	528.4	978.1	1620.6
– S.D. Objective	$ Million	133	161	202	279
Optimal Policy					
– S.D. Price	$/ML	114.0	179.2	199.5	266.6
– S.D. Objective	$ Million	55	45	44	52
Deviation					
– S.D. Price	% change	–55.6	–66.1	–79.6	–83.5
– S.D. Objective	% change	–58.9	–71.8	–78.3	–81.3

the gain in mean welfare (mean objective) and reduction in income variability (S.D of objective) associated with the optimal policy increases.

The model results confirm that with greater water scarcity there is more to be gained by improving the management of irrigation water storages. Where inflows are frequently high, storages are likely to be full or near full most of the time and there may be little scope to improve outcomes by holding any more water in storage. When inflows are lower and less reliable, there is more to be gained by holding water in storage to insure against drought conditions. This is an important result given predictions of reduced water availability across much of the Murray-Darling Basin in the future as a result of the effects of climate change.

4 Carryover rights and capacity sharing

An alternative to centralised storage management is to decentralise the process by designing some system of property rights allowing individual irrigators to exercise a degree of control over storage decisions. In this paper, two specific decentralised approaches to storage management are considered: carryover rights and capacity sharing. A decentralised approach to storage management may help to address some of the problems of centralised storage management outlined earlier in the paper including asymmetric information and transaction costs in water trade.

A decentralised approach to storage management allows irrigators to make their own storage decisions, taking into account their private information on water needs. In the presence of asymmetric information between irrigators and dam managers, decentralised storage management may result in releases from storage more closely aligning with the preferences of irrigators, which could potentially increase returns to irrigators in the long run. Further, by making their own storage decisions irrigators can effectively influence the reliability of their entitlement such that it better matches their preferences. More closely aligning individual water entitlements with reliability preferences will reduce the volume of temporary water trade required and reduce transaction costs associated with trade.

Carryover rights

Carryover rights can be more precisely defined as inter-seasonal transfer rights: the right to transfer allocations between seasons. Specifically, a carryover right allows each water user to hold over a proportion of their current season's water allocation for use in future seasons. Without carryover provisions, any unused allocations are returned to the common pool and shared among water users in future periods. Carryover rights have been in place in many New South Wales and Queensland irrigation systems for some time and have recently been introduced into a number of Victorian and South Australian systems.

Introducing carryover provisions allows irrigators to make storage decisions according to their specific preferences. Carryover rights may help irrigators overcome some of the problems associated with central storage management such as asymmetric information and transaction costs associated with trade. Carryover is, however, an incomplete property right since it does not explicitly define rights to dam capacity (or to storage losses), and as such does not ensure dam capacity is rationed efficiently.

Carryover rights are subject to exclusivity problems: carryover decisions have external impacts which influence other users of the same storage. Carryover water consumes scarce storage space and contributes to storage losses either through evaporation or through storage spills. Under an announced allocation system, these external effects are socialised across all irrigators in the system. For example, when water is carried over, no adjustments are made for associated increases in storage losses: effectively any increase in storage loss is socialised, such that those who do not carry over water are adversely affected by those who do.

In practice, carryover provisions often have a number of restrictions imposed on their use. For example, there may be limits on the amount of water that can be carried over in any season. Carryover rights may not be perpetual in that water can be carried over from one season to the next but not necessarily held over indefinitely. The motivation for placing such restrictions on carryover may be to limit the potential for external impacts. However, where these restrictions are binding they can prevent a more efficient intertemporal allocation of water being achieved. Access to carryover over water may also be subject to sovereign risk as has been demonstrated in a number of recent instances where irrigators have been denied access to carryover water during drought periods.

Continuous accounting

Standard carryover rights operate on a seasonal (water year) time scale. Continuous accounting is a form of carryover where users' accounts are updated on a more frequent (generally daily) time scale. With continuous accounting, any water not used in each time period automatically caries over to the next period (day). Each user has a single water balance such that there is no distinction made between 'carryover water' and water allocations. As of 2005-06, the Border Rivers, Gwydir and Namoi regions in NSW had implemented continuous accounting (MDBC 2007).

Continuous accounting can in some respects be considered a compromise between standard carryover rights and capacity sharing. For example, under continuous accounting, limits are generally placed on the volume of water each user can accrue rather than on the proportion of allocations which can be carried over. These limits could potentially be based on a share of available storage capacity. However, even where this occurs, there are significant differences between continuous accounting and capacity sharing. Most notably, continuous accounting carryover still involves centralised allocation announcements and does not redefine water rights at the source.

Capacity sharing

The basics

Capacity sharing is a system of allocating property rights to water from shared storages proposed by Dudley (Dudley and Musgrave 1988). Capacity sharing involves redefining water entitlements into separate storage space rights and water/inflow rights. Each entitlement holder in an irrigation system is allocated a share of the total system storage capacity, as well as a share of total inflows (and losses). Users are able to manage these capacity shares independently: determining how much water to use (or sell) and how much to leave in their share of storage. Users in effect have their own water account which receives stochastic deposits (inflows) which can be withdrawn (released) as the user requires.

Capacity sharing results in water entitlements which more closely reflect the physical realities of the water supply system: constrained storage capacity, variable water inflows and significant storage and delivery losses. Capacity sharing ensures that storage space is efficiently rationed and external effects are minimised, by ensuring losses are internalised. Unlike carryover rights, capacity sharing completely replaces the traditional announced allocation system. The dam manager no longer needs to make allocation announcements and their role becomes one of water accounting: recording each user's inflows and withdrawals to monitor the quantity of water in each user's account.

Under capacity sharing, trade in water involves withdrawing water from the seller's account and depositing it into the buyer's account. This is equivalent to temporary water trade or trade in allocations under an announced allocation system. In contrast, trade in permanent water involves trade in storage space rights and inflow rights. Queensland water authority SunWater has successfully introduced capacity sharing into two of their irrigation systems in southern Queensland (St George and MacIntyre Brook). The capacity sharing schemes at St George and MacIntyre Brook are the subject of ongoing ABARE research (Hughes et al. 2009).

While capacity sharing minimises external effects relative to carryover rights, it does not result in perfectly independent water entitlements. In particular, there is the issue of 'internal spills'.

Internal Spills

Internal spills occur when an individual capacity share becomes full and receives surplus inflows (while other users' shares are less than full), necessitating the reallocation of surplus water to other water users. Where there exists an efficient market in water (temporary trade), any method of reallocating this water (for example arbitrary reallocation or some form of auctioning) will result in an efficient allocation of surplus water across users. Given well-specified property rights (to storage and water), internal spills will not prevent an optimal allocation of water being achieved in the short run. However, internal spills may be a problem if they are frequent and large such that individual irrigator inflows become significantly dependent on the actions of other irrigators.

In practice, internal spills are likely to occur infrequently, since capacity share holders will have an incentive to use or sell water (or to purchase additional storage space) whenever there is a significant probability of an internal spill occurring. For example, where the volume of water in an individual's capacity share is high and/or there is a significant expectation of a high inflow event. In systems where users have accurate up-to-date information on capacity share volumes and expected inflows, and where the transaction costs of withdrawing water or selling water (or purchasing additional storage space) are low, internal spills should be relatively rare.

Storage losses

Another complication with capacity sharing is the allocation of storage losses, the main component of which is evaporation losses. Evaporation losses are a function of the surface area of the storage and prevailing weather conditions. Given that dam banks are sloped, surface area varies significantly as the volume of water in the dam changes. In order to maintain exclusivity, storage losses allocated to individual users should be calculated as a function of their capacity share volume, such that users with more water in storage are exposed to a higher proportion of total storage losses. Ideally, evaporation losses should be shared such that each user is exposed to their marginal contribution to total evaporation loses. Under certain conditions, this can be approximated by allocating total evaporation losses in proportion to the volume of water in each user's capacity share (Hughes et al. 2009).

Additional benefits

There are a number of benefits associated with capacity sharing in addition to those mentioned above. One of these additional benefits is reduced regulatory uncertainty faced by irrigators. Under a standard announced allocation system, irrigators are exposed to regulatory or government uncertainty, since the potential yield and reliability of water entitlements are dependent to some extent on the policies of dam managers. For instance, the allocation rules used by central authorities may be complex and subject to a degree of discretion, making it difficult for irrigators to predict announced allocations. Furthermore, uncertainty may surround the allocation rules themselves, given they may be altered over time and in response to different sets of circumstances.

Under a capacity sharing system, the yield and reliability of any given water entitlement depends only on irrigator water use/storage decisions and the hydrology of the water supply system. This reduced uncertainty may make it easier for irrigators to compare the yield and reliability of water entitlements across different regions and may assist irrigators in making their own forward planning decisions, including crop choice, planting area and capital investment decisions.

Another potential benefit of capacity sharing is that it defines rights to water at the source, i.e. the point of storage. Defining water rights at the source (or 'source tagging') can improve the efficiency of water allocation in a number of ways including: internalising delivery losses, facilitating unbundling of water rights (including separate rights to delivery capacity) and addressing third party effects of inter system water trade in connected river systems Heaney et al. (2006).

In most irrigation systems, water is transported significant distances through natural water courses and irrigation channels, which can be subject to significant delivery losses including evaporation and seepage. A proportion of these delivery losses may be flow dependent (Heaney et al. 2006), such that total delivery losses will vary depending on the volume of water ordered by irrigators, the timing of water orders within the year and the location of water use. When delivery losses are internalised there will be incentives to trade water into locations with lower delivery losses or to time releases to occur during periods when delivery losses are lower.

Where water rights are defined at the point of the farm, third party effects (in terms of the reliability / yield of entitlements) can arise when trading water in connected river systems, particularly where water entitlements are traded upstream of a tributary (Heaney et al. 2006). Under a capacity sharing system, the yield and reliability of water entitlements is tied to the system of origin and such effects are limited.

Another potential problem that can arise with an announced allocation system is insider trading. There may be incentives for insider trading to occur when individuals obtain information about allocation decisions prior to their announcement. With capacity sharing, no central allocation decisions are required, reducing the potential for insider trading.

Other Issues

Most irrigation water storages also provide water for uses other than irrigation, including urban, stock and domestic and environmental water use. Under capacity sharing, these other water uses could be allocated separate capacity shares which they could then manage independently

(Dudley and Musgrave 1988). Such a system would also facilitate trading between irrigation, urban and environmental water users. Capacity sharing may be particularly beneficial to environmental water managers, whose role is likely to increase in significance in the future.

The adoption of capacity sharing is likely to involve substantial set up costs. However, once in place, the operating costs are likely to be relatively low. In fact the operating costs may potentially be lower than those incurred under traditional announced allocation systems as has been the case for SunWater at St George (SunWater 2008). Some of the initial costs incurred in setting up a capacity sharing system would include the costs of developing a computer based accounting system, educating and consulting with irrigators, and making required changes to regulations.

One potential constraint to the introduction of capacity sharing may be irrigator concerns surrounding the entitlement conversion process. There may be resistance from irrigators if it is perceived some entitlement holders are going to be potentially worse off (and others better off) after the transition. While an efficient allocation of storage capacity and inflow shares will be achieved regardless of the initial allocation (so long as there exists an efficient secondary market), from a practical perspective these distributional issues are important.

The analysis in this paper has focused on a simple representative water supply system involving a single major water storage. In practice there can exist a range of more complicated water supply systems, with multiple storages and multiple connected rivers. While implementing capacity sharing may be more challenging in complex water supply systems, capacity sharing should not be viewed as a method which is only suited to simple systems. For example, there are a number of options for dealing with multiple storages including defining separate rights to each storage, or defining rights to combined system storage capacity (Dudley 1990b). The implementation of capacity sharing in more complex water supply systems is not considered in detail in this paper but remains a potential subject for future research.

5 Conclusion

This paper has outlined, in the context of a simple model, a number of reasons why a centralised storage management approach may result in an inefficient allocation of water resources, including asymmetric information and transaction costs in water trade. Clearly it is unlikely in practice that central managers will be able to obtain full information on the water preferences of irrigators. In the presence of such asymmetric information, central dam managers may adopt a sub-optimal storage (release) policy. Further, under a centralised storage management policy, a substantial amount of seasonal water trade may be required to achieve an efficient allocation of water across different irrigators. Where there are significant transaction costs in water trade, a water property rights system which reduces this trade requirement will be welfare enhancing.

The simple optimisation model developed in this paper was applied to a case study region in order to demonstrate quantitatively the potential effects of sub-optimal storage policy on the incomes of irrigators. Using the model, a representative aggressive storage policy was compared with an estimated optimal storage policy. The model demonstrated the ability of optimal storage policy to generate both increased mean incomes and reduced variability of incomes. Given reasonable parameter value assumptions, the model estimated an increase in mean surplus to irrigators of 11.8 per cent and a reduction in the variability of surplus of more than 66 per cent. The model also demonstrated that the gains from optimal storage management (both in terms of mean and variability of incomes) increase substantially as the level of water availability reduces.

An alternative to centralised storage management is to decentralise the process, by introducing property rights allowing irrigators to make independent storage decisions. A decentralised approach has the potential to overcome some of the problems of centralised management such as asymmetric information and transaction costs in water trade. Two decentralised approaches to storage management are considered in this paper: carryover rights and capacity sharing.

Carryover rights have been adopted, in varying forms, in the majority of irrigation systems in the Murray-Darling Basin. However, carryover rights are an incomplete solution, since they do not define explicit property rights to storage capacity or to losses associated with storage. As a result, carryover rights generate external effects, where individual irrigator carryover decisions affect other irrigators in the system. In an attempt to minimise these external effects, significant restrictions are often placed upon carryover rights which further weaken their effectiveness.

Capacity sharing is a property rights system proposed by Dudley (Dudley and Musgrave 1988), involving redefining water entitlements into separate storage capacity rights and water/inflow rights. Unlike carryover rights, capacity sharing ensures storage space is efficiently rationed and losses are internalised. Capacity sharing has a number of other potential benefits relative to systems of carryover rights including: defining water rights at the source rather than at the farm and replacing the traditional announced allocation system.

The concept of capacity sharing is considered, both by Dudley (Dudley and Musgrave 1988) and in this paper, within the context of relatively simple water supply system (where all water is sourced from a single storage). While there may exist some concern about the suitability of capacity sharing in more complex systems, it is not obvious the concept could not be sufficiently generalised. The ability for the capacity sharing framework to be applied to a range of more complex water supply systems remains a subject for potential future research.

In many cases, centralised storage management polices implemented by state governments may not be in alignment with the overall water preferences of irrigators. While carryover rights have been introduced to help address this problem, these are subject to significant limitations. Further, the announced allocation framework adds an unnecessary layer of complexity and uncertainty to irrigator water entitlements. It is clear there exists significant scope to improve the management of irrigation water storages. Capacity sharing is a promising approach which deserves further consideration by policy makers.

Appendix Model assumptions

Unit of time

The model time unit is the financial year, encompassing the irrigation season which typically operates between August and May. As such, the model focuses on inter-seasonal rather than intra-seasonal water allocation. This large time unit simplifies the modelling and overcomes a number of data limitations. However, an annual time scale prevents the model from representing the significant intra-seasonal variability typically observed in both the supply and demand for water.

Supply of Water

A normal distribution is fitted to approximately 100 years of historical local rainfall data (the average of annual rainfall at Griffith and Leeton). Data was obtained on historical combined annual storage inflows (Blowering and Burrinjuck) between 1975 and 2007, from the NSW Department of Water and Energy (2006) PINNEENA database. A conditional inflow distribution was estimated via a simple linear OLS regression of inflows against rainfall between 1975 and 2007, such that the mean of the inflow distribution is a linear function of rainfall and the standard deviation is constant. The estimated rainfall and inflow distribution parameters are shown in table 7, along with other supply parameter assumptions. The marginal delivery cost of water is set with reference to irrigation water marginal usage charges (see IPART 2006).

The fixed water requirement includes town water and basic environmental water. Estimates for these flow amounts are based on observed historical allocations for town, stock and domestic and other water requirements as well as deviations between recorded outflows and irrigation water use. It is also assumed that the fixed water requirement (town, stock and domestic, and minimum environmental water) is provided whenever sufficient water is available. That is, the fixed requirement takes priority over irrigation water demands.

6 Model case study supply side parameter assumptions

description	parameter	units	value
Conditional Inflow mean	IN_{μ}	MLs	265 760 + 5 930R_t
Conditional Inflow SD	IN_{σ}	MLs	670 683
Rainfall mean	R_{μ}	Mm	406.6
Inflow SD	R_{σ}	Mm	109.8
Storage capacity	S_{MAX}	MLs	2 657 410
Minimum storage level	S_{MIN}	MLs	27 240
Delivery cost	Mc	$ per ML	5
Conveyance loss	L	%	25
Town, Stock and Domestic water	F	MLs	100 000
Basic environmental Water		MLs	150 000

An evaporation loss function was developed, using historical time series data on mean annual storage levels and mean annual pan evaporation and relationships between surface area and storage volume for each of the two dams obtained from the PINEENA database. The resulting function specifies total annual evaporation as a function of the start of year storage level and the annual inflow volume.

Given an annual timescale, the model may potentially underestimate dam spills in cases where a large proportion of seasonal inflows occur early in the season prior to any outflows occurring. One way of overcoming this problem would be to estimate seasonal spills from historical data similar to the approach of Brennan (2008). However, the lack of an adequate time series of dam spill data has prevented this approach being adopted here.

Demand for Water

The demand side of the model assumes two irrigators, one representative of broadacre / general security entitlement holders, another representative of horticulture / high security entitlement holders. Each irrigator's demand for water is assumed to be a function of price and local rainfall. Nested constant elasticity functions are used to capture the effect of local rainfall and price on demand for irrigation water. Price elasticities and rainfall elasticities for irrigation water have been set in the model with reference to a review of available econometric literature, (for example, Brennan 2006, Bell et al. 2007, Bjornlund and Rossini 2005 and Wheeler et al. 2008). For a detailed discussion of this literature see Hughes et al. (2009).

In a full allocation year it is assumed each irrigator demands a water allocation equal to their nominal entitlement. The market price of water in a full allocation year is set to a specific value based on observation of historical data in the region.

It is assumed horticulture water demand becomes perfectly inelastic once a threshold level is reached, beyond which permanent horticulture plantings may die because of lack of water. In reality, crop destruction occurs incrementally as the oldest, less valuable, tress will be allowed to die first, while water is allocated to the most valuable trees. The assumption of a perfectly inelastic demand curve at a fixed point is a simple method of capturing the basic effect of extreme water scarcity on horticultural agriculture. In the event water availability is low enough that the minimum threshold level of water for horticulture is not available, the model imposes a penalty representing the Net Present Value (NPV) cost of horticultural crop destruction based on unpublished ABARE estimates for the Murrumbidgee region.

7 Model case study demand side parameter assumptions

description	parameter	units	value
Water entitlement (Irrigator 1)	E_1	MLs	2 029 360
Water entitlement (Irrigator 2)	E_2	MLs	279 000
Price elasticity of demand (Irrigator 1)	α_1		–1.0
Price elasticity of demand (Irrigator 2)	α_2		–0.5
Price of water (when $A = 1$ and R = mean)	P^*	$	40
Rain elasticity of demand (for both irrigators)	φ		–0.2
Irrigator 2 (horticulture) minimum water threshold	Q_2^{Min}		0.4

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