Management of irrigation water storages:

carryover rights and capacity sharing

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Disclaimer (National Program for Sustainable Irrigation)

Foreword

The dry conditions experienced in the Murray-Darling Basin in recent years have seen unprecedented reductions in the availability of water for irrigation. Climate change predictions suggest that significant reductions in water availability will be observed across the Basin in the long term. At the same time, there is increasing demand for environmental water to maintain the health of ailing river and wetland systems.

Irrigation water is an increasingly scarce commodity. Therefore, it is important that Australia finds ways to maximise the productive value of available irrigation water resources.

This project, which received funding support from the National Program for Sustainable Irrigation, investigates one important area of potential water allocation reform: the management of water storages. The report considers how providing water users with greater control over storage decisions could lead to improvements in the efficiency of water allocation over time. In particular, this report considers capacity sharing; a system where irrigators are allocated explicit property rights to storage capacity in major reservoirs.

Phillip Glyde
Executive Director
May 2009

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Summary

This report represents the first part of a two part project investigating the management of irrigation water storages. The report focuses on the economics of storage management and the potential advantages of a capacity sharing approach. The second part of this project examines in detail two capacity sharing schemes implemented in Queensland – St George and MacIntyre Brook. The results of the second part of the project are to be presented in a subsequent ABARE research report: *Capacity sharing in the St George and MacIntyre Brook irrigation schemes in southern Queensland*.

Water storage management

Water storages (reservoirs) play a vital role in the supply of water for irrigation farms. Storages smooth variation in the supply of water and in the value of water over time. Appropriate management of water storages is particularly important in Australia, given the extreme variability of inflows and predictions of lower and more variable inflows within the Murray-Darling Basin because of climate change.

The management of irrigation water storages involves comparison of the benefits of consuming water today against the expected 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 in the current period) given prevailing storage levels. However, determining what proportion of available water to store for the future (and how much to consume now) is a complex problem given the presence of substantial uncertainty over future inflows and water demands.

Centralised storage management

For a centralised storage management policy to achieve an efficient allocation of water across time and across irrigators, a number of conditions must be met. First, the dam manager requires complete information on the water needs of irrigators. Second, trade in water allocations must be efficient and costless. Under these conditions, the optimal aggregate amount of water would be released each period and this would be efficiently allocated across individual irrigators via trade in water allocations.

In practice, these conditions may not be met and a centralised approach may lead to an inefficient allocation of water. In particular there may be asymmetric information between the storage manager and irrigators, and transaction costs in water trade.

Asymmetric information

Asymmetric information means that irrigators are likely to have information on their water demands that is not available to dam managers. Obtaining information on water preferences from individual irrigators may be difficult for a number of reasons. First, water preferences are likely to vary significantly across different irrigators because of differences in crop types.

Second, irrigators' water preferences are likely to be subject to significant change over time. With asymmetric information, a central manager may implement a sub-optimal release (allocation) policy, that will ultimately reduce average returns to irrigators in the long run.

Transaction costs in water trade

Transaction costs refer to costs incurred when making an economic exchange. There is evidence to suggest that irrigators face significant transaction costs when trading water allocations in the Murray-Darling Basin. Water trade can be subject to both direct financial transaction costs such as government and brokers' fees, and non-financial indirect transaction costs such as time costs incurred by irrigators. Under a simple announced allocation system, substantial temporary trade in water allocations may be required to achieve an efficient allocation of water across different irrigators in each time period.

High and low reliability entitlements

High and low reliability entitlement systems (referred to as general and high security entitlements in New South Wales) are relatively common in the Murray-Darling Basin. High and low reliability entitlement systems have the potential to reduce temporary water trade requirements, and reduce irrigators' exposure to transaction costs, by providing water rights which more closely match the reliability preferences of individual irrigators (Freebairn and Quiggin 2006). However, systems of high and low reliability entitlements do have a number of practical limitations.

Implications for investment

While not considered in detail in this report, in practice it is likely that storage management policies will have important implications for irrigator investment decisions. For example, storage management policies, by influencing the yield-reliability of water entitlements, will tend to influence the relative attractiveness of different irrigated activities. 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.

A water storage model

As a part of this study, an economic model of the water storage problem facing a representative irrigation system was developed. The model incorporates representations of the demand for water by irrigators and the irrigation water supply system (e.g. inflows, storage and associated losses). The model is stochastic, in that inflows into storages and rainfall onto irrigation farms are subject to random variation, based on a defined probability distribution estimated using historical data. A detailed discussion of the model is contained in appendix A.

The optimisation model developed was applied to a case study region to demonstrate the potential benefits of improvements in storage policy. The case study region is based on the Murrumbidgee region in New South Wales. Although the case study is intended to be illustrative in nature, the results presented in this report are intended to be broadly applicable to other regions. Model parameter values were set with reference to historical data and estimates from econometric literature. A summary of model assumptions is contained in appendix B.

Results

Using the model, an arbitrary 'aggressive' release (allocation) rule was compared with a theoretically optimal release rule. The estimated optimal release policy involves holding more water in storage reserves, relative to the aggressive policy.

The estimated optimal release rule involves a small reduction in mean water use, in turn for a substantial increase in mean storage reserves. The optimal release rule acts to minimise variation in the supply and value of water over time. The model demonstrates that optimal storage policy can lead to an increase in mean irrigator incomes and a substantial reduction in variability of incomes. The model results show an estimated increase in the mean economic value of water of 11.8 per cent and a reduction in variability of more than 63 per cent.

A sensitivity analysis conducted using the model also demonstrated that the gains from optimal storage management (both in terms of mean and variability of incomes) increase substantially as water availability reduces. The results confirm that with greater water scarcity, there is more to be gained by improving the management of irrigation water storages. That is, 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 because of the effects of climate change.

Carryover rights and capacity sharing

An alternative to centralised storage management is a decentralised approach, in which individual irrigators are given greater control over storage decisions. Decentralised approaches have the potential to address the problems of centralised storage management. In this report, two decentralised approaches to storage management are considered: carryover rights and capacity sharing.

Carryover rights

A carryover right allows water users to hold over a proportion of their seasonal water allocation for use in future seasons. 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.

While carryover rights may help irrigators overcome some of the problems associated with central storage management, carryover rights are an incomplete solution. Carryover rights are incomplete because they do not explicitly define rights to storage capacity or to associated storage losses. As such, individual carryover decisions have external effects which influence other users of the same storage. In an attempt to minimise these external effects, significant restrictions are often placed on carryover rights, which further weaken their effectiveness. Access to carryover 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.

Capacity sharing

Capacity sharing is a system of allocating property rights to water from shared storages proposed by Dudley (Dudley and Musgrave 1988; Dudley and Alaouze 1989; Dudley 1990a; Dudley 1992). Under capacity sharing, each entitlement holder in an irrigation system is assigned a share of the total system storage capacity and a share of total inflows. Users are free to manage these capacity shares independently; determining how much water to use (or sell) and how much to leave in their share of storage.

Capacity sharing results in water entitlements which more closely reflect the physical realities of the water supply system. Unlike carryover rights, capacity sharing ensures that storage space is efficiently rationed and losses are internalised. Capacity sharing has a number of other potential benefits relative to systems of carryover rights. Capacity sharing replaces the traditional announced allocation system and, in doing so, removes a layer of regulatory uncertainty. Capacity sharing also involves redefining water rights at the source, which offers a number of potential efficiency improvements, including the potential to internalise water delivery losses.

One complication with capacity sharing is the occurrence of internal spills – where individual water accounts reach capacity and forfeit their inflows to other water users. However, the economic costs of internal spills are negligible and internal spills are likely to occur infrequently in practice. Another important consideration in the transition to capacity sharing will be to minimise any actual or perceived distributional effects, by ensuring the newly defined capacity share water entitlements adequately preserve all existing irrigator water entitlements.

Capacity sharing is typically considered in the context of relatively simple water supply systems, where all water is sourced from a single storage. While there may be some concerns about the suitability of capacity sharing in more complex systems, it is not obvious that the concept could not be sufficiently generalised. The ability of the capacity sharing framework to be applied to a range of more complex water supply systems remains a subject for potential future research.

1 Introduction

This report represents the first part of a two part project investigating the management of irrigation storages. This report focuses on the economics of storage management and the potential advantages of a capacity sharing approach. The second part of this project examines in detail two capacity sharing schemes implemented in Queensland – St George and MacIntyre Brook. The results of the second part of the project are to be presented in a subsequent ABARE research report: *Capacity sharing in the St George and MacIntyre Brook irrigation schemes in southern Queensland*.

Water storages serve to reduce variability in the supply of irrigation water. The intertemporal management of these storages involves a 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 and expectations of future conditions.

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). Yield refers to the long run mean release/allocation level, while reliability refers to the variability of releases. A conservative rule would on average release a smaller percentage of available water for immediate consumption, holding more over in storage for future periods, resulting in higher reliability. The storage polices implemented in Victorian irrigation systems tend to be significantly more conservative than those implemented in New South Wales.

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 the mean incomes of irrigators 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 property right. This paper considers two such property rights systems in detail: carryover rights and capacity sharing. Carryover rights are an extension to existing water property rights which allow a proportion of seasonal water allocations to be held for use in future seasons. Carryover rights have been widely adopted within the Murray-Darling Basin, in various forms. However, for a number of reasons, carryover rights do not represent an ideal solution to the storage problem.

Capacity sharing is an alternative system of allocating property rights to water and was first 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 and a share of inflows into, and losses from, the storage. Capacity sharing has been adopted successfully by SunWater at St George in south-west Queensland and more recently in the nearby MacIntyre Brook region. Capacity sharing has a number of potential advantages over traditional water property rights systems, however it remains largely untested outside Queensland.

The first section of this report 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 this report presents the results of a quantitative analysis of irrigation storage management for a representative irrigation region. The third section considers two alternatives to centralised storage management: carryover rights and capacity sharing.

2 Water storage management

The management of irrigation water storages involves a consumption-storage problem: water can either be released from storage and consumed in the current period or held in storage for use some time in the future. While this type of consumption-storage problem is common in economics, the water storage problem does have a number of unique features.

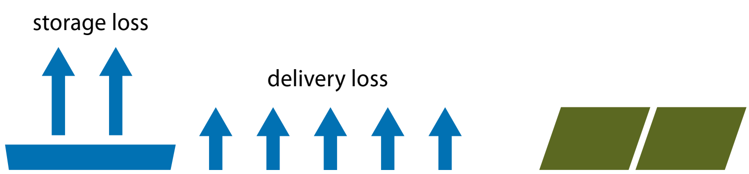
One of the unique features of the irrigation water storage problem is the magnitude of uncertainty surrounding the future supply of water. The primary source of this uncertainty is weather variability, with inflows into storages being the product of highly variable rainfall and resulting catchment run-off. 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 compared with collective water storage in major dams.

One main role of large irrigation water storages is to help mitigate this variability, particularly supply variability. By retaining a proportion of available water in storage, dam managers can accumulate a buffer stock which effectively smooths variability in water supply. Determining how much water to retain in storage is a complex problem, given uncertain future inflows and water needs.

The water storage problem

For the purposes of this discussion, the storage problem facing a simple irrigation scheme is considered, as shown in figure a. While in practice irrigation schemes may involve a range of additional complexities not included in this example, the essence of the storage problem is relatively universal. In this simple irrigation scheme there is a single storage (dam) which receives variable inflows, upstream of an irrigation area comprising a number of irrigated farms.

a A simple irrigation scheme

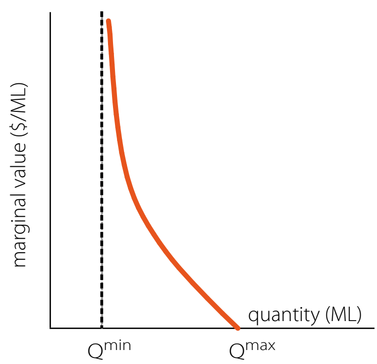


Irrigation water is released from the storage and transported to farms via natural water courses (for example rivers) and irrigation channels. Losses occur both in storage and in the delivery of water through evaporation and seepage. It is assumed there exists no on farm storage and no in stream or tributary flows downstream of the storage.

In each time period there is a certain amount of water available, equal to the start of period storage level (water carried over from the previous period), plus within period inflows, less any storage losses. Each period a proportion of this available water is released for irrigation and a proportion remains in storage for use in future periods. These time periods can be thought of as water years (financial years) although theoretically the unit of time could equally be months or days.

Increasing irrigation water use generates benefits to irrigators by increasing the yield of crops, which in turn increases revenues and profits. Marginal increases in crop yields tend to decline as total water use increases, and at some point additional water may cease to generate increases in yield (a point referred to as maximum yield). Conversely as total water use declines, there may exist a threshold below which crops die because of water stress; at this point the marginal benefit of additional water use will be high. Crop death is particularly costly for irrigators with perennial plantings.

b An irrigator demand curve for water



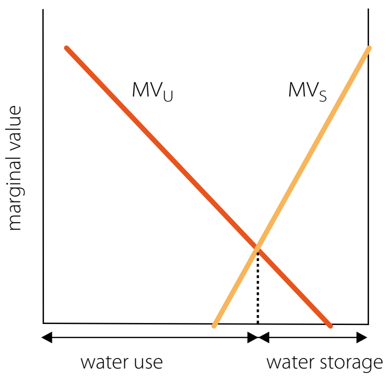
The marginal benefit or marginal value of water to an irrigator can be represented by a demand curve. The demand curve displays the irrigators willingness to pay for irrigation water (equivalent to the marginal benefit/value) for each level of water use. The demand curve slopes down since the marginal value of water use declines as total water use increases. In practice, demand curves for irrigation water will be influenced by a range of factors in addition to yield effects, including input and output prices and the amount of direct rainfall the farm receives. The aggregate demand curve for the irrigation region can in turn be represented as the aggregation of individual irrigator demand curves.

There may be a marginal cost associated with using irrigation water (the cost of transporting water from dam to farm and applying it to crops). For most levels of water use, the marginal cost is likely to be well below the marginal benefit. Therefore, for the purposes of this discussion it is assumed that the marginal cost is zero.

In the hypothetical case where inflows into storage are certain; where each period the dam is filled and enough water is available to provide all irrigators with their maximum level of water use, the marginal value of water would be equal in each time period and there would be no incentive to store any water for future periods. In contrast, in the case where inflows are variable; and there exists a chance of a drought occurring, water availability in a drought year would be low and the marginal value of water use high. Therefore, it may be optimal to forgo some water use during periods of high availability (low marginal value) in order to store more water for low availability (high value) periods.

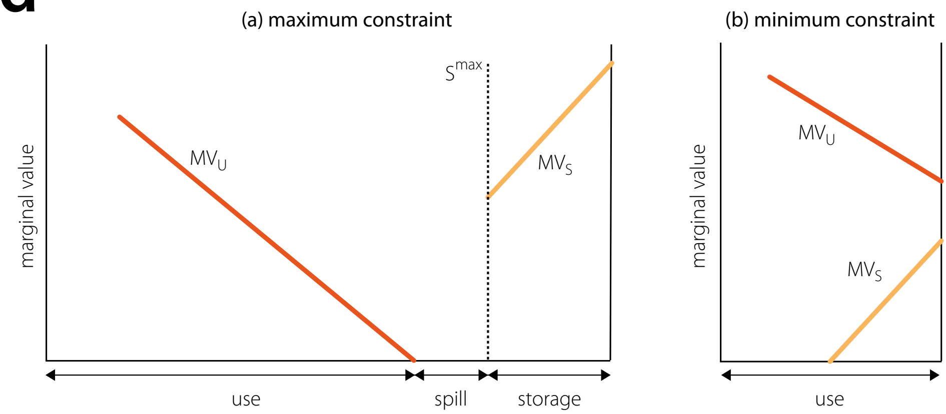
The essence of the water storage problem is to compare the marginal value of consuming water with the marginal value of storing water, where the marginal value of water in storage is equal to the expected marginal value of future water use, discounted into today's dollars and adjusted for storage losses. The total benefits of water use will be maximised in the long run where the marginal value of water use is equal to the marginal value of water in storage, subject to constraints on water storage.

c The storage problem, non binding storage constraint



This problem is demonstrated diagrammatically in figure c (adapted from Brennan 2008), where MV_U and MV_S are the aggregate marginal value curves for water use and water storage respectively. The marginal value of storage is decreasing in total storage, since the future expected marginal value of water is decreasing in total water use. Figure d illustrates how constraints on storage may in certain cases limit the equalisation of marginal values. Figure d (a) illustrates a high water availability period, where water use is maximised and the storage reaches capacity and spills over. Figure d (b) illustrates a low water availability period, where the minimum storage constraint is binding (no water is stored).

d The storage problem, binding storage constraints



Centralised storage management

In Australia, the storage management decision tends to be centrally controlled. This occurs via an announced allocation system, where each season the dam manager (generally a state government body or a state government owned entity) announces a percentage allocation – the percentage of nominal water entitlement volume available for use or trade by the entitlement holder within that season. For a centralised storage management policy to achieve an efficient allocation of water across time and space, a number of conditions must be met. In this section those conditions are outlined, along with reasons that they may not be met in practice.

For the purposes of this discussion a simplified example of an irrigation water system, as outlined above, can be used. In this example it is assumed that the water storage decision is managed by a central agency, that there exists one class of entitlement and that irrigators have no access to carryover rights. Further, it is assumed that there are multiple irrigators and there exists unrestricted intra-regional trade in water allocations. A number of potential complications to this simple example, such as high and low reliability entitlement systems, intra and inter-seasonal allocation and the potential for unused allocations, are considered later.

The first condition required for centralised management to achieve an optimal allocation of water is that the dam manager has perfect information. Specifically, the dam manager requires perfect information on the aggregate demand curve for water use and the expected aggregate demand curve for future water use (the marginal value of water use and marginal value of water storage). Effectively the dam manager needs to know the marginal value of water for each point in time and each set of circumstances. Given this information, the dam manager would be in the position to develop an optimal release rule, which would for each point in time and for each state (situation) specify the optimal aggregate amount of water to be released from the storage (the optimal allocation percentage).

The second condition required for centralised management to be optimal, is that water trade is efficient and costless, that is there are zero transaction costs. Under these conditions, the optimal aggregate amount of water would be released each period, with this water being efficiently allocated across irrigators via trade in water allocations. Under these conditions the allocation of water across time and space would be efficient. The next section considers two reasons why these conditions may not be met: the existence of asymmetric information between the storage manager and irrigators; and the presence of transaction costs or restrictions on water trade.

Asymmetric information

Dam managers may obtain approximations of aggregate water demand (current and expected) through observing traded prices on water markets and through regular discussions with representative irrigators. However, it is unlikely that dam managers will obtain full information on aggregate water demand without knowing all of the individual water demands. In practice, the costs of acquiring this information from individual irrigators are likely to be prohibitive. Hence the term asymmetric information; individual irrigators have better information on their water needs than is available at a reasonable cost to central managers.

Obtaining information on water needs from irrigators is difficult for a number of reasons. Firstly, irrigators are likely to display highly diverse preferences for water. For example, different irrigators may be engaged in different activities, each with specific water requirements. A common example is the significant differences in water requirements between annual and perennial plantings. Other potential sources of diversity include spatial variation (differences in soil type and local climate) and variation in risk preferences across irrigators.

An additional complication is that irrigators' water preferences are likely to change significantly over time. For example, they may change 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. The more diverse irrigators' preferences are and the more they change over time, the more difficult and costly it will be for a central agency to obtain full information.

With asymmetric information, a central manager may implement a sub-optimal release (allocation) policy, which will lead to a sub-optimal distribution of water over time and ultimately lower average returns to irrigators in the long run. A central manager with incomplete information may choose to adopt a simple aggressive release policy, for example release all available irrigation water in each period (a detailed discussion of prevailing centralised storage management polices in Australia is located at the end of this chapter). Such an aggressive allocation policy may not result in an ideal level of water reliability, from an irrigators' perspective. In practice, asymmetric information may affect both inter-seasonal water allocation (between years) as well as intra-seasonal allocation (within water years). This distinction is discussed in detail below.

Intra and inter-seasonal allocation

In practice water allocation occurs on an annual water year or irrigation season cycle, approximately coinciding with the financial year. In each water year, an allocation applies specifying the volume of water available for use within the year. Given uncertainty over seasonal inflows, allocations are announced progressively, often at monthly intervals. Typically, the initial allocation made at the commencement of the season is relatively conservative and the allocation is increased as additional inflows arrive later in the season. Water managers are understandably averse to decreasing allocations once they have been announced, although recent drought conditions did result in small allocation reductions in some regions.

In the absence of any carryover rights, the central manager maintains control over inter-seasonal water allocation. However, irrigators do have a degree of flexibility with regard to intra-seasonal water use, since irrigators can use announced allocations at any time within the current season. The market price of water reflects the option value (the option to delay water use) attached to early season allocations; there is generally a premium placed on early season allocations which gradually reduces as the market price of allocations converges to a spot price at the end of the season (Brennan 2006).

While the announced allocation system does provide irrigators with the right to delay the use of allocations until later in the water year, it does not allow them to bring forward later year allocations. This can be a problem where the intra-seasonal allocation of water is overly conservative – where early season allocations are too low and there is water available in storage that remains unallocated.

Dam managers may adopt a conservative approach as a result of uncertainty over expected storage and delivery losses. Under the current entitlement system, dam managers must ensure that enough water is available to deliver all announced allocation volumes and cover all of the associated losses. Where the dam manager has imperfect information on water demands, specifically where there is uncertainty over when allocations will be used, this will increase uncertainty over expected losses. For example, the longer irrigators delay using allocations, the greater the associated storage losses. In order to avoid the possibility of reductions in announced allocations, dam managers may hold excess water in storage to insure against the risk of higher than anticipated losses.

In the short run, the intertemporal allocation of water may be adversely affected by lag times in allocation announcements. For example where allocation announcements occur at monthly intervals, it may be up to a month before inflows received in the dam become allocated and available for use.

Transaction costs

Transaction costs refer to costs incurred when making an economic exchange. These can include search costs, information costs, bargaining costs and costs incurred in administering and enforcing a transaction. There is evidence to suggest that 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, and non-financial costs, such as time costs incurred by irrigators.

box 1 **Unused allocations**

The discussion above has implicitly assumed that all allocated water is used within the period it is allocated, yet in practice this may not be the case. While the proportion of allocations not used by irrigators has declined in recent times as irrigation water has become increasingly scarce, unused allocations remain a common occurrence. Under an announced allocation system, with no carryover rights, any unused allocations at the end of the season are returned to the common pool and shared among all water users.

Unused allocations may occur if there are constraints in the delivery or trade of water, or where the marginal benefit of water use (or the market value of water) is less than marginal cost of water use. 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 intertemporal water management.

For example, situations may arise where large allocation increases occur late in the water year, potentially as a result of overly conservative early season allocations (for reasons discussed in the previous section). At the end of a season, the marginal benefit of applying water to a crop may be very low. Moreover, there may be restrictions on carrying this water over to the next season and/or transaction costs and constraints on water trade. Irrigators may attempt to store any unused allocations on farm, either by investing in on farm storage or by applying the water to the farm in order to increase the soil moisture level. However, on farm storage will tend to be less efficient and more costly than central storage.

Unused allocations result in an increase in storage levels and an improvement in the reliability level of water entitlements. It has been noted by Brennan (2007) that the removal of institutional constraints on trade may result in an increase in the utilisation of allocations. This may inadvertently have a detrimental effect on the reliability of water entitlements within an irrigation system. This is not to say that constraints on trade should be retained for this purpose. Ideally, appropriate reliability should be achieved explicitly with some form of storage property rights, as discussed in the following chapter.

The size of government application fees and the amount of paper work involved vary significantly across jurisdictions (see Allen Consulting 2006). The time taken by governments to approve trades imposes costs on irrigators – again this varies by jurisdiction (in the range of one to seven days according to Allen Consulting (2006)). In addition to direct transaction costs, irrigators may face significant search costs (the costs associated with finding willing sellers or buyers) particularly in regions where the market for water is 'thin' (where there is little trade volume) or where there exists a lack of well developed exchanges or brokers (or a lack of irrigator knowledge about exchanges and or brokers).

As noted by Freebairn and Quiggin (2006), while transaction costs may be expected to decline as water markets mature and improvements are made to property rights systems and associated institutions, the fundamental complexity of water rights (reflective of the complexity of water as a commodity) would suggest that 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).

Under a simple announced allocation system, with a single class of entitlement and no carryover rights, substantial temporary trade in water allocations may be required to achieve an efficient allocation of available water across irrigators in each season or period. This can be illustrated with a simple example as shown in figure e.

Demand elasticity refers to the responsiveness of demand to changes in price (defined as the percentage change in the quantity demanded in response to a given percentage change in price). In this example there are two irrigators, irrigator A has an elastic demand curve for water (responsive to price) while irrigator B has an inelastic demand curve for water (less responsive

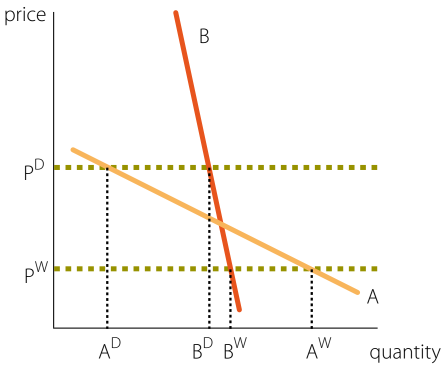
box 2 Constraints on water trade

Currently there exist a range of constraints on permanent water trade at an inter-regional level, especially on trade out of an irrigation region (see Goesch et al. 2006; Peterson et al. 2004; Goesch et al. 2008). For example, trade in permanent entitlements out of irrigation areas is currently capped at 4 per cent of total water entitlements in any one year. While there has been a commitment under the National Water Initiative (NWI) to remove this cap, this will not occur until at least 2014 in the northern catchments of the basin (Goesch et al. 2008).

In this report the focus is predominantly on the efficiency of temporary trade (trade in allocations) rather than permanent trade (trade in entitlements). However, there are a number of constraints placed on inter-regional temporary water trade, although these constraints are often less explicit. For instance, restrictions on inter-regional trade may take the form of lengthy delays in the processing of trades. In some cases these delays can be more than a month in duration (Goesch et al. 2008).

Intra-regional temporary trade tends to be subject to fewer instructional constraints (Peterson et al. 2004). Often, constraints imposed on temporary intra-regional water trade reflect real world hydrological constraints or environmental concerns (Peterson et al. 2004; Brennan 2006). Hydrological constraints may involve delivery capacity constraints, for example, a river choke point or simply the inability to transfer water upstream, which can place a practical limit on the volume of water than can be traded upstream of confluences in multiple river systems (Peterson et al. 2004; Brennan 2006).

e Water requirements of two irrigators under variable supplies



to price). Irrigator A is representative of more flexible farming activities (for example, broadacre) and irrigator B is representative of activities which require consistent levels of water use (for example, horticulture). P_W represents the market price of water in a wet (high allocation) year while P_D is the higher market price of water during a dry (low allocation) year. For simplicity, it is assumed that the demand curves are the same in both states (wet and dry).

From the diagram it can be seen that irrigator B demands a similar amount of water in each state of nature (that is, wet and dry), while the demand for water by irrigator A varies significantly between the states of nature. Under an announced allocation system, with a single class of water entitlement, substantial temporary trade will need to occur to generate an efficient allocation of water. For example, if both irrigators own identical water entitlements (A and B receive equal allocations in both states), 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 individual entitlement reliability levels with individual irrigator reliability preferences will tend to reduce the need for temporary water trade and hence reduce irrigators' exposure to associated transaction costs. One approach is to define different classes of water entitlements with distinct reliability levels (i.e. high and low reliability entitlements). However, this approach is not without its limitations. For more detail see below.

High and low reliability entitlements

High and low reliability entitlement systems (referred to as general and high security entitlements in New South Wales) are relatively common in the Murray-Darling Basin. High and low reliability entitlement systems have the potential to reduce temporary water trade requirements, and reduce irrigators' exposure to transaction costs by providing water rights which closely match the reliability preferences of individual irrigators (Freebairn and Quiggin 2006). However, a two reliability level approach does have a number of limitations.

In practice there exists a spectrum of reliability preferences. Under a two level reliability system, irrigators will need to hold a mix of the two entitlement classes to achieve a specific reliability level. This may involve some additional cost for irrigators, particularly where there are transaction costs associated with permanent trade. A two level reliability system also places an artificial upper and lower bound on available reliability levels. A high and low reliability entitlement system may also involve additional administrative effort, with governments needing to make two separate allocation announcements. Moreover, governments will need to define and communicate reliability levels clearly. This may be difficult given uncertainty over the future climate.

Under a high and low reliability system there is a need to ensure that 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 general security entitlements is achieved. For example, where there is a market preference for high security over general security entitlements, a water authority could purchase general security entitlements and sell high security entitlements (at a ratio determined by hydrological constraints).

Such a system would use market preferences for high and general security entitlements, to reveal information about the regions aggregate reliability preference. The system would be one way of addressing the information problems of a standard announced allocation system. However, there are obvious costs associated with a water authority taking such an active role, including the transaction costs of engaging in the market and any additional administrative effort and regulatory requirements. Further, determining the appropriate conversion ratio between high and low security at any point in time may be problematic given significant uncertainty over future climatic conditions. An embargo was recently placed on the conversion of entitlements between general and high security in the Murrumbidgee region because of concern over the accuracy of conversion rates (New South Wales Department of Water and Energy 2008b).

Implications for investment

In the previous discussion it has been assumed that the irrigation capital stock is fixed. Consistent with this approach, in the model presented later, it is assumed that irrigators cannot make any additional investments to increase the area set up for irrigation, improve water use efficiency or change irrigation activities. For example, in the applied example of the model, it is assumed there is a fixed maximum demand for water (fixed nominal volume of entitlements) and fixed proportions of less flexible activities (for example, horticulture) and more flexible activities (for example, broadacre).

In practice, it is likely there will be significant interdependence between storage management polices (the yield-reliability of water entitlements) and irrigator investment decisions. This interdependence has been demonstrated in a number of other models. 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 broad activities (horticulture, dairy and broadacre) is a function of the water availability probability distribution (the yield and reliability of water entitlements) and the relative costs and returns.

To this point the focus has been on how a centralised storage management policy may not adequately match existing water demands. However in the long run, a fixed centralised storage policy may also 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 New South Wales systems, where the storage policy is significantly more aggressive.

Further, the higher water supply and price variability associated with aggressive storage polices may act as a general constraint on investments in water use efficiency. For example Hafi et al. (2006) and McClintock (2009) demonstrated how water price variability is likely to significantly slow the adoption of water efficiency technologies.

Centralised storage management in practice

As discussed, the state governments have responsibility for managing the major water storages (announcing water allocations). As such, storage management policies (allocation rules) can differ significantly across jurisdictions. For example, the storage management polices employed in Victoria tend to be significantly more conservative (for example lower yield and greater reliability) than those employed in New South Wales (Murray-Darling Basin Commission 1999) and Queensland. While there are a number of differences between states, there are a number of elements common to most storage management polices. These are outlined below.

Many irrigation systems in the Basin operate a two reliability level entitlement system. The allocation of water to these entitlement classes generally occurs on a priority basis: water is allocated to high reliability entitlements first, before remaining water is allocated to low reliability entitlements. Reserves may be held in storage to maintain the reliability of high reliability entitlements. Other than reserves held for high reliability entitlements, water may remain in storage between seasons as a result of: carryover rights, unused allocations, or where total available water exceeds the maximum limit on water entitlements (generally 100 per cent of the nominal value of entitlements). Clearly the maximum level of water use in a system has implications for system reliability. For a given supply system, a higher maximum level of water use will result in a reduction in mean storage levels and reliability. This issue is not considered in detail in this paper.

Dam managers must also provide for minimum environmental water requirements (as specified in water sharing plans), town water, and stock and domestic water. These water requirements generally take priority over irrigation water needs. The dam manager must also hold enough water to cover any losses associated with storing and delivering water. Generally, once all of the above water requirements have been met, remaining water is allocated to low reliability entitlement holders (up to the maximum limit). Below is a simplified representative allocation rule for low reliability entitlement allocations.

Low reliability allocation = Total available water in storage, less
Minimum environmental water, less
Town and stock and domestic water, less
Any carryover from previous period, less
High reliability allocation, less
Any high reliability reserve, less
Expected storage and delivery losses.

Victoria

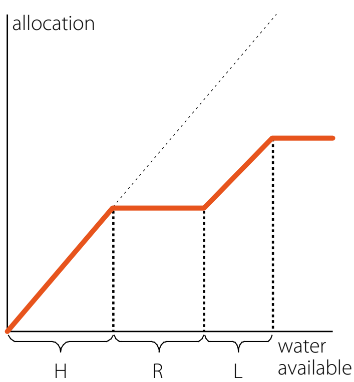
Water entitlements in Victoria have undergone a number of reforms (introduced 1 July 2007) including the unbundling of water entitlements into separate water, use and delivery rights. These reforms also involved the definition of separate high reliability and low reliability entitlements, with the newly created low reliability entitlements replacing the previous system of sales water. In Victoria, water allocations are determined by state government water corporations, such as Goulburn-Murray Water. As discussed, the storage management polices implemented in Victoria tend to be relatively conservative. This conservative approach is evidenced by the relatively high proportion of high reliability water entitlements in most Victorian systems (table 1).

1 Water entitlement volumes in major Victorian irrigation systems

	entitlement volume (ML)		
	high reliability	low reliability	high reliability percentage of total
Greater Goulburn	891 956	395 393	69
VIC Murray – Dart to Barmah	291 645	124 997	70
VIC Murray – Barmah to SA	867 692	165 953	84

Source: Victorian Department of Sustainability and Environment (2008).

f Stylised water allocation rule - Victoria



The Victorian approach to water allocation involves allocating water to high reliability entitlements first, then providing storage reserves to ensure water is available for next season's high reliability entitlements (under drought inflows), and only then allocating any remaining water to low reliability entitlements (Goulburn-Murray Water 2008). Figure f is a stylised representation of the typical Victorian storage management policy (allocation or release rule), adapted from Brennan (2008).

In figure f, the dotted (45 degree) line represents all water available being allocated to irrigators, (ignoring other water requirements and losses) and the solid line represents the allocation rule. **H** refers to total high reliability entitlement volume, **R** to high reliability reserves and **L** to low reliability volume.

New South Wales

In New South Wales, water allocations are determined by the Department of Water and Energy. High reliability entitlements are referred to as high security and low reliability entitlements general security. Relative to Victoria, New South Wales irrigation systems have a relatively small proportion of high reliability entitlements.

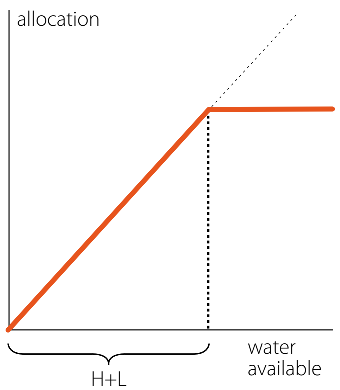
2 Water entitlement volumes in major NSW irrigation systems

	entitlement volume (ML)		
	high reliability	low reliability	high reliability percentage of total
NSW Murray	198 011	1 953 508	9
Murrumbidgee	298 021	2 043 432	13

Source: NSW Department of Water and Energy (2004).

The water allocation rules used in determining water allocations are listed in the relevant water sharing plans (New South Wales Department of Water and Energy 2004). The Murrumbidgee plan states that the water supply system must be managed such that a minimum of 95 per cent of high reliability entitlements can be provided under a repeat of the worst period of low inflows on record. The plan states that sufficient volumes of water must be set aside in storage to meet the 95 per cent requirement. According to the water sharing plan, general security allocations are only to be made where the high security allocation is at least 95 per cent.

g Stylised water allocation rule - NSW



Given the relatively small volume of high reliability entitlements and the relatively reliable historical inflows into the Murrumbidgee region, it is likely that minor reserves (relative to those in Victoria) would be required to achieve the 95 per cent requirement. For example, even under the extreme drought conditions of recent years, where inflows have been well below previous lows, the lowest final allocation for high security entitlements has been 90 per cent, recorded in 2006-07 and 2007-08. Given the relatively small proportion of high reliability entitlements, the aggregate allocation rule will, for a typical New South Wales system, be reasonably approximated by the low reliability allocation policy – release all available water up to the maximum (100 per cent) limit as in figure g (again ignoring other water requirements and losses). Under such a policy, large storage reserves only occur in very wet years (see figure i).

Queensland

In Queensland, water allocations are announced by water corporation SunWater, in accordance with rules specified in the resource operation plans (water sharing plans) for each catchment (QLD Department of Natural Resources 2007, 2008). High reliability entitlements are represented as high priority entitlements and low reliability represented as medium priority. In general, only a relatively small proportion of water entitlements are defined as high priority. In the St George, MacIntyre Brook and Border rivers irrigation systems, all irrigation entitlements are defined as medium priority. Individual systems with substantial proportions of high priority entitlements include Bundaberg and Emerald.

The resource operation plans specify that reserves equal to one year's supply should be held in storage for high priority entitlements and that water will not be allocated to medium priority entitlements unless high priority entitlements have received a 100 per cent allocation. Allocations to medium priory allocations are calculated as total available water, less high priority allocations and reserves, and less storage and delivery loss provisions. Given the small proportion of high reliability entitlements in most Queensland systems, the aggregate storage management policy (allocation rule) can be adequately approximated (as for New South Wales) as shown in figure g.

Decentralised storage management

An alternative to centralised storage management is to decentralise the storage decision – allow irrigators to make their own storage decisions. In this report, two decentralised approaches to storage management are considered: carryover rights and capacity sharing. These property rights structures have the potential to address some of the problems of centralised storage management, including asymmetric information and transaction costs in water trade.

A decentralised approach to storage management involves irrigators making their own storage decisions, taking into account their private information on water needs. In the presence of asymmetric information (where the central manager has less information on water demands than irrigators), a decentralised storage management policy 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.

By making their own storage decisions, irrigators can influence the reliability level of their entitlement such that it better matches their individual preferences. For example, irrigators who value high reliability can leave more water in storage and use less now, effectively increasing the reliability of their entitlement. More closely aligning individual water entitlements with individual reliability preferences will tend to reduce the volume of temporary water trade required and thus reduce irrigators' exposure to transaction costs associated with trade.

3 Case study

In this section, the economic model outlined in appendix A is applied to a case study region to demonstrate the potential benefits of improvements in storage policy. The case study region is loosely based on the Murrumbidgee region in New South Wales. However, it should be noted that the case study is intended to be illustrative in nature only and is in no way an attempt to forecast the likely effects of changes to storage management polices in the Murrumbidgee region.

The choice of the Murrumbidgee region is one of convenience, based primarily on data availability. It is intended that the results presented here are sufficiently general to be broadly applicable to other regions.

The Murrumbidgee region

The Murrumbidgee region is located in southern New South Wales and covers an area of around 87 000 square kilometres. Of the 4169 square kilometres used for irrigation, 60 per cent is used to irrigate cereals (including rice) with a further 26 per cent devoted to irrigated pasture. Horticulture represents a relatively small proportion of irrigated land in the region (table 3).

3 Agricultural land use in Murrumbidgee, 2000-01
square kilometres

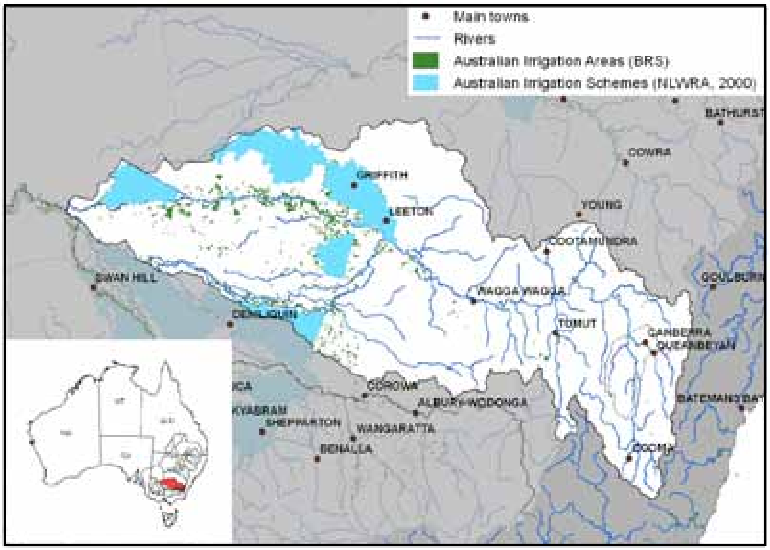
	dryland	irrigated
Native vegetation (grazing)	46 788	–
Pasture	10 193	1 074
Cereals **a**	10 319	2 521
Cotton	0	158
Oilseeds and legumes	2 547	38
Horticulture	39	300
Total **b**	72 012	4 169

a Includes rice. **b** Columns do not add as some minor activities were excluded.
Source: ABS 2001, ABARE estimates.

The region operates under an announced allocation system, with irrigation water entitlements separated into general and high security entitlements.

The allocations announced during the particularly dry year of 2006-07 demonstrate this distinction, with general security entitlement holders receiving a 15 per cent allocation while high security entitlement holders received a 95 per cent allocation. High security water

map 1 The Murrumbidgee region



4 Water entitlements and allocations in the Murrumbidgee region, 2006-07

	no. of licences	entitlement (ML)	allocation (ML)
General security	736	2 029 360	303 962
High security	92	279 004	264 960
Town and domestic and stock	466	55 679	55 770
Conveyance losses **a**	5	375 968	269 324
Supplementary water	220	189 823	189 941
Other **b**	17	26 056	25 933
Total	1 536	2 955 890	1 109 889

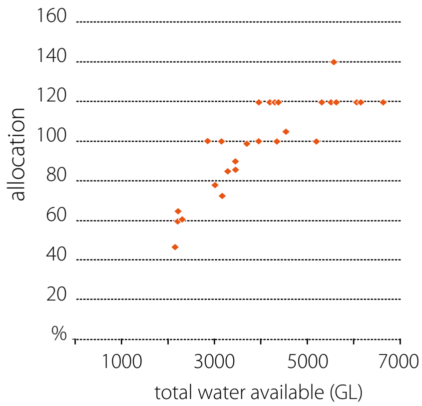
a Includes 'Coleambally Irrigation', 'Murrumbidgee Irrigation' and 'Regulated River'. **b** Includes 'Aboriginal Cultural', 'Research' and 'Local Water Utility'.
Source: NSW Department of Water and Energy (2008a).

entitlements are most likely to be held by irrigators with permanent horticultural plantings, which require access to a more reliable water supply. Carryover provisions were introduced in the region in 1999. Of the two main water storages in the Murrumbidgee region, the Blowering dam has a storage capacity of around 1600 gigalitres, while the Burrinjuck dam can store around 1000 gigalitres.

The Murrumbidgee region: some empirical data

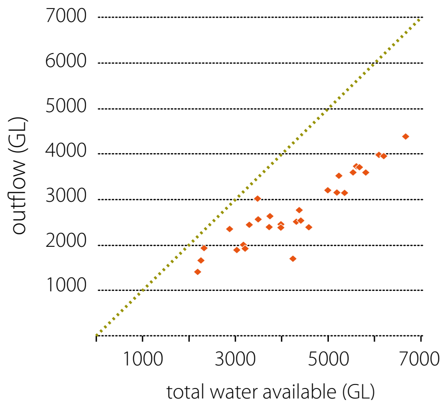
Figure h plots water allocations in the Murrumbidgee region against total water availability between 1980-81 and 2006-07. Total water availability is defined as start of season water storage plus net within season inflows. Allocations represent total allocations (the

h Allocations and total water available in the Murrumbidgee region



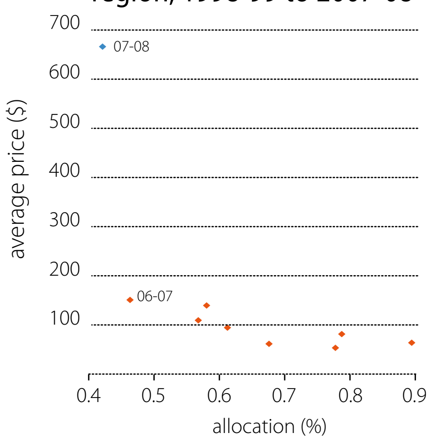
Source: NSW Department of Water and Energy (2006; 2008a).

i Outflows and total water available (initial storage plus net season inflows), in the Murrumbidgee region, 1976-77 to 2006-07



Source: NSW Department of Water and Energy (2006; 2008a).

j Annual allocations and volume weighted average annual water prices, in the Murrumbidgee region, 1998-99 to 2007-08



Sources: : NSW Department of Water and Energy (2006; 2008a); Water exchange (2008) and Murrumbidgee water exchange (2008).

combination of general and high security), adjusted for carryover amounts. Allocations have, as would be expected, a positive relationship with water availability. For high levels of water availability, allocations approach a maximum level, currently 100 per cent of entitlements, although historically allocations of 120 per cent and 140 per cent were recorded. The last allocation in excess of 100 per cent was made in 1993-94.

Figure i plots outflows against total water availability in the region between 1976-77 and 2006-07. The difference between the data points and the dashed line provides a crude measure of the volume of water which is carried over in storage.

Figure j plots annual average volume weighted water prices against annual water allocations between 1998-99 and 2007-08. As expected, there is a negative relationship between water prices and water allocation volumes. In 2007-08, water prices were extremely high in the region.

Model assumptions

The model operates on an annual (water year) time scale. Model parameters were estimated econometrically using historical data or drawn from econometric literature where possible. The model assumes two representative irrigators: irrigator 1 is representative of broadacre/annual crops and irrigator 2 is representative of horticulture/perennial crops. Inflow and rainfall probability distributions were estimated using historical data on annual inflows and rainfall for the region.

The Murrumbidgee is a relatively complicated water supply system with two major storages and a connection to the snowy mountains hydroelectric scheme. However, the model 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 Beare et al. (1998). For more detail on model assumptions and solution procedures, see appendix B.

Results

Two distinct storage policies are evaluated in this case study: a base case policy representative of a simple centralised storage management 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 only occur when water availability exceeds 100 per cent of entitlement volumes. As discussed previously, this rule can be considered a reasonable approximation of the typical centralised policy adopted in New South Wales irrigation systems.

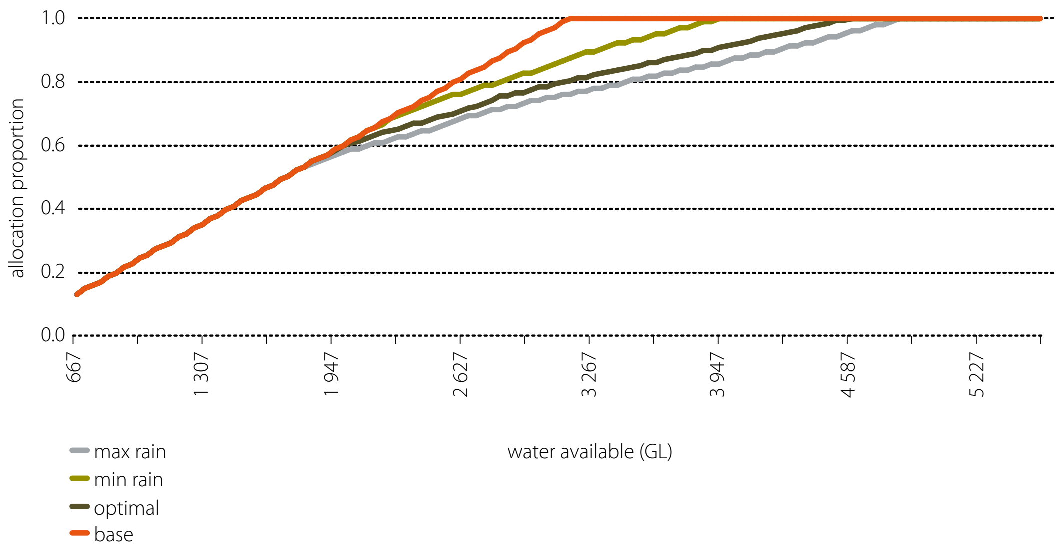
The optimal policy represents the release policy which would be adopted by a central planner with full information. Equivalently, the optimal policy can be interpreted as the aggregate release policy which would result under an effective decentralised system of storage management. The difference in welfare (as measured by mean water rents) between the two policies represents the potential gains from improving storage management policy in the presence of information asymmetry. Since irrigators in the Murrumbidgee region have had carryover rights for some time, part of any increase in welfare will already have been achieved in this region.

Further, capacity sharing or carryover rights systems are not modelled explicitly and transaction costs associated with water trade are not included in the model. Therefore, this model demonstrates the potential benefits of adopting a decentralised approach to storage management under asymmetric information, excluding any of the other potential benefits discussed earlier.

Policy functions

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

k Estimated optimal release rule



For significantly high and low levels of water availability, the optimal policy and the base case policy converge. At high levels of availability it is optimal to allocate the maximum allocation (100 per cent), and for low levels of availability it is optimal to allocate all available water. In between these extremes, the optimal policy allocates less water than the base case policy and carries over more water in storage. The optimal policy is dependent on the rain state, while the base case policy is assumed to be invariant to the rain state. In low rainfall years, demand for water is higher and the optimal policy involves allocating relatively more water; in high rainfall years, demand for water is lower and the optimal policy involves allocating relatively less water.

Simulation results

Given the estimated policy function, Monte Carlo simulations were performed and probability distributions over key variables generated. Monte Carlo simulation involves repeatedly solving the model for different levels of inflow and rainfall, drawn from the assumed probability distributions. Tables 5, 6 and 7 contain the simulation results for key model variables, including the mean value, standard deviation (SD) and coefficient of variation (CV).

The optimal storage policy results in a small reduction in mean water allocations (-0.6%) relative to the base case policy, but 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 the mean economic value of water (objective function value, see appendix A and B for detailed definition).

5 Simulation results, base policy rule

	units	mean	SD	CV
Allocation	%	82.8	20.86	0.25
Price	$/ML	65.7	257.0	3.91
Storage level	%	14.0	21.8	1.55
Evaporation loss	GL	66.9	16.4	0.24
Water demand/use				
– Irrigator 1 **a**	GL	1 662.4	444.3	0.27
– Irrigator 2 **b**	GL	250.0	37.5	0.15
Economic value of water	$ million	353.8	132.9	0.38

a Representative of broadacre irrigators. **b** Representative of horticulture irrigators. **SD:** Standard deviation. **CV:** Coefficient of variation (ratio of SD to mean).

6 Simulation results, optimal policy rule

	units	mean	SD	CV
Allocation	%	82.3	15.2	0.18
Price	$/ML	55.1	114.0	2.07
Storage level	%	33.0	25.0	0.76
Evaporation loss	GL	74.8	16.6	0.22
Water demand/use				
– Irrigator 1 **a**	GL	1 649.7	324.1	0.20
– Irrigator 2 **b**	GL	250.4	26.8	0.11
Economic value of water	$ million	395.5	54.6	0.14

a Representative of broadacre irrigators. **b** Representative of horticulture irrigators. **SD:** Standard deviation. **CV:** Coefficient of variation (ratio of SD to mean).

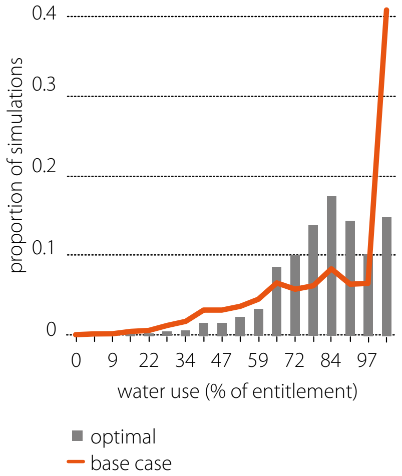
7 Simulation results, deviation from base

	units	mean	SD	CV
Allocation	%	–0.6	–27.2	–26.7
Price	%	–16.3	–55.6	–47.0
Storage level	%	134.8	14.7	–51.2
Evaporation loss	%	11.8	1.6	–9.2
Water demand/use				
– Irrigator 1 **a**	%	–0.8	–27.1	–26.5
– Irrigator 2 **b**	%	0.2	–28.6	–28.7
Economic value of water	%	11.8	–58.9	–63.3

a Representative of broadacre irrigators. **b** Representative of horticulture irrigators. **SD:** Standard deviation. **CV:** Coefficient of variation (ratio of SD to mean).

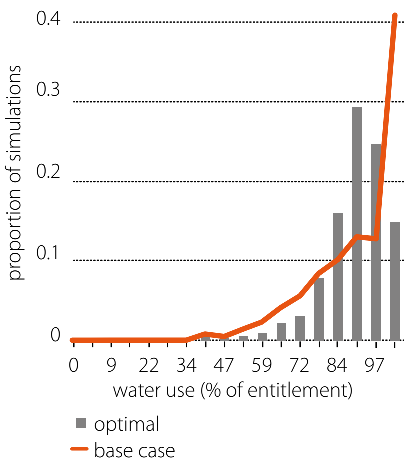
l Histogram of water use as percentage of entitlement

Irrigator 1 (broadacre)



m Histogram of water use as percentage of entitlement

Irrigator 2 (horticulture)



The effect of the optimal policy rule on water use varies depending on the state of the world. When water availability is high the optimal policy may result in a reduction in water use and associated rents relative to the base case. However when a drought occurs, the additional water in storage ensures that water use is higher during this period under the optimal policy. Given that the marginal value of water use during a drought period will be greater than the marginal value of water use during a wet period, an increase in mean water rents is observed despite a small decline in mean water use and allocations.

The optimal policy has an even greater effect on the variability of water use and water value. The variability of water use (as measured by the coefficient of variation) for both irrigators is substantially reduced (irrigator 1: -26.5%, irrigator 2: -28.7%), while the variability in the economic value of water is reduced by 63.3 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.

Overall, the modelling results are consistent with similar studies undertaken by Brennan (2008) and Dudley (1988) in that a sub-optimal centralised release policy results in a relatively small reduction in mean incomes and a substantial increase in the variability of incomes. Figure l and figure m display histograms for water demand/use for the two representative irrigators under the base case and optimal policies. These histograms display the frequency with which water use falls into each of a number of defined ranges.

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 l and m 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). In the model, the rainfall variable measures rainfall in the irrigation area downstream of the storage (that is, not rainfall in the storage catchment); as such, the link between rainfall and inflows is empirical rather than directly hydrological. Therefore the 3:1 ratio between inflow and rainfall reductions is imposed on the model, through exogenous shocks, rather than being an internal relationship.

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 8 and 9.

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. It is important to note 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 the gain in mean economic welfare and reduction in income variability 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 over in storage. When inflows are lower and less reliable there is more to be gained by holding water over 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 because of the effects of climate change.

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

	units	scenario			
Rainfall mean	% change	0	–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 value of water	$ million	354	315	273	206
Optimal policy					
– mean price	$/ML	55.1	69.3	89.1	128.1
– mean value of water	$ million	395	382	362	332
Deviation					
– mean price	% change	–16.3%	–39.9%	–63.3%	–76.9%
– mean value of water	% change	11.8%	21.2%	32.6%	61.8%

9 Sensitivity analysis, reduction in inflow/rainfall, variance effects

	units	scenario			
Rainfall mean	% change	0	–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					
– SD price	$/ML	257.0	528.4	978.1	1 620.6
– SD value of water	$ million	133	161	202	279
Optimal policy					
– SD price	$/ML	114.0	179.2	199.5	266.6
– SD value of water	$ million	55	45	44	52
Deviation					
– SD price	% change	–55.6%	–66.1%	–79.6%	–83.5%
– SD value of water	% change	–58.9%	–71.8%	–78.3%	–81.3%

SD: Standard deviation.

4 Carryover rights and capacity sharing

In this section, two decentralised approaches to storage management are described in detail: carryover rights and capacity sharing.

Carryover rights

A carryover right allows each water user to hold over a proportion of their seasonal water allocation for use in future seasons. For example, if an irrigator used 80 megalitres of a 100 megalitre allocation, then under a system of unrestricted carryover, the amount of water available to the irrigator the following year would be equal to the allocation for that year plus 20 megalitres (the volume carried over from the previous year). Without carryover provisions any unused allocations are returned to the common pool and shared among water users.

Introducing carryover rights allows irrigators to make storage decisions in accordance with their specific preferences and increases their ability to individually manage intertemporal risk. In this way, 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, as previously discussed. However, carryover is an incomplete property right since it does not explicitly define rights to dam capacity (air space) or storage losses.

One of the major drawbacks with carryover rights is the existence of external or third party effects; that is, carryover decisions made by individual irrigators can have effects on 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, the effects of carryover on spills and storage losses are socialised (shared) across all irrigators in the system. For example, situations may arise where an irrigator or group of irrigators carries over large volumes of water, filling the storage, preventing other irrigators from carrying over their allocation and increasing the possibility of dam spills, which may adversely affect future allocations for other irrigators. Even relatively small increases in carryover may have external effects because of the socialisation of evaporation losses. 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 carryover water are adversely affected by those that do.

Carryover provisions are often limited by a number of restrictions imposed on their use. For example, there may be limits on the amount of water which can be carried over in any season. Moreover, 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. Access to carryover 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. For example, access to carryover water was restricted in the Macquarie region in New South Wales as part of drought contingency measures during the 2006-07 season (State Water Corporation 2007).

The motivation for placing such restrictions on carryover may be to limit the potential for external effects. However, where these restrictions are binding, they can prevent a more efficient intertemporal allocation of water being achieved. Table 10 contains carryover limits which have applied in the Murrumbidgee region in recent years and the corresponding proportion of allocations actually carried over. For a number of years total region carryover has approached the upper limit. This would suggest that the limit is binding, at least for some irrigators.

10 Carryover limit and actual carryover in the Murrumbidgee region

water year	carryover limit	total carryover
2000–01	0.10	0.09
2001–02	0.15	0.14
2002–03	0.15	0.07
2003–04	0.15	0.04
2004–05	0.15	0.10
2005–06	0.15	0.08
2006–07	0.15	0.13

Source: NSW Department of Water and Energy (2008a).

Since the introduction of carryover in the 1990s, it has become widespread throughout New South Wales and Queensland. In the New South Wales Murray-Darling Basin, around one-third of the water available in 2005-06 was carried over from the previous year (Murray-Darling Basin Commission 2007). Carryover rights were recently extended to high security accounts in New South Wales and have recently been made available in Victoria.

Carryover rules vary over time and across regions. For example, the recently introduced carryover provisions in the Goulburn and Murray regions of Victoria allow irrigators to carryover up to 30 per cent of the volume of high and low reliability water shares, while in the Murrumbidgee region a carryover limit of 15 per cent applied between 2001-02 and 2007-08. This limit was increased to 30 per cent in 2008-09. As illustrated by the preceding examples, recent low inflows in the Murray-Darling Basin have coincided with the introduction of carryover into new regions and the expansion of carryover limits. This expansion in carryover in response to dry conditions is not unexpected, given that the benefits of improving the intertemporal management of water increase as water becomes more scarce, a result confirmed by the modelling presented later in this paper.

Continuous accounting

Standard carryover rights operate on a seasonal (water year) timescale. Continuous accounting is a form of carryover where users' accounts are updated on a frequent (generally daily) timescale. With continuous accounting, any water not used in each time period, automatically carries 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 New South Wales had implemented continuous accounting (Murray-Darling Basin Commission 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 be based on a share of available storage capacity, however, even where this occurs there are significant differences between continuous accounting and capacity sharing. For example, continuous accounting carryover still involves centralised allocation announcements and does not redefine water rights at the source. As Dudley (1993) noted, capacity sharing has a number of potential advantages relative to continuous accounting carryover.

Capacity sharing

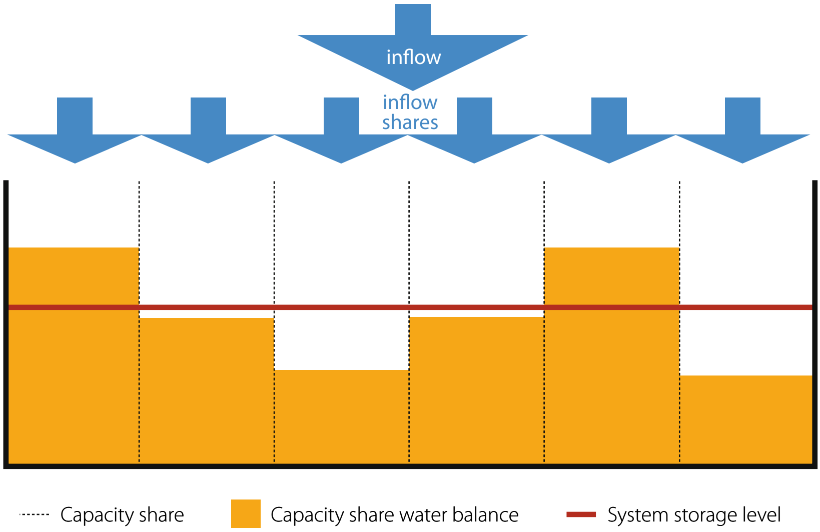
The basics

Capacity sharing is a system of allocating property rights to water from shared storages proposed by Dudley (Dudley and Musgrave 1988; Dudley and Alaouze 1989; Dudley 1990a; Dudley 1992). Under capacity sharing, water entitlements are redefined into storage space rights and physical water rights. Each entitlement holder in an irrigation system is assigned a share of the total system storage capacity and a share of total inflows. Users are free 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 (releases) 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 minimises the third party effects of storage decisions, for example by ensuring losses are internalised (individual water users are responsible for their individual contribution to total losses). 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 sellers account and depositing it into the buyers 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. Figure n is a conceptual diagram of a capacity sharing system.

n Conceptual diagram of a capacity sharing system irrigation scheme



Queensland water authority SunWater has successfully introduced capacity sharing into two of their irrigation systems in southern Queensland. Capacity sharing has been operating in the St George region since 2000 and was introduced into the McIntyre Brook region from 1 July 2008.

While capacity sharing minimises external effects relative to carryover rights, there may be some complications. In particular there is the issue of internal spills.

Internal spills

Under capacity sharing, irrigators are able to manage their capacity shares largely independently of each other, avoiding some of the exclusivity problems associated with carryover rights. However, there is still the potential for some interactions between individual capacity shares. In particular, there is the issue of 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.

Dudley and Musgrave (1988) describe two alternative approaches to the allocation of internal spills: equity sharing and efficiency sharing. Efficiency sharing involves the reallocation of surplus water to the highest value water users, while equity sharing allocates internal spills equally to all water users, as long as their capacity share is not full. However, where there exists an efficient secondary market in water (temporary water trade), both methods should result in an efficient allocation of surplus water across users. Given a large number of water users, well specified property rights to storage and water, and efficient markets, an optimal allocation of water will be achieved at each point in time, regardless of the occurrence of internal spills.

However, internal spills do result in interactions between water accounts which, if anything, may marginally increase uncertainty over future account inflows. That is, where internal spills are significant, irrigator expectations over future water availability will be a function of both expected system inflows and expected internal spill volumes. While internal spills may have limited effects on allocative efficiency, they do result in some distributional effects: internal spills transfer water between users without compensation. However, given that internal spills are likely to occur during periods of high water availability (low marginal value), the economic value of these distributional effects is likely to be relatively small.

An alternative approach to the allocation of internal spills is for users to maintain rights to internal spills and for this water to be temporally stored in the available storage capacity across other users' accounts. Users would then have the opportunity to sell water or purchase (or create) storage space after the event. Such an approach may satisfactorily deal with the distributional effects but is unlikely to lead to any significant improvement in allocative efficiency. Under this approach there remain some interactions between water accounts, relating to storage capacity rather than water. For example, an irrigator's expectation of available storage capacity will be a function of their own expected storage levels and their expectation of the storage levels of other users' accounts. Finally, such an approach may be of little practical value during large inflow events where the dam approaches full in a short period of time.

In practice, internal spills are likely to occur infrequently, since capacity shareholders 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, internal spills are more likely to occur 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. Internal spills should be relatively rare 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. Data from the St George capacity sharing scheme, presented in *Capacity sharing in the St George and MacIntyre Brook irrigation schemes in southern Queensland*, shows a small number of high inflow events where irrigators' capacity to respond was exceeded and significant internal spills occurred. However, the size of such events, relative to the storage capacity at St George, was extreme and unlikely to be replicated in many other systems in the Murray-Darling Basin.

Storage losses

Another issue 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 typically sloped, surface area varies significantly as the volume of water in the dam changes. 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 direct proportion to the volume of water in each user's capacity share (see appendix C for more detail).

Additional benefits

There are a number of benefits associated with this system of water rights in addition to those mentioned above. One of the additional benefits is a reduction in the regulatory uncertainty faced by irrigators (Dudley and Musgrave 1993). Under a standard announced allocation system, irrigators are exposed to regulatory or government uncertainty, since the potential yield and reliability level of water entitlements are dependent on the policies of dam managers. For instance, the allocation rules used by central authorities may be complex and may be 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. For example, there have been a number of recent instances where water allocation and carryover rules have been altered or superseded by highly discretionary temporary arrangements in response to unprecedented declines in water availability.

Under a capacity sharing system the yield and reliability of any given water entitlement depends only on irrigators' water use/storage decisions and the hydrology of the water supply system. In the terminology of Dudley (Dudley and Musgrave 1988), water users can estimate their water supply probabilities with greater confidence. This reduced uncertainty may make it easier for irrigators to compare the yield and reliability of water entitlements across different regions. Further, a reduction in uncertainty would assist irrigators in making their own planning decisions, including crop choice and planting area decisions and capital investment decisions.

Another potential benefit of capacity sharing is that it defines rights to water at the source (that is, the point of storage), equivalent to source tagging of water entitlements, (ABARE 2005; ACIL Tasman 2003). Under a standard announced allocation system, rights to water allocations are defined at the point delivery (the farm). Defining water rights at the source (or source tagging) can improve the efficiency of water allocation by: 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 both be subject to significant water 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 water rights are defined at the source, delivery losses can be allocated to individual irrigators, ensuring that irrigators internalise these losses and act to minimise them. For example, there may be incentives to trade water entitlements into locations with lower delivery losses (closer to the storage) and to time releases (withdrawals) to occur during periods when, for hydrological or climatic reasons, delivery losses are lower.

As noted by Heaney et al. (2006), where water rights are defined at the point of the farm, third party effects (regarding the reliability/yield of entitlements) can arise when trading water in connected river systems. For example, where water entitlements are traded upstream of a tributary, this may decrease the yield/reliability of entitlements in the upstream system while potentially increasing the yield/reliability of entitlements in the downstream region (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. While not considered here in detail, the implications of source tagging and capacity sharing for water trade in complex connected river systems remains a potential subject for future research.

The unbundling of access rights under capacity sharing can also facilitate efficient allocation of delivery infrastructure in the event that delivery capacity constraints are binding. This can occur through the allocation of delivery capacity rights (similar to storage capacity rights) which can be traded between irrigators within the system. Whether this is a more efficient method of allocating access delivery infrastructure, will depend on the frequency with which delivery constraints are binding and the transaction costs which may be involved.

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

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). For example, local urban water utilities can manage an urban capacity share, while a nominated environmental manager could manage an environmental share. Such a system would also facilitate trading between irrigation, urban and environmental water users.

Capacity sharing would afford these water users the same advantages it offers irrigators, specifically the ability to independently manage yield and reliability. Capacity sharing may be particularly beneficial to environmental water managers, whose role is likely to increase in significance as governments buy back more water from irrigators for the environment. Capacity sharing would give an environmental manager more flexibility to make strategic water releases to achieve specific environmental objectives, such as the generation of high flow events to flood key wetland sites (Beare et al. 2006). Further, capacity sharing would ensure that the storage of water by environmental managers does not have any external effects on other water users such as irrigators.

Potential problems

For irrigators to make storage decisions independently, they will need to combine their private information on demand for water with the information set of the dam manager. More specifically, irrigators need to obtain and interpret available information on expected future inflows and expected storage losses. This may require some additional effort and learning on the part of irrigators. According to Alaouze (1991), concern over this potential information burden is one reason some policy-makers have been averse to the introduction of capacity sharing at the individual irrigator level.

One way irrigators could minimise these information costs would be by managing their capacity shares in small groups. For example, a group of irrigators in a particular location who share similar water needs could pool their capacity shares and manage them cooperatively. Such an approach could result in lower information/decision costs where there exist economies of scale in making water allocation decisions. These groups could even nominate a manager to make storage decisions on their behalf. The appropriate level of aggregation would then be a trade off between these economies of scale and potential asymmetric information problems.

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 be lower than those incurred under traditional announced allocation systems as has been the case for SunWater at St George (SunWater pers. comm. 2008). Some of the costs incurred in setting up a capacity sharing system include the costs of: developing a computer-based accounting system; educating and consulting with irrigators; and determining the appropriate capacity share sizes to allocate entitlement holders. For example, hydrological modelling may be required to determine the storage and inflow shares which will best preserve the potential yield of existing entitlements.

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 there is the perception that some entitlement holders are going to be 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. Capacity sharing is unlikely to gain the acceptance of irrigation communities if irrigators are not confident that capacity share entitlements provide similar claims over water in the long run.

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 (aggregated) 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.

6 Conclusion

Water storages play a vital role in the supply of water for irrigation farms. Storages serve to smooth variation in the supply of water and equalise the marginal value of water over time. The management of these storages is an important but difficult task. Determining what proportion of available water to store for the future, and how much to consume now, is a complex problem given the presence of substantial uncertainty over future inflows and water demands.

In Australia, major irrigation water storages are centrally managed via the announced allocation system, where each season a water manager determines the amount of water available for use now (water allocations) given prevailing storage levels. Under certain conditions a centralised approach could achieve an efficient allocation of water resources; specifically, if the water manager had perfect information on the water demand preferences of irrigators and there existed an efficient (costless) market in water allocations.

In practice, the water manager is unlikely to have perfect information on the water preferences of irrigators. There is likely to be asymmetric information; irrigators are likely to know more about their water demands than the water manager. Also, there are likely to be significant transaction costs in water trade. A centralised announced allocation approach relies heavily on trade in water allocations to allocate water between irrigators with varying reliability preferences. Given these practical difficulties, a decentralised approach, where irrigators are enabled to make there own storage decisions, may be preferable.

To demonstrate the potential costs of inefficient storage management, an economic model of the water storage problem facing a representative irrigation system was developed. This model was applied to a case study region, the Murrumbidgee. Model parameter values were set with reference to historical data and estimates from econometric literature. Using the model, a suboptimal aggressive release rule was compared with a theoretically optimal release rule.

The estimated optimal release rule generated a small reduction in mean water use in turn for a substantial increase in mean storage reserves. The model demonstrated the ability of the optimal policy to lead to an increase in mean irrigator incomes and a substantial reduction in variability of incomes. The model estimated an increase in the mean economic value of water of 11.8 per cent and a reduction in variability of more than 63 per cent. The model also demonstrated that the gains from optimal storage management, both in terms of the mean and variability of incomes, increase substantially as water availability reduces.

In this report two decentralised approaches to storage management were considered in detail: carryover rights and capacity sharing. Carryover rights have the potential to overcome some of the problems of centralised storage management. 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 on carryover rights which further weaken their effectiveness.

Capacity sharing is a property rights system proposed by Dudley (Dudley and Musgrave 1988), which involves redefining water entitlements into separate storage capacity rights and water/inflow rights. Unlike carryover rights, capacity sharing ensures that storage space is efficiently rationed and that losses are internalised. Capacity sharing has a number of other potential benefits relative to systems of carryover rights. Capacity sharing replaces the traditional announced allocation system and in doing so removes a layer of regulatory uncertainty from existing water entitlements. Capacity sharing involves redefining water rights at the source which creates a number of potential efficiency improvements, including the potential to internalise water delivery losses.

One complication with capacity sharing is the occurrence of internal spills – where individual water accounts reach capacity and forfeit their inflows to other water users. However, the allocation efficiency implications of internal spills are negligible and in practice internal spills are likely to occur infrequently. Another important consideration in the transition to capacity sharing will be to minimise any actual or perceived distributional effects, by ensuring the newly defined capacity share water entitlements adequately preserve all existing irrigator water entitlements.

Capacity sharing is typically considered in the context of relatively simple water supply systems, 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 that 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.

appendix A A water storage model

This section defines the water storage problem more precisely in the form of a stochastic dynamic optimisation problem. A number of economists have modelled the irrigation water storage problem in this way (Dudley 1988; Dudley and Hearn 1993; Beare et al. 1998; Brennan 2008; Alaouze 1992; Howitt et al. 2002). For a detailed review of the relevant economic literature, see Brennan (2007a). The model presented here does not necessarily extend the theoretical literature; rather the aim is to construct a simple model in order to demonstrate the economic concepts involved. An additional motivation for maintaining simplicity is to allow the model to be solved using stochastic dynamic programming techniques. An applied example of the model is presented later in the paper.

The model focuses on the storage management problem within a single irrigation region in isolation from neighbouring regions. It also assumes that the irrigation region contains a single water storage. A single storage model can be interpreted as an aggregated representation of a multiple storage system (see Perera and Codner 1988). Further, the model assumes that there is no on farm water storage, that the single storage receives stochastic inflows and that there are no in stream or tributary flows downstream of the storage.

In practice, the demand for water will be dependent on a range of factors, including input and output prices. Given these prices, irrigators face a production decision which involves determining the optimal use of a range of inputs, such as land, labour, fertiliser and water. For the purposes of this model, a simple demand curve for water is assumed and these other factors are treated as exogenous.

In the long run, irrigators also face capital investment decisions, where irrigators decide how much land to develop for irrigation and whether to invest in additional or improved irrigation infrastructure. Again for simplicity, it is assumed that the capital stock and the land developed for irrigation is fixed. Irrigator's capital investment decisions are considered in more detail in Hafi et al. (2001), Hafi et al. (2006) and Brennan (2006).

The timescale of the theoretical model is essentially arbitrary. However, an annual timescale is used in the model case study. As such the model case study focuses more on inter-seasonal water allocation than on intra-seasonal water allocation.

Demand for irrigation water

The demand for irrigation water is assumed to be a function of the price of water and the level of local water availability. From equation 1, the 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 (that is, rainfall is variable and adheres to a specified probability distribution). In the model, water users i, are intended to represent individual irrigators, however this could easily be generalised to include other types of water users such as urban water utilities and environmental water holders.

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

Where:

Q = water demand
p = the market price of water
R = local rainfall/soil moisture
d = demand function

Supply of irrigation water

The model assumes that a centralised allocation system is used, involving a single class of water entitlement (that is, there is no distinction between high and low security entitlements). Under this system, each irrigator has a nominal entitlement V, and each period the social planner (central dam manager) 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 cannot 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 in period t, (and that the equilibrium price p will be that which clears the market). For each irrigator, net trade can be calculated as the difference between final demand Q, and the initial allocation in period t, as in equation 3.

2 $$A_t \sum_i V_i = \sum_i Q_{i,t}$$

$$A \leq 1$$

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 the system in any time period is equal to the initial water storage level, S_{t-1}, plus inflows less storage evaporation losses, as in equation 4. Inflows are assumed to be generated by an exogenous stochastic process. Evaporation losses (equation 5) are assumed to be an increasing function of the storage level (since the surface area of a storage tends to increase with the storage level). Storage evaporation losses may in reality depend on a range of factors, including prevailing weather conditions.

In each period t, system outflows Out, must be less than total water availability W, as in equation 6. Outflows include allocated irrigation water plus transmission losses incurred in delivery (see 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 $$Out_t \leq W$$

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

Where:

W = total water availability
S = volume of water in storage
IN = inflows into storage
Out = total water outflow
tl = transmission loss parameter
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 less outflows. The storage volume is constrained by the maximum storage capacity S_{MAX}, and the minimum storage level S_{MIN}, which represents dead or unusable storage.

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 timescales, however, it may become less realistic for longer time periods. For example, in a model with an annual timescale, a large proportion of inflows may occur early in the period prior to the release of outflows, 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 use surplus; where water use surplus is calculated as the area under the demand curve less the marginal cost (delivery cost) of supplying that water. In the body of the report this water use surplus is referred to as the economic value of water.

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

Where:

β = discount factor
mc = the short run marginal cost of supplying irrigation water

Implicit in the objective function is the simplifying assumption that water users are risk neutral. In practice, irrigators may be risk averse and may explicitly value any reductions in the variability of returns. The objective function is stated in expected terms because future allocations and associated water rents are dependent on the future state of the world (water availability W and local water availability R), which is uncertain. The model can be solved using stochastic dynamic programming techniques. An applied example of the model is presented in the next section.

appendix B Model assumptions

Unit of time

The model time unit is the financial year, which encompasses 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 also overcomes a number of data limitations. The annual timescale is consistent with the approach of Brennan (2008). An annual timescale prevents the model from representing the significant intra-seasonal variability typically observed in both the supply and demand for water. The model of Beare et al. (1998) uses a monthly timescale and as such focuses more on intra-seasonal allocation of 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. A conditional inflow distribution was estimated, via a simple linear OLS regression of inflows against rainfall between 1975 and 2007. The mean of the inflow distribution is a linear function of rainfall, and the standard deviation is assumed constant. The estimated rainfall and inflow distribution parameters are shown in table 11, along with other supply parameter assumptions. The marginal delivery cost of water is set, with reference to irrigation water marginal usage charges (IPART 2006).

11 Model case study supply side parameter assumptions

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

SD: Standard deviation.

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 a 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.

An evaporation loss function was developed, specifying total annual evaporation as a function of the start of year storage level and the annual inflow volume. Historical time series data was used to estimate relationships between the initial total storage volume, total annual inflows and mean annual storage volumes at Burrinjuck and Blowering dams. Relationships between surface area and storage volume for each of the two dams were obtained from New South Wales Department of Water and Energy (2008a) with mean annual pan evaporation for Blowering and Burrinjuck dams being estimated using historical time series data. The evaporation loss function was derived by combining all of these relationships.

Given the annual timescale used in the analysis, the model may underestimate dam spills in cases where a large proportion of seasonal inflows occur early in the season before any outflows occur. One way of overcoming this problem would be to estimate seasonal spills from historical data, similar to the approach used by Brennan (2008). However, the lack of an adequate time series of dam spill data has prevented this approach from 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 (see in box 3).

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/mean rainfall year is set to a specific value, based on observation of historical data in the region (see figure j).

It is assumed that 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, in that 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 extreme water scarcity has on horticultural agriculture. In the event that 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.

box 3 Econometric analysis of demand for irrigation water

To date there has been limited econometric analysis of irrigation water demand in Australia. This has been in part because of a lack of suitable data given that water markets are still relatively new. The majority of elasticity estimates in the literature have until recently derived indirectly from mathematical programming models.

Mathematical programming models of irrigation demand often ignore the yield effects of reduced water availability and assume production technologies are highly inflexible. Under these assumptions a producer's main response to reduced water availably is to move away from irrigated production into dry land production. Given these assumptions, such models often give low elasticity estimates relative to econometric studies (see Scheirerling et al. 2006).

Econometric studies of irrigation water demand in Australia have been conducted by Brennan (2006), Bell et al. (2007), Bjornlund and Rossini (2005), and Wheeler et al. (2008). Bell et al. (2007) conducted a comprehensive econometric analysis of demand for irrigation water, compiling a large farm level data set with the cooperation of the Australian Bureau of Statistics, which enabled them to estimate the elasticity of demand for irrigation water for 10 agricultural industries. The results of Bell et al. (2007) confirm prior expectations that demand for water in higher value activities such as fruit and vegetables is more inelastic (-0.8) than for other lower value activities such as grains (-1.4) and dairy (-1.4).

Wheeler et al. (2008) estimated a demand elasticity of -0.52 in the short run and -0.81 in the long run, using monthly water trade data for the Goulburn-Murray Irrigation district region between 1997 and 2007. Wheeler et al. (2008) also accounted for seasonality impacts and the effect of drought and local rainfall deficit. Brennan (2006) and Bjornlund and Rossini (2005) also conducted econometric analyses on water trade data in the Goulburn-Murray region in Victoria. Brennan (2006) estimated a demand function for water which included the effect on demand of local rainfall. Brennan (2006) observed the expected negative relationships between price and availability (allocations) and between price and local rainfall. Bjornlund and Rossini (2005) estimate a demand equation for irrigation water which included a range of additional explanatory variables, such as commodity prices and evaporation rates. Bjornlund and Rossini (2005) estimated a significant positive relationship between evaporation and water prices.

Scheierling et al. (2006) conducted a meta analysis on the elasticity of demand for irrigation water which included 24 US studies. The 24 studies adopted three broad approaches: mathematical programming (13); field experiments (7); and econometric studies (4). Field experiments yielded the lowest elasticity (most inelastic) estimates, while econometric studies yielded on average the highest. They estimated a mean price elasticity of -0.48 across all studies, with estimates ranging from 0.001 to 1.97. The average estimates were -0.45 for mathematical programming, -0.15 for field experiments and -0.62 for econometric studies. Scheierling et al. (2006) estimated a meta regression model to investigate the variation in these estimates. One key result was that high value crops were associated with significantly lower elasticity estimates.

Finally, data on annual water prices and allocation volumes in the Murrumbidgee region were gathered for this paper, as shown in figure 14. Simple econometric analysis on this data set generates a price elasticity estimate of approximately -0.4 (over the period from 1998-99 to 2006-07).

12 Model case study demand side parameter assumptions

description	parameter	units	value
Water entitlement (Irrigator 1)	E_1	ML	2 029 360
Water entitlement (Irrigator 2)	E_2	ML	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

Solving the model

The model can be solved as a stochastic dynamic programming problem, with a single policy variable A, and two state variables W and R. The model is formulated as a discrete time and discrete state space, infinite time horizon problem. The model is shown below in recursive bellman equation form.

11 $$V_t(W_t, R_t) = \max_{A_t}\left\{G(A_t, W_t, R_t) + \sum_{W_{t+1}}\sum_{R_{t+1}} P(A_t, W_t, W_{t+1}, R_{t+1})(\beta V_{t+1}(W_{t+1}, R_{t+1}))\right\}$$

Where V denotes the value function, P the transition probability matrix and G the within period pay off or objective value and β the discount factor. The model is solved using the value chain iteration method.

The probability transition matrix gives the probability of observing water availability W_{t+1} and rainfall level R_{t+1} next year, given this year's W_t and allocation level A_t. The probability of observing rainfall state R_{t+1} is drawn directly from the assumed rainfall distribution and is independent of W_t, A_t. For any given allocation A_t and water availability W_t, the end of period storage level S_t can be calculated (subject to the storage capacity constraints). Given the storage level, the probability of observing water availability W_{t+1} is then calculated based on the assumed conditional inflow probability distribution.

It is assumed that current season inflows are known when allocation decisions are made. In reality, allocation decisions are made incrementally over the course of a season, which allows the dam manager to increase allocations as additional inflows arrive. As such, final allocation announcements are highly reflective of the inflows occurring within the current season. Further, the majority of inflows typically occur early in the season during winter and spring, while the demand for irrigation water peaks later in the season around summer.

appendix C Sharing of evaporation losses

This appendix provides a simple mathematical representation of the sharing of evaporation losses from water storages under a system of capacity sharing.

The storage

Assume there exists a single water storage with the following characteristics:

K = Effective (usable) storage capacity

V_t = Volume of water in storage at time t

$SA_t\,(V_t)$ = Surface area of the storage at time t (a function of volume)

$E_t\,(SA_t)$ = Evaporation losses from the storage at time t (a function of surface area)

Assume the surface area-volume relationship is linear with a constant (equation 12), where the constant gives the surface area of the storage at a zero usable storage volume, i.e. at the dead storage level. Assume evaporation loses are linearly related to surface area (equation 13).

12 $$SA = \beta V + c$$

13 $$E = m.SA$$

The capacity shares

Assume the storage is shared by two users under a capacity sharing system as follows:

Two water users, $i : 1, 2$

k_i = User i's storage capacity $(\sum k_i = K)$

$v_{i,t}$ = User i's volume in storage at time t $(\sum v_{i,t} = V_t)$

cs_i = User i's capacity share percentage $(cs_i = k_i / K)$

Marginal evaporation losses

User 1's marginal contribution to storage evaporation losses can be calculated as in equation 14 below.

14 Marginal evaporation loss of user 1

$$
\begin{aligned}
&= mSA\{v_{1,t} + v_{2,t}\} - mSA\{0 + v_{2,t}\} \\
&= m(\beta(v_{1,t} + v_{2,t}) + c) - m(\beta v_{2,t} + c) \\
&= m(\beta v_{1,t})
\end{aligned}
$$

Where evaporation losses are allocated according to the above equation, users would be exposed to their marginal evaporation losses for any given volume level. However, under the above approach total evaporation losses are not allocated (fixed losses remain unallocated). To avoid distorting incentives, the fixed losses could be allocated in accordance with capacity share sizes rather than volumes (equation 15).

15 Total evaporation loss allocated to user 1

$$
= m(\beta v_{1,t} + c.cs_1)
$$

Volume sharing of evaporation losses

Under volume sharing of evaporation losses, total storage losses are allocated to individual users in proportion to the volume of water in their account, as in equation 16.

16 Total evaporation loss allocated to user 1

$$
\begin{aligned}
&= mSA\{v_{1,t} + v_{2,t}\}\left(\frac{v_{1,t}}{v_{1,t} + v_{2,t}}\right) \\
&= m(\beta(v_{1,t} + v_{2,t}) + c)\left(\frac{v_{1,t}}{v_{1,t} + v_{2,t}}\right) \\
&= m\left(\beta v_{1,t} + c.\left(\frac{v_{1,t}}{v_{1,t} + v_{2,t}}\right)\right)
\end{aligned}
$$

Where c is small, i is large (and/or v_1 is close to mean v_i) then volume sharing of losses (equation 16) approximates marginal sharing of evaporation losses (equation 15). In practice, c is likely to be relatively small and i relatively large. Therefore under certain conditions, in particular a linear surface area-volume relationship and a small contribution from fixed evaporation losses, volume sharing will acceptably approximate marginal evaporation losses for each user.

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