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Evaluating improvements in water use efficiency as a salinity mitigation option in the South Australian Mallee areas

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Efficient investment in salinity mitigation requires an understanding of how different landscapes respond to alternative land and water use options at both a regional and a broader scale. A simulation modeling framework that integrates the relationships between land use, vegetation cover, surface and groundwater hydrology and agricultural returns was developed. The model presented here has been used to estimate the direct and external benefits of improved water use efficiency in the Mallee irrigation areas of South Australia.

Upstream investments in water use efficiency can generate substantial external benefits to downstream users through improved water quality. Given the non-exclusive and diffuse nature of these benefits, achieving the socially optimal level of improvement in water quality is likely to require institutional arrangements that promote collective investment and public expenditure.

Keywords
Investment, irrigation, water quality, externalities, hydrology

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Introduction

Land clearing and the establishment of irrigation have facilitated the development of high value agricultural production in Australia's Murray Darling Basin. However, land clearing and irrigation have also imposed costs. The replacement of native vegetation with crops and agricultural systems has substantially increased the amount of water entering groundwater systems and, as a result, led to rising water tables. As water tables rise, there is increased discharge of salt into streams and soil. Higher stream and soil (dryland) salinity can reduce the productive capacity of agricultural resources, adversely affect infrastructure such as roads and rural services that support agriculture, and affect the quality and variety of a range of environmental assets including wetlands, floodplains and riverine ecosystems.

Strategies have been, and continue to be, implemented to address the problem of salinity in the riverine environment. The Salinity and Drainage Strategy was introduced in 1989 to manage irrigation salinity along the River Murray in New South Wales and Victoria, and increased salt concentration in the lower River Murray in South Australia. The Draft Basin Salinity Management Strategy, released by the Murray Darling Basin Commission in September 2000, proposed a series of end of valley salinity targets for 2015 as well as foreshadowing the need to develop longer term initiatives. The Commonwealth and state governments agreed in November 2000 to fund a national salinity and water quality program.

Investing in a portfolio of initiatives requires an understanding of how different landscapes respond to alternative land and water use options at both a regional and a broader scale. To evaluate salinity management options in the Murray Darling Basin, a simulation modeling framework that integrates the relationships between land use, vegetation cover, surface and groundwater hydrology and agricultural returns was developed at ABARE, in cooperation with the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

To date, a catchment model has been developed to estimate the benefits and costs of reforestation as a tool for salinity management under a range of hydrological conditions in the Macquarie–Bogan catchment located in New South Wales (Heaney, Beare and Bell 2000). The results of this work suggest that broad scale reforestation as a tool for managing dryland and instream salinity may impose significant costs on agriculture and rural economies more generally. These costs are incurred as a result of reduced surface water yield and increased salt concentration of surface water flows in the near term. A targeted approach to reforestation may still be cost effective. The model was used to identify the influence of different hydrological and land use characteristics on the costs and benefits of reforestation. Reforestation targeted to regions that have high groundwater salinity levels and fast responding aquifers may generate substantial net salinity benefits under reforestation.

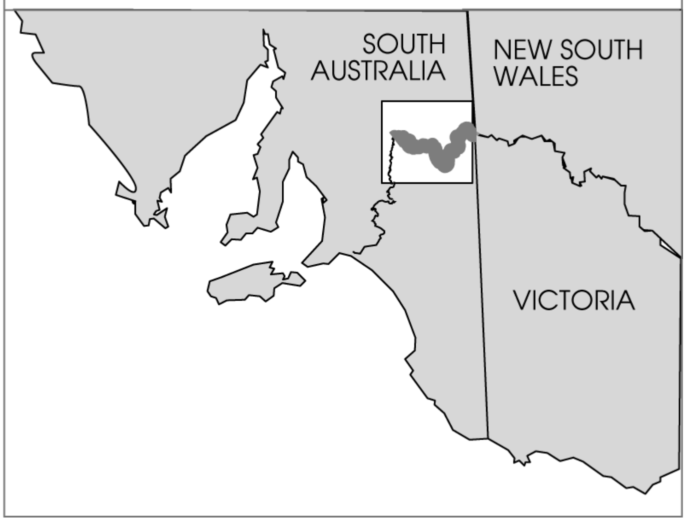
A model has been developed to estimate the benefits of improved water use efficiency as a tool for salinity management in irrigation areas. In particular, the model was extended to examine salinity mitigation options in the irrigation areas of the South Australian Mallee, the results of which are presented here. Investment in changing dryland agricultural and irrigation practices can have significant implications for salinity management in irrigation areas, as the use of water for irrigation can speed up the rise in groundwater levels.

Benefits from improvements in water use efficiency may be derived in two ways. First, internal benefits may accrue to the individuals undertaking the action as a result of more efficient agricultural production. Second, improved water use efficiency may decrease the amount of groundwater leakage, thereby decreasing the amount of saline groundwater being transported to the river system. The benefits derived from improved water quality are not captured by the individuals taking the action but, instead, accrue to downstream users. As these external benefits are nonexclusive and diffuse, institutional arrangements or public investment may be needed to get the optimal level of investment in water use efficiency.

South Australian Mallee region

The study region for this analysis covers a 20 hectare strip along the River Murray from the South Australia/Victoria border to Morgan (figure 1). Horticulture crops, predominantly citrus and some stonefruit and vegetables and, more recently, grape production, cover almost 40 000 hectares in the South Australian irrigation areas. The irrigation areas along the river are shown in figure 2. Water for irrigation is sourced solely from the Murray River. Irrigation areas were first established as early as the 1880s in settlement schemes involving state and federal governments. These government schemes were followed, from the 1950s, by other group irrigation schemes, many of which were funded privately. Irrigation has developed almost entirely in a strip fashion adjacent to the river to minimise the costs of water delivery.

Figure 1: **South Australia Mallee study region**



In the South Australian portion of the Murray Darling Basin, the salinity of groundwater underlying the irrigation areas is close to and in many areas exceeds, the salinity of seawater. As a result of irrigation development and the clearance of native vegetation within this saline environment, the Mallee zone of South Australia is a significant source of salt. Furthermore, all of the salt mobilised in the Mallee zones of Victoria and South Australia is expected to reach the Murray River as a result of direct seepage. In contrast, less than half of the salt mobilised in catchments with poorer drainage features actually reaches the rivers, with the salt being retained in the landscape. As a result, salt loads in the Mallee zone from South Australia to Morgan are predicted to increase substantially. Over the next 30 years, much of this increase in salt contribution will result from the expanding groundwater mounds beneath irrigation areas although, progressively, additional salt loads induced from the Mallee dryland areas will begin to dominate (MDBMC 1999).

Model specification

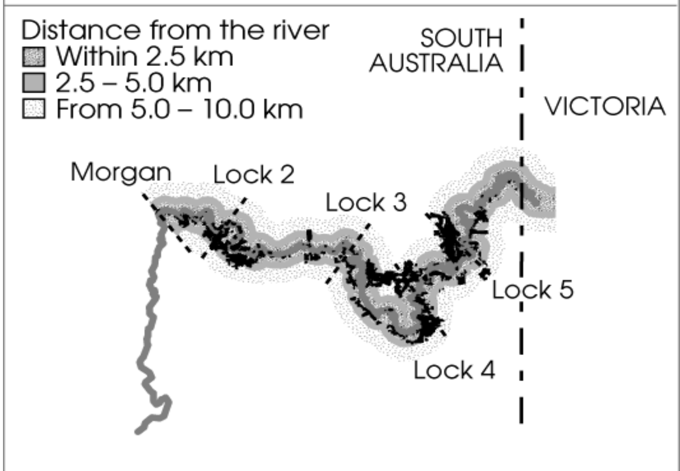
Within the modeling framework, economic models of land use are integrated with a representation of hydrogeological processes in each catchment. The hydrogeological component incorporates the relationships between rainfall, evapotranspiration and surface water runoff, the effect of land use change on groundwater recharge and discharge rates, and the processes governing salt accumulation in streams and soil. In the agro-economic component of the model, land use is allocated to maximise economic return from the use of agricultural land and irrigation water. Incorporated in this component is the relationship between yield loss and salinity for each agricultural activity. Thus, land use can shift with changes in the availability and quality of both land and water resources.

The framework is a dynamic representation of the relationship between the hydrological cycle and the economic returns to alternative land uses. In the South Australian Mallee version of the model, the interactions between precipitation, vegetation cover, surface water flows, groundwater processes and agricultural production are modeled at a river reach scale. In turn, these reaches are linked through surface and groundwater flows. The modeling approach is described in more detail in Bell and Heaney (2000) and Bell and Klijn (2000).

In the Mallee, ground water flows directly to the Murray River. The rate at which salt stored in groundwater is transported to the river is dependent upon, among other things, the size of an irrigation development, irrigation efficiency, the underlying geology of the irrigated area, and the distance between the irrigation development and the river valley. As the distance from the river increases, the time before a change in the level of recharge is fully reflected in the level of groundwater discharge increases substantially. A methodology has been developed to assess the impact of changes in these parameters on salt loads by an irrigation development (Watkins and Waclawik 1996; AWE 2000).

Discharge induced from an upstream irrigation area can increase the salinity of water supplies, reducing returns to downstream irrigated activity and imposing costs to industrial and household users. To represent this externality explicitly, agricultural activity in the Mallee from the border to Morgan was broken down into a series of independent land management units. These units were selected on the basis of existing regional salt load modeling (Watkins and Waclawik 1996) and are located from the South Australian border to Lock 5, Lock 5 to Lock 4, Lock 4 to Lock 3, Lock 3 to Lock 2 and Lock 2 to Morgan (figure 2)

Figure 2: **South Australia Mallee region**



While the clearance of native vegetation has contributed to increased recharge in the Mallee, the most significant source of recharge is development of irrigation along the river. To allow for a range of hydrological response times, reflective of the distance of the irrigation development from the river valley, the management units in the Mallee model were split into three bands – within 2.5 kilometres from the Murray River, between 2.5 and 5 kilometres from the river and between 5 and 10 kilometres from the river. These bands are also shown in figure 2.

Agro-economic component

The management problem considered is that of maximising the economic return from the use of agricultural land in the Mallee by choosing between alternative steady state land use activities in each year. There are four land use activities, *j*, specified: irrigated crops, irrigated horticulture, dryland crops and dryland pasture.

Each region is assumed to allocate its available land each year between the above activities to maximise the net return from the use of the land in production, subject to constraints on the overall availability of irrigation water:

(1) $$max \sum_j \frac{p_j}{r} x_j(L_j, sw_j) - \frac{csw}{r} \sum_j sw_j$$

subject to

(2) $$\sum_j sw_j \le sw^* \text{ and } \sum_j L_j \le L^*$$

where x_j is output of activity *j*, L_j is land used in activity *j*, sw_j is surface irrigation water used for activity *j*, *r* is a discount rate, and *csw* is the unit cost of surface water for irrigation. The net return to output for each activity is given by p_j and is defined as the revenue from output less the cost of inputs, other than land and water, per unit of output.

For each activity, the volume of output depends on land and water use (or on a subset of these inputs) according to a Cobb-Douglas production function:

$$(3) \qquad x_j = \begin{cases} A_j L_j^{\alpha_{Lj}} sw_j^{\alpha_{swjt}} & 0 < \alpha_{Lj} + \alpha_{swj} < 1 \quad for\ j = 1,2 \\ A_j L_j^{\alpha_{Lj}} & 0 < \alpha_{lj} < 1; \qquad for\ j = 3,4 \end{cases}$$

where A_j, α_{Lj}, and α_{swj} are technical coefficients in the production function. Note, the technical coefficients on irrigation water are time dependent to capture the impact of changes in salt concentration in the Murray River.

The costs to irrigated cropping and horticulture resulting from yield reductions caused by increased river salinity are modeled explicitly. The impact of saline water on the productivity of plants is assumed to occur by the extraction by plants of saline water from the soil. The electro-conductivity of the soil, $EC_{e,}$ reflects the concentration of salt in the soil water and reduces the level of output per unit of land input (land yield) and per unit of water input (water yield). This is represented by modifying the appropriate technical coefficients, α_{ij}, in the production function for each activity from the level of those coefficients in the absence of salinity impacts, for *I = L, sw*. That is,

$$(4) \qquad \alpha_j(t) = \alpha_j^{\max}\left[\frac{1}{1+\exp\left(\mu_{0j} + \mu_{1j} EC_e\right)}\right]$$

where μ_0 and μ_1 are productivity impact coefficients determined for each activity and α_j^{max} is the level of those coefficients in the absence of salinity.

Hydrological component

There are two parts to the hydrological component of the model. The first is the distribution of precipitation and irrigation water between surface water runoff, evapotranspiration and groundwater recharge. As the South Australian Mallee is characterised by a lack of surface water runoff, precipitation and irrigation water is either returned to the atmosphere through evaporation or transpiration or it enters the groundwater system as recharge. The annual average rainfall for the region is approximately 270 mm. Under native vegetation the estimated rate of groundwater recharge is slightly less than 1 mm. Land cleared for cropping is estimated to have a recharge rate of around 10 mm (Kennett-Smith, Cook and Walker, 1994; Cook et al. 1997).

Irrigation water entering the groundwater system depends, in part, on the volume of water applied and efficiency of application. Water application rates for horticulture are around 10 megalitres per hectare a year, equivalent to 1000 mm of precipitation. Much of the more recent irrigation development in the Mallee is characterised by highly efficient drip irrigation technology whereas the older developments use overhead sprinkler systems. Average efficiency rates (defined as that proportion of the water diverted for irrigation that does not enter the groundwater system) are estimated to be between 75 and 80 per cent (Anthony Meisner, Department of Environment, Heritage and Aboriginal Affairs, pers com, November, 2000). Water use efficiency of 80 per cent corresponds to 200 mm of groundwater recharge per year.

Soil structure can also affect recharge rates. While soils in the Mallee are generally sandy, some areas have underlying layers of Blanchetown clay that inhibit drainage into the groundwater system. Maximum infiltration rates through Blanchetown clay are estimated to be around 100 mm a year (Watkins and Waclawik 1996). Tile drainage is used in these areas to avoid waterlogging. Irrigation drainage is represented in the model though either an increase in irrigation efficiency to reflect re-use or as a return flow to the river carrying no additional salt load.

The second part of the hydrology component is the determination of groundwater discharge. The equilibrium response time of a groundwater flow system is the time it takes for a change in the rate of recharge to be fully reflected in a change in the rate of discharge. The equilibrium response time does not reflect the actual flow of water through the groundwater system but the transmission of water pressure. The response time increases rapidly with the lateral distance the water flows in the Mallee due to the flat terrain and resultant low hydrological pressure.

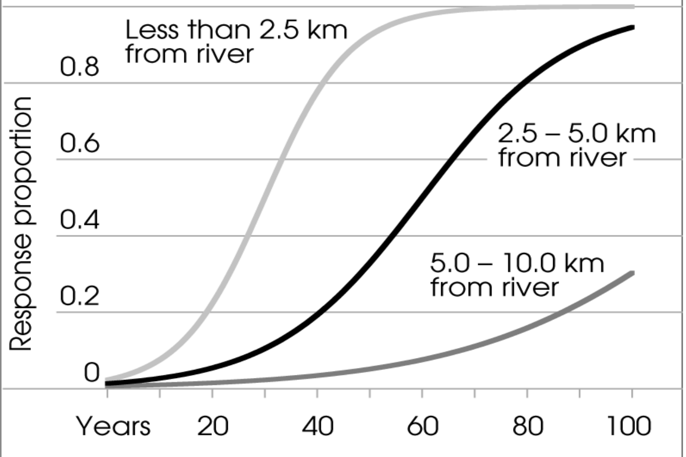
Assuming the contributions of recharge are additive and uncorrelated over time, it is possible to model gross discharge directly, thereby avoiding the need to explicitly model groundwater levels. In the approach adopted here, total discharge rate *D* in year *t* is a logistic function of a moving average of recharge rates in the current and earlier years according to:

$$D(t) = R(0) + \sum_{i=t-m}^{t} \left[R(i) - R(i-1)\right] \left\{1 + \exp\left[\left(\upsilon_{half} - i\right) / \upsilon_{slope}\right]\right\}^{-1} \tag{5}$$

where *R(0)* is the initial equilibrium recharge rate, *m* is the number of terms included in the moving average calculation, and υ_{half} and υ_{slope} are the time response parameters. The moving average formulation allows the accumulated impacts of past land use change to be incorporated as well as to model prospective changes. Typical response profiles for the three land use bands are shown in figure 3.

Saline groundwater discharge can be intercepted through groundwater pumping for subsequent disposal in evaporation ponds. In some areas of the Mallee, there is groundwater discharge to the flood plains, which is mobilised in flood events and does not contribute to the problem of high salt concentrations. Reductions in average saline discharge from these effects are accounted for in calculating river salt and water balances.

Figure 3: **Weighting function for contribution of past recharge to discharge**



Model calibration

The data required to calibrate the model are extensive. The procedure is outlined in more detail in Bell and Heaney (2000) and presented briefly here.

Land areas were calculated about the Murray River using an ARQ Info buffer procedure. Irrigation areas were obtained from a GIS coverage provided by Planning SA. Land values for horticultural activities were obtained from the South Australian Valuer General's Office. ABARE farm survey data were used to apportion the remaining area between dryland cropping, pasture and nonagricultural uses and to estimate the net present value of the returns to these activities.

The volume of irrigation water used in each reach was obtained from the Department of Water Resources and split between the land use activities using application rates for the crops grown in the region derived from ABARE farm survey data.

To calculate initial values for the production function parameters in (3), the total rent accruing to each activity was first calculated as the summation of rent associated with use of land and other fixed inputs to production and surface water. That is:

(6) $$RentTotal_j = RentL_j + RentSW_j + RentOther_j$$

where

$$RentL_j = L_j(0) * p_{\min}$$

(7) $$RentSW_j = sw_j(0) * \tilde{csw}$$

$$RentOther_j = L_j(0) * \left(p_j - p_{\min}\right)$$

where p_{min} is the net return to land and other fixed capital structures in their marginal use and $\tilde{csw}$ is the opportunity cost of surface water for irrigation in the initial period and is assumed to be $100/ML.

Initial values for the production function coefficients for each activity were then determined as:

$$\alpha_{Lj}(0) = \frac{RentL_j}{RentTotal_j}$$

(8) $$\alpha_{swj}(0) = \frac{RentSW_j}{RentTotal_j}$$

$$A_j = L_j(0)^{1-\alpha_{Lj}(0)} sw_j(0)^{-\alpha_{swj}(0)}$$

Within a simulation, these coefficients are then adjusted from the initial values according to equation (4). The coefficients in equation (4) were derived from estimated yield losses caused by irrigation salinity (MDBC 1999) by equating the decline in average physical product of irrigation water with the yield loss function.

The Murray Darling Basin Commission has linked its hydrological modeling to estimates based on cost impacts of incremental increases in salinity. Costs downstream of Morgan are imputed as a function of per unit EC changes in salt concentration. The analysis considers agricultural, domestic and industrial water uses (MDBC 1999). Using the cost functions derived in this model, each unit increase in EC at Morgan is imputed to have a downstream cost of $65 000. This cost is included in the analysis presented here.

The groundwater response functions were obtained from Watkins and Waclawik (1996). Groundwater salinities along with recharge rates under pre-clearing and current land use activities were obtained from Barnett et al. (2000). Projected groundwater discharge and salt load to the Murray River to the year 2100 (Barnett et al. 2000) were used to calibrate the remaining hydrological parameters. Flows and salt loads at the South Australian border were obtained from Jolly et al. (1997).

Results

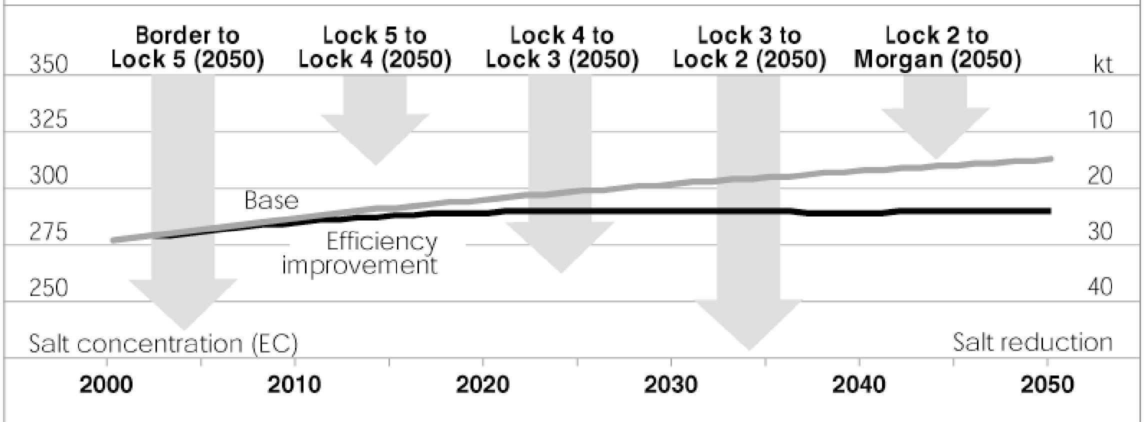
The results presented in this paper are for an improvement in water use efficiency across all irrigators in the South Australian Mallee region. In this analysis, there are no effects sourced upstream of the South Australian border. With no intervention to address salinity, there is expected to be an increase in salt concentration of the River Murray at Morgan by around 20 per cent over the next 100 years from around 277 EC to 334 EC caused by increased saline discharge from the irrigation areas in South Australia. In response to the increase in stream salinity, a gradual switch out of irrigated activities into dryland production is expected. Using a discount rate of 5 per cent, the cost of instream salinity to agricultural and horticultural production in the South Australian Mallee is estimated to be around $6.3 million, in net present value (NPV) terms, over the 100 year period. These costs are incurred as a result of yield losses caused by the reduction in the quality of water used for irrigation. Most of these costs are incurred between Locks 3 and 4 and Locks 2 and 3. This is reflective of the amount of horticultural production and their downstream location. In addition to this direct cost is the imputed cost of the increase in salt concentration downstream of Morgan, estimated to be around $32 million NPV over the 100 year period.

As a comparison to the baseline described above, an alternative simulation was conducted in which water use efficiency was improved by 5 per cent to reduce the amount of leakage into the groundwater system. With more efficient irrigation, less water is needed to produce the same amount of output. The volume of water saved by irrigators is available for sale or for use in further agricultural production. The capital costs of improving irrigation efficiency are not included in this analysis.

Salinity benefits from improvements in irrigation efficiency are derived from reductions in the discharge of saline water directly into streams, which leads to a reduction in the salt load and concentration of river flows. Improving water use efficiency in the South Australian Mallee region leads to an overall reduction in salt load of around 160 000 tonnes, or around 20 per cent in 2050. This corresponds to a reduction in salt concentration at Morgan of 23 EC (figure 4). Reflecting the delayed response of the groundwater flow system, it takes between seven and ten years before a change in groundwater recharge is reflected in a reduction in discharge of saline groundwater into the river.

The extent to which a reduction in salt loads and concentration is achieved depends on, among other things, the response time of the groundwater aquifer (in turn, dependent on the distance of the irrigation area from the river), the volume of the reduction in groundwater leakage and the underlying groundwater salinity. As a result, the reduction in salt loads varies between reaches (figure 4). In absolute terms, the greatest reductions are in the reaches between Locks 3 and 2 and between the border and Lock 5.

Figure 4: **Reductions in salt loads and EC at Morgan following a 5 per cent increase in water use efficiency**



The total economic benefits derived from a 5 per cent improvement in water use efficiency over the South Australian Mallee region is estimated to be around $11 million NPV over 100 years. The salinity benefits are derived in two ways. There is an increase in agricultural revenue as a result of increased availability of irrigation water and an associated small increase in per hectare net revenue as producers incur lower water costs. These benefits are internal to the region where the efficiency improvements were undertaken – that is, those producers undertaking the action capture the benefits.

In addition, benefits are also derived externally to the region undertaking the action. Benefits are also derived from the improvement in the quality of irrigation water available for downstream users. As a result of this improvement, agricultural yields are improved and revenue increased. Further, there is also a reduction in the imputed cost of salinity downstream of Morgan of around $13 million NPV over the 100 year period.

The distribution of external and internal benefits is important from a public policy perspective as policy intervention is usually required to facilitate optimal investment in salinity mitigation actions when some benefits are derived externally. In order to determine the distribution of the total benefits between those that are internal and external, simulations were undertaken in which water use efficiency was improved in only one reach. The distribution of the total benefits of undertaking the action is shown in figure 5.

Figure 5: **Investing in irrigation efficiency**

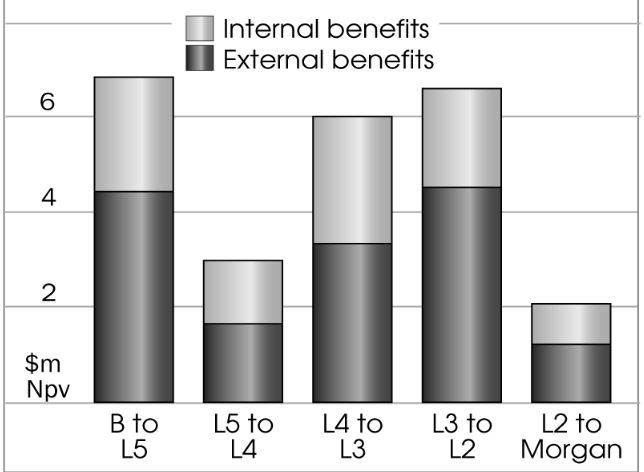


Figure 5 shows that if an action to improve water use efficiency was undertaken in the reach between the South Australian border and Lock 5, the total benefits to the South Australian Mallee zone are estimated be around $6.8 million NPV over a 100 year period. Of this, around $2.4 million is derived from the increase in agricultural production as a result of water savings.

The remainder of the total benefits is derived from the improvement in water quality as the irrigation water now has a higher production yield. In the scenario presented here, the users undertaking the efficiency improvement use the water they have saved to extend agricultural production. The benefits accruing downstream are, therefore, a result of higher production yield from irrigation, rather than an increase in the volume of irrigation water applied. If, on the other hand, upstream users sold the water saved, downstream users would benefit both from the increase in volume of irrigation water available and from the improvement in water quality.

Concluding remarks

Improving water use efficiency in the South Australian Mallee region has the potential to improve water quality and generate economic benefits. As these benefits accrue both internally and externally to the region undertaking the action, the challenge facing policy makers is to implement institutional arrangements that lead to an efficient combination of private and public investment in improved irrigation practices and infrastructure.

If the benefits derived from the increased agricultural revenue from water savings exceed the cost of undertaking the salinity management action, all other things being equal, irrigators will undertake improvements in water use efficiency themselves. All downstream water users will reap a positive externality from their action. However, from the combined perspective of all water users, the investment in improving efficiency is likely to be below that which would be collectively optimal.

The benefits derived from improvements in water quality are nonexclusive. This is likely to mean that there is a financial incentive for individuals to free ride on the actions of others. Hence, downstream irrigators and urban and industrial users will not have a sufficient incentive to make upstream investments in improving water quality.

Institutional arrangements may provide incentives for collaborative action among downstream users. As the irrigation areas in South Australia are managed by centralised irrigation authorities, the institutional arrangements may already be in place to facilitate this collaborative action.

As the benefits accruing to water users below Morgan are diffuse spatially, high transactions cost may prevent the collaboration of downstream users to encourage investment upstream. In this case, there may be a need for a broader policy response and government expenditure to achieve the level of investment that is required to undertake salinity mitigation action.

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