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Economic cost of environmental flows in an unregulated river system*

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This paper applies a stochastic dynamic programming framework, incorporating links to hydrological and biophysical models, to assess the economic costs of environmental flows in an unregulated river system in the Namoi Valley of northern New South Wales, Australia. Structural adjustment decisions are included in the model to account for farmer responses to changes in environmental flows through the introduction of a water sharing plan. The results of the analysis indicate that the proposed level of environmental flows reduces water extractions by around 6 per cent, and imposes an opportunity cost of less than 1 per cent in terms of reduced net income over a 20-year period.

Key words: dynamic programming, environmental flows, irrigation.

1. Introduction

There has been increasing concern about a range of environmental issues relating to the use of natural resources by agricultural systems. In particular there is substantial evidence of declining health of many Australian river systems as a result of increased irrigation extraction (Thomas and Cullen 1988; Environment Protection Authority 1997).

While environmental concerns have been a primary driver of major institutional reform to the management of rivers in New South Wales (NSW), the nature of the environmental problems and associated policy responses differ depending on whether the river is regulated or unregulated. Most major inland rivers in NSW are regulated meaning that their supply is controlled or augmented by releases from publicly owned dams and weirs. In contrast, unregulated rivers have no such public infrastructure to control (i.e. regulate) river flows to users and this results in highly variable flows that are solely dependent on climatic conditions in the catchment.

Although over extraction of water is the common source of environmental problems, the timing of extractions takes on more significance in unregulated

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rivers. Environmental problems in unregulated systems often arise in drier periods when flows are naturally low to moderate. During these times pools contract, water quality deteriorates, oxygen levels fall and native fauna compete for declining food supplies (DLWC 2002). Irrigation extractions at this time can lead to a rapid decline in water quality and insufficient water volumes to support habitats required for the survival of aquatic plants and animals. Environmental flow policies in unregulated systems therefore tend to focus on the protection of low to moderate flows by setting minimum pumping thresholds and placing limits on daily extractions. Environmental problems in regulated systems on the other hand, are often related to the nature of river regulation itself which markedly changes the seasonality of flows to the detriment of aquatic flora and fauna. Environmental flow policies in these systems often aim to restore some elements of natural flow variability which are achieved by altering the release pattern of water storages. Thus because of this latter ability it provides water managers with far more flexibility in achieving environmental objectives in regulated systems compared to unregulated systems which must rely solely on limitations to extractions.

The Water Management Act (2000) was introduced by the NSW Government to address the types of environmental problems outlined above and to achieve a more efficient allocation of resources through redefining water property rights. Most significantly, the Act specifies that water must be allocated for the fundamental health of a water source as the first priority. Additional allocations of water to the environment attempt to provide benefits in the form of improved water quality, natural ecosystem health and aquatic biodiversity.

Water Management Committees were given the task of developing environmental flow rules within their Water Sharing Plans to achieve a better balance between environmental and consumptive uses of water. In unregulated river systems, this has resulted in changed access rules to river flows for irrigation purposes, raising the prospect of economic costs to irrigated agriculture. These costs reflect reduced agricultural returns associated with the implementation of environmental flow policies.

Whilst the extent of economic costs associated with environmental flows has been a subject of enduring interest across the Murray–Darling Basin, much of the focus has been on large regulated rivers rather than unregulated rivers. The nature of river flows, institutional arrangements governing access to water and the type of adjustment options available to irrigators in unregulated systems contrasts with that of regulated systems. Consequently, there are difficulties in simply extrapolating economic costs of environmental flow policies estimated for regulated river systems to unregulated river systems.

The objective of this paper is to measure the economic costs to irrigated agriculture of environmental flows through the introduction of a Water Sharing Plan in an unregulated river system. The case-study region is the Mooki River subcatchment of the Namoi Valley in northern NSW, Australia. The study involved the development of a stochastic dynamic programming model that interacted with a catchment hydrology model and models of on-farm storage dynamics, irrigation scheduling and crop response to soil moisture deficits. In addition to measuring changes to the annual farm production decisions, the study also considered the role of longer term on-farm adjustment options (investment in on-farm storage, area available for irrigation and more efficient technologies) in ameliorating the economic costs of environmental flows.

2. The study region

The Mooki River subcatchment (Mooki) is a relatively small unregulated river catchment that lies at the eastern end of the Namoi Valley, and is approximately 50 km south of the main regional centre of Gunnedah. The Mooki is regarded as a ‘stressed’ river, meaning that potential demand from extractive users is high relative to the natural flows in the river. If all users pumped water at the same time there would be insufficient water for all existing extractors and the environmental needs of the river.

The Mooki is an ephemeral system and displays a highly variable flow pattern throughout the year. Zero river flows occur for approximately 25 per cent of the time and the longest recorded period of zero flow was for 674 days. The median flow is 10 megalitres per day (ML/day), with flows greater than 100 ML occurring 18 per cent of the time, and flows greater than 1000 ML/day only occur 4 per cent of the time. Extremely high flows of greater than 3000 ML/day occur less than 2 per cent of the time (Department of Infrastructure Planning and Natural Resources 2005).

Due to variability in river flows and the small number of days on which flow is available for extraction, on-farm water storages are essential for ensuring irrigation availability throughout the irrigation season. Water is extracted by irrigators into on-farm storages whenever sufficient flow is present, making it available for irrigation later in the season.

Prior to the introduction of environmental flows, the only restriction on water use in unregulated rivers was the cease-to-pump threshold. This provided some basic protection of low flows from extraction and allowed flows to build up to levels whereby irrigators in downstream river reaches could access water. In the case of the Mooki, the cease-to-pump threshold was set at a flow level of 50 ML/day. In theory, all flows above the cease-to-pump threshold could be accessed by irrigators although in practice irrigators only extracted a proportion of these flows because of limits on pump and on-farm storage capacities.

The Water Sharing Plan (the Plan) for the Mooki River commenced on 1 July 2004, and the water sharing rules are designed to provide for the environmental needs of the river as well as directing how water will be allocated and shared among different users. The Plan sets a limit on overall extractions on an annual basis and also sets a total daily extraction limit for each flow class. The revised cease-to-pump threshold of 100 ML/day in the Plan protects low flows whilst the daily extraction limits are a way of sharing available flows above the threshold between extractive users and the environment.

Table 1 Flow sharing rules for the water sharing plan in the Mooki River subcatchment (ML/day)

Description	Flow class	Flow class level (FL)	Total daily extraction limit
Very low flows	Cease-to-pump threshold	≤ 100	0
High flows	C class	100–1000	800
Very high flows	D class	1000–3000	1500
Extremely high flows	E class	> 3000	2100

Source: Department of Infrastructure Planning and Natural Resources (2005).

Prior to the Plan there was no restriction on access to flows once the cease-to-pump threshold was exceeded.

The flow classes are defined as the cease-to-pump threshold for very low flows, C class for high flows, D class for very high flows and E class for extremely high flows. The total daily extraction limits and flow values for each flow class are given in Table 1. The effect that the flow rules have on extractions can be best shown by an example. If the river was flowing at 150 ML/day the flow would be classed as a C class flow (100–1000 ML/day) and just 50 ML of extraction would be permitted on that day. This is because the first 100 ML of daily flow is protected by the cease-to-pump threshold. The rules also place an upper limit on extractions for each flow class. Thus if river flows were 950 ML/day, then 800 ML/day would be allowed for extraction and the balance of 150 ML/day would remain as an environmental flow.

The volume of water physically extracted by an individual user may be further limited by additional constraints on pump capacity and the size of on-farm storage. The overall result of the flow sharing rules is that irrigated agriculture has less access to very low flows (due a lift in the cease-to-pump threshold) and reduced access to moderate and higher flows (due to the establishment of the total daily extraction limit). Hence, the new rules affect both the timing of access and the volume that can be extracted compared to the previous access rules.

3. A bioeconomic model of the Mooki subcatchment

3.1 The biophysical model

A biophysical modelling system was developed that integrated data from a catchment hydrology model with models of on-farm storage dynamics, soil moisture and irrigation scheduling, and crop growth responses (Figure 1). The on-farm storage dynamics, soil moisture and water balance calculations were conducted on a daily time step basis and used daily weather data for Gunnedah for the period 1957–1993. The Integrated Quantity–Quality Model (IQQM) developed by the Department of Natural Resources was used to estimate the hydrology data for the study.

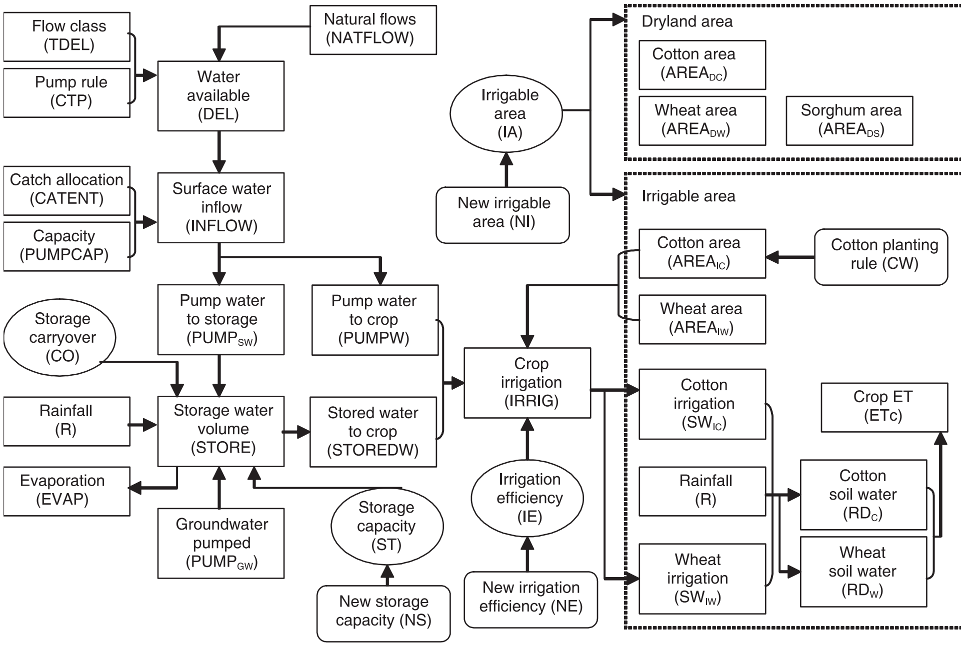

Figure 1 The biophysical model.

The biophysical model included detailed responses for on-farm storage, water access, soil moisture and irrigation scheduling, and crop yield response. The volume of water held in the on-farm storage is calculated daily (τ) as:

$$STORE_{\tau} = STORE_{\tau-1} + R_{\tau} + PUMP_{SW\tau} - SW_{IC\tau} - SW_{IW\tau} - EVAP_{\tau}, \quad (1)$$

where $STORE$ is daily stored water volume (ML), R is additions from daily rainfall (ML), $PUMP_{SW}$ is water pumped into storage from surface water (ML), SW_{IC} and SW_{IW} are stored water applied to irrigated cotton and irrigated wheat (ML) and $EVAP$ is evaporation losses (ML). The initial value of $STORE$ is given by the amount of water carryover from the previous year.

The calculation of the potential daily inflows from surface water differs depending upon whether historical rules or water sharing plan rules apply. The actual daily inflows used in the model (DEL) are therefore a function of the daily flows ($FLOW$) derived by the hydrology model and the rules given in Table 1.

The amount of water that an individual farmer can extract from the river on a given day ($INFLOW$) is governed by DEL, the total catchment volumetric entitlement ($CATENT$), and the individual irrigator's surface water volumetric entitlement (SE). The resulting equation governing daily water supply to an individual farm is:

$$INFLOW_{\tau} = DEL_{\tau}(SE/CATENT). \quad (2)$$

The daily water requirements of the irrigated crops are met from soil moisture, and when soil moisture is depleted to a refill point an irrigation event is triggered. A water balance equation, based on the Penman–Monteith approach for estimating evapotranspiration (Allen *et al.* 1998), was used to calculate soil moisture for each crop. Full details of the specification of the storage dynamics, soil moisture dynamics and irrigation scheduling equations can be found in Jones and Aluwihare (2007).

Crop yield is a function of a range of environmental and management factors. An adaptation of the approach of Yaron and Dinar (1982) was used to estimate crop yield response as a function of water supply at different growth stages:

$$Y = Y_{\max} - \sum_{n=1}^{N} d_n CD_n, \tag{3}$$

where Y is crop yield (t/ha), CD_n is the number of critical days in growth period n, $Y_{\max}$ is the maximum yield obtainable for $CD_n = 0$ for all n, N is the number of growth periods, and d_n is the loss in crop yield per critical day in growth period n (t/ha). This equation was combined with a growth index (Fitzpatrick and Nix 1975) to represent the responses of plants to the three major climatic determinants of crop growth and development: light, temperature and moisture.

3.2 The stochastic dynamic programming model

Dynamic programming is a widely used technique for water storage problems, particularly for issues involving optimal reservoir development and management. Reviews of the use of this techniques for such applications can be found in Yeh (1985) and Kennedy (1986).

A stochastic dynamic programming model (SDP) was developed using the language Fortran 95 to measure the opportunity costs of the Plan and to evaluate the benefits of any structural adjustment and management options implemented to ameliorate the effects of changes to flow rules. The SDP model is solved by standard backward recursion for a time horizon (T) of 20-years. Each stage (t) is represented by a single crop growth year defined as the period, 1 June to 31 May, with the principal crops being irrigated cotton and wheat. The SDP model uses the biophysical models illustrated in Figure 1 to derive state transitions and the biological parameters required for the stage return function.

The model included four state variables to represent the capacity of on-farm storage (ST), the area laid out to irrigation (IA), the percentage of irrigation land where irrigation efficiency technologies have been adopted (IE), and the volume of water carried over from the previous period and held in storage at the commencement of the crop growth year (CO). The decision variables include investment in additional on-farm storage capacity (NS), investment in additional irrigable area (NI), investment in new irrigation efficiency technology expressed as the percentage of the area improved (*NE*), and a cotton planting rule based upon the amount of water to apply to cotton (ML/ha) for determining the area sown to irrigated cotton (*CW*). A description of each state and decision variable and the range of discrete values for each case study are given in Table 2.

The capital costs for the investments in storage capacity, irrigable area and irrigation efficiency are given in Table 3. In the case of the irrigable area state and investment decision, the potential irrigable area is limited to reflect the fact that, at the catchment level, a large proportion of the authorised area for irrigation has already been developed for this purpose. The technology that is used to represent the irrigation efficiency technology is a subsurface drip irrigation system that leads to water savings of approximately 40 per cent and

Table 2 Parameter values for determining the discrete state and decision variables values for stochastic dynamic programming model

	Unit	Minimum	Maximum	Increment
State variables:				
On-farm storage (*ST*)	ML	4500	6750	250
Irrigable area (*IA*)	ha	4000	6250	250
Irrigation efficiency (*IE*)	%	0	100	25
Storage carryover (*CO*)	ML	0	CO_{max}	1000
Decision variables:				
Invest in storage (*NS*)	ML	0	500	250
Invest in irrigable area (*NI*)	ha	0	500	250
Invest in irrigation efficiency (*NE*)	%	0	25	25
Cotton planting rule (*CW*)	ML/ha	3	13	1

CO_{max} is the maximum capacity of the storage, and is determined by the on-farm storage state *ST*.

Table 3 Model data

Parameter	Description	Unit	Value
TA	Total farm area	ha	17 788
SE	Surface water volumetric entitlement	ML/year	27 449
$PUMPCAP$	Surface water pump capacity	ML/day	2625
B_1	Volumetric adjustment for cotton planting rule	%	10
P_{CL}	Cotton lint price	$/bale	500
P_{CS}	Cotton seed price	$/t	250
P_{IW}	Wheat price	$/t	172
VC_{IC}	Cotton (irrigated) variable cost	$/ha	2126
VC_{IW}	Wheat (irrigated) variable cost	$/ha	500
M_{DW}	Dryland wheat gross margin	$/ha	297
C_{VOL}	Volumetric entitlement cost	$/ML	8.00
C_{PUMP}	Surface water pumping cost	$/ML	1.0
K_{NS}	Capital cost of new storage	$/ML	2500
K_{NI}	Capital cost of new irrigation	$/ha	900
K_{NE}	Capital cost of new irrigation efficiency	$/ha	5000
β	Discount rate	%	5

higher cotton yields (Raine *et al.* 2000). It is assumed that a maximum of 25 per cent of the irrigable area can be converted to higher irrigation efficiency in any given year without sacrificing crop area for the following year. The cotton planting rule determines the area of irrigated cotton by dividing the expected amount of water available for irrigation by CW, the amount of water per hectare to allocate for the cotton crop.

The state transitions for each state variable are described as follows.

Storage capacity:

$$ST_t = ST_{t-1} + NS_{t-1}. \tag{4}$$

Irrigable area:

$$IA_t = IA_{t-1} + NI_{t-1}. \tag{5}$$

Irrigation efficiency:

$$IE_t = IE_{t-1} + NE_{t-1}. \tag{6}$$

Carryover of on-farm storage:

$$CO_t = STORE_{t-1,\tau=365}. \tag{7}$$

The state transition for the carryover of on-farm storage is derived by the biophysical model and is conceptually represented by Equation (1). The volume of water in the on-farm storage is calculated on a daily basis and the carryover is the volume of water in the storage on 31 May of the previous stage. This state transition is stochastic as it depends upon random river flows ($INFLOW$) and the irrigation water requirements for irrigated cotton and wheat (SW_{IC} and SW_{IW}).

The annual stage return (π) is a function of irrigated and dryland crop gross margins (GM), water costs (W_{COST}), capital costs for the structural adjustment decisions (K_{COST}), and farm fixed costs (F_{COST}):

$$\pi_t = (GM_{IC,t} + GM_{IW,t} + GM_{DW,t}) - W_{COST,t} - K_{COST,t} - F_{COST,t}, \tag{8}$$

where the subscripts IC, IW and DW refer to irrigated cotton, irrigated wheat and dryland wheat, respectively. The individual crop gross margins are derived as follows:

$$GM_{IC} = A_{IC}(Y_{CL}P_{CL} + Y_{CS}P_{CS} - VC_{IC}), \tag{9}$$

$$GM_{IW} = A_{IW}(Y_{IW}P_{IW} - VC_{IW}), \tag{10}$$

$$GM_{DW} = A_{DW}M_{DW}, \tag{11}$$

where A is crop area of irrigated cotton, irrigated wheat or dryland wheat, Y is crop yield derived from Equation (5), P is price, VC are variable production costs excluding water costs, and the subscripts CL and CS refer to cotton lint and cotton seed. Parameter values for prices and variable costs are given in Table 3. The crop areas are constrained by the total farm (TA) and irrigable areas:

$$A_{IC} = (CO + b_1 SE)/CW, \tag{12}$$

$$A_{IW} = IA - IF - A_{IC}, \tag{13}$$

$$A_{DW} = TA - IA, \tag{14}$$

where b_1 is a factor for the proportion of the surface water entitlement to be included in the cotton planting area calculation, and IF is the irrigable fallow area (ha). The water costs are derived as follows:

$$W_{COSTt} = \sum_{\tau=1}^{365} INFLOW_\tau (C_{VOL} + C_{PUMP}), \tag{15}$$

where C_{VOL} is the cost of surface volumetric water (\$/ML), C_{PUMP} is the costs of pumping surface water (\$/ML). The capital costs for the new storage and irrigable area are a function of the decision variables and the unit capital costs:

$$K_{COSTt} = K_{NS}NS_t + K_{NI}NI_t + K_{NE}NE_t IA_t, \tag{16}$$

where K_{NS}, K_{NI} and K_{NE} are the capital costs of new storage capacity (\$/ML), new irrigable area (\$/ha) and irrigation efficient technologies (\$/ha).

The objective function of the model is an expected net present value (NPV) and is obtained from the maximisation of π over a 20-year period. Solution is obtained from the stochastic dynamic programming recursive equation:

$$V_t(\mathbf{X}_t) = \max_{\mathbf{D}_t}[E\{\pi(\mathbf{X}_t, e_t)\} + \beta E\{V_{t+1}(\mathbf{X}_{t+1})\}], \tag{17}$$

where $V_t(\cdot)$ is the optimal value function from period t to the end of the planning horizon (T), $\mathbf{X}_t$ is the set of state variables (ST_t, IA_t, IE_t, CO_t), $\mathbf{D}_t$ is the set of discrete decision variables (NS_t, NI_t, NE_t, CW_t), e_t is an error term that determines the probability distribution for π, E is an expectations operator and β is the discount factor.

4. Simulation scenarios

The SDP model was solved at a catchment level for the following two policy scenarios to measure the economic impacts of environmental flows in the Mooki:

- BASE: the historical sharing rules;
- PLAN: the Water Sharing Plan.

Parameter values for the Mooki scenarios were derived from a farm survey by Bennett and Bray (2001) and Powell (2001). In addition to the water policy and catchment structure scenarios, the model was solved with and without longer term structural adjustment options. The 'without' adjustment option excludes the investment decisions, thus only the carryover state variable (*CO*) and the cotton planting rule decision (*CW*) are active in the SDP model. The 'with' adjustment option allows all state and decision variables. This restriction on long-term adjustment allows for a measure of the benefits of management options to ameliorate the effects of environmental flows.

Preliminary runs of the SDP model indicated that the irrigation efficiency investment decisions (*NE*) were rarely selected. Consequently the irrigation efficiency state variable (*IE*) was excluded from the main analysis of the economic costs of environmental flows. The impact that the adoption of irrigation efficient technologies has on the results was included as sensitivity analysis.

5. Mooki river flow availability

Like many other unregulated rivers in Australia, the Mooki has a highly variable inter- and intra-annual flow pattern, which directly influences the ability of landholders to extract water for irrigation. To determine temporal flows the IQQM model was simulated for the period 1957–1993, the period for which IQQM hydrology data was available, which indicated that Mooki river flows are mostly low with a median flow of just 10 ML/day.

The probability of daily flows achieving a certain flow threshold were derived from the IQQM model results (Figure 2), and illustrate a number of points about the nature of flows in the Mooki. First, there is a low probability of very high daily flows (class D greater than 1000 ML/day) (ranging between 4 and 9 per cent depending on the month) or extremely high flows (class E greater than 3000 ML/day) (3–6 per cent depending on the month). Second, there is little seasonality associated with achieving these higher flow categories indicating some randomness in major rainfall events rather than predictable patterns. Finally, while there is monthly variability in accessing daily flows above the cease-to-pump thresholds (of either 50 or 100 ML/day), there is some seasonality with increased probabilities of access evident in the June to September period.

The impact of PLAN on access to flows can be seen by comparing the probabilities of flows under the 50 ML/day (BASE) and 100 ML/day (PLAN) cease-to-pump thresholds. Adoption of the higher cease-to-pump threshold results in a notable reduction in the probability of accessing daily river flows. The difference in access becomes more pronounced in August–November. For example, in September there is a 37 per cent probability that flows can be accessed on any given day under BASE, whereas for PLAN the probability of accessing flows declines to 20 per cent.

A reduction in the probability of accessing daily river flows does not in itself necessarily infer a lower volume of water extracted throughout an

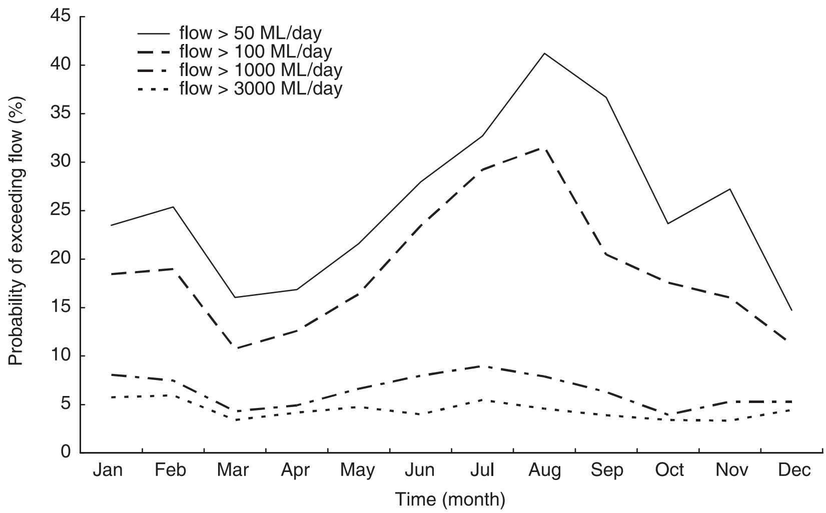

Figure 2 The probability of Mooki river flows exceeding defined daily flow rates (%).

irrigation season. The other key drivers of water extraction are the total daily extraction limit set for each flow class, the timing of water availability versus crop demands, the capacity of on-farm storages and the policy flexibility given to irrigators to carryover water from one year to the next. Moreover, although the probability of accessing daily flows is less, there may still be enough days available throughout the irrigation system to extract the demanded irrigation volumes.

The bio-physical model was solved to derive annual extractions for the period 1957–1993 for the current irrigation infrastructure of 4500 ML on-farm storage and 4000 ha of land available for irrigation of which 457 ha is sown to cotton. This resulted in the mean annual volume of water extracted under BASE being 9235 ML (standard deviation 3527 ML) and under PLAN 8643 ML (standard deviation 3493 ML), a 6.4 per cent decline. Consequently, although there is a considerable reduction in the probability of accessing daily flows due to PLAN, this effect is ameliorated to some extent by the length of the irrigation season and the number of days available to access river flows. Not surprisingly, PLAN also reduces the reliability of extractions with the coefficient of variation increasing slightly from 0.38 to 0.40.

6. Economic results

6.1 Economic cost of the Mooki water sharing plan

The economic cost of PLAN was estimated firstly for the current on-farm storage capacity and irrigation area, that is, no structural adjustment options available. Consequently, the only choices available in the model to respond to

Table 4 The expected net present value averaged across all states for the policy scenarios BASE and PLAN for with and without structural adjustment options available

	Without adjustment options	With adjustment options
BASE ($ m)	78.4	83.5
PLAN ($ m)	77.7	83.1
Economic cost ($ m)	0.6	0.4
Economic cost (%)	0.8	0.4

reduced water availability is the area planted to cotton and the volume of water to carryover in the on-farm storage.

The expected NPV was averaged across all states to estimate the economic cost of PLAN compared to BASE (Table 4). There was a reduction in expected NPV from $78.4 million to $77.7 million due to the introduction of environmental flows, an average economic cost of $0.6 million (a 0.8 per cent reduction). This is considerably less than the estimated reduction in access to river flows of 6.4 per cent. This result indicates that the introduction of the Plan would have a negligible impact upon agricultural returns at the catchment level, particularly when compared to other sources of income variability such as crop prices.

There was no significant difference in the area planted to cotton between BASE and PLAN, with the area increasing from 460 ha for nil storage carryover to 560 ha with 4000 ML of storage carryover. The difference in expected NPV between BASE and PLAN is largely due to lower cotton yields in the catchment resulting from reduced access to river flows. The cotton area remains positive when no storage carryover water occurs because there is the expectation that access to daily flows will still occur within the irrigation season. This result indicates that the optimal area to plant to cotton is not simply a function of known water supply, but expectations of future access is also important in the planning decision.

The economic cost of PLAN was secondly estimated for the case where longer term on-farm adjustment to irrigation infrastructure was allowed in the model. These adjustments are in addition to the cotton planting rule and allow the model to increase storage capacity and modify the area available for irrigation in response to environmental flows.

The expected NPV for BASE was $83.5 million and for PLAN was $83.1 million (Table 4), an economic cost of $0.4 million (a 0.4 per cent reduction). This economic cost was proportionally less than the scenario of without structural adjustment options, and suggests that there may be a positive role for investment in new irrigation infrastructure to ameliorate the effects of reduced access to river flows.

Introducing structural adjustment options not only reduced the opportunity cost associated with the PLAN, but also resulted in a higher expected

Table 5 The expected net present values ($ m) for with structural adjustment options derived for the policy scenarios BASE and PLAN for selected initial on-farm storage and irrigation area states

		On-farm storage capacity (ML)			
		4500	5000	5500	6000
BASE					
Irrigation area (ha)	4000	80.6	80.6	80.7	80.7
	4500	82.1	82.1	82.1	82.1
	5000	82.9	82.9	83.0	83.6
	5500	84.3	84.2	83.9	84.3
	6000	85.4	85.7	85.3	85.7
PLAN					
Irrigation area (ha)	4000	79.7	79.9	79.5	80.0
	4500	81.3	81.5	80.9	81.4
	5000	82.9	83.2	82.6	82.6
	5500	84.5	84.9	84.2	84.2
	6000	85.2	85.7	85.8	85.1

NPV (by approximately 7 per cent) than in the without adjustment option scenario. The expected NPV for PLAN with adjustment ($83.1 million) was also higher than BASE without adjustment ($78.4 million). This result indicates that investment in irrigation infrastructure at a catchment level may increase agricultural returns by a greater extent than the impact of introducing environmental flows in the Mooki.

The expected NPV for a range of initial on-farm storage and irrigation area states are given in Table 5 for the with adjustment options scenario. Although there is a reduction in the expected NPV of PLAN when averaged across all states (of 0.4 per cent), there is variability in the economic impact across initial state variable combinations. In some cases, the expected NPV for PLAN is slightly greater than BASE (usually less than 1 per cent greater) due to a combination of the random sampling and the resulting (sometimes favourable for PLAN) timing of daily access to river flows between the two scenarios. Increasing the initial area of irrigation had a modest positive effect on expected NPV, whereas larger initial storages had only very slight long-term economic benefits. The result suggests that the initial storage size is close to optimal, and increasing storage capacity leads to higher overhead costs and minimal long-term marginal returns. Another factor that influences the expected NPV values is the higher overhead costs that are associated with larger irrigation area and storage states. The inclusion of higher overhead costs with irrigation infrastructure can lead to a lower expected NPV for some initial states with the maximum irrigation area and storage capacity values.

There were only small differences in the optimal investment decisions between the BASE and PLAN scenarios, thus only the results for the latter are reported for a number of selected initial on-farm storage and irrigation area states (Table 6). The optimal steady-state irrigation area is between 5500

Table 6 The optimal structural adjustment decisions for new storage capacity (ML) and area available for irrigation (ha) for the policy scenario PLAN for selected initial on-farm storage and irrigation area states

		On-farm storage capacity (ML)			
		4500	5000	5500	6000
New storage (NS)					
Irrigation area (ha)	4000	0	0	0	0
	4500	250	0	0	0
	5000	250	0	0	0
	5500	250	0	0	0
	6000	250	0	0	0
New irrigation (NI)					
Irrigation area (ha)	4000	500	500	500	500
	4500	500	250	500	500
	5000	500	500	500	500
	5500	250	250	250	250
	6000	0	0	0	0

and 6000 ha with investment in new irrigation area being selected at all state values up to this level. This suggests that the capital costs associated with establishing larger irrigation areas are more than offset by the benefits gained from the use of that additional area even though this occurs irregularly. Investment in additional on-farm storage size occurs only at the lowest state value giving an optimal steady-state on-farm storage size of between 4500 and 5000 ML in the Mooki. Overall, we conclude that the extent of irrigation area is the greatest constraint to catchment level returns in the Mooki and that further investment is found to be profitable (either under the BASE or PLAN).

Increasing the steady-state irrigation area and storage capacity under the case of a water sharing plan could potentially result in higher water use than under the previous flow rules with no structural adjustment. This concept was evaluated by incorporating a steady-state storage of 5000 ML and irrigation area of 6000 ha in the bio-physical model and solving for PLAN for the period 1957–1993. The resulting average annual water extraction of 9695 ML (standard deviation 4289 ML) was 5 per cent greater than estimated for BASE in Section 5 (9235 ML).

6.2 Sensitivity analysis

Sensitivity analysis was undertaken on a number of potentially important model variables to determine the difference in expected NPV between the PLAN and BASE scenarios. The variables considered were the discount rate, cotton price, the capital costs of new storage and irrigation area, and alternative cease-to-pump thresholds to reflect higher environmental flow policies (Table 7). Variation in the parameter values for the storage and irrigation area capital costs did not affect the results and accordingly were not reported.

Table 7 The economic impact in terms of the difference between PLAN and BASE of variations to key model parameters (%)

Discount rate at 10%	0.6
Cotton price increased by 10%	0.3
Cease-to-pump threshold of 200 ML/day	0.9
Cease-to-pump threshold of 300 ML	1.9
Cease-to-pump threshold of 400 ML	2.4
Cease-to-pump threshold of 500 ML	3.3

The discount rate was increased from 5 to 10 per cent. This resulted in a substantial decrease in the expected NPV for both scenarios, with the difference between BASE and PLAN increasing slightly to 0.6 per cent. Cotton lint and cotton seed prices were increased by 10 per cent, which resulted in a slight decrease in the difference in NPV between PLAN and BASE to 0.3 per cent. Consequently, the results are insensitive to modest changes in cotton price.

Given on-going concerns about river health there is some prospect that environmental flows might have to be increased in some catchments in the future. While there is uncertainty about the form that such intervention might take, and hence who bears the costs, additional analysis was conducted to test the sensitivity of irrigation in the catchment to higher environmental flows. New environmental flow policies were created by applying successively higher (200, 300, 400 and 500 ML) cease-to-pump thresholds while keeping other aspects of the PLAN rules constant. Increasing environmental flows through imposition of higher cease-to-pump thresholds increases the agricultural costs in the Mooki from 0.9 per cent (200 ML cease-to-pump threshold) to 3.3 per cent (500 ML cease-to-pump threshold).

7. Discussion

River flows and irrigation water availability in the Mooki subcatchment has a history of high annual variability. The effect of introducing a water sharing Plan to the Mooki is to further reduce the availability of irrigation water at low flows and to place a cap on extractions during high flows. Not only does this limit the amount of water that can be extracted, the plan also results in a reduction in the number of days that river flows can be accessed.

The average volume of water extracted for irrigation was estimated to decline by 6.4 per cent due to the Plan. The resulting economic impact, as measured by the decline in expected net present value, was found to be considerably less at just 0.8 per cent. If investment decisions are included to allow for structural adjustment in response to changes in water policy, the opportunity cost of the Plan was further reduced to 0.4 per cent. The inclusion of investment decisions also led to an increase in the expected net present value, indicating the importance of infrastructure change, with or without a water sharing plan.

The economic costs for individual farms in the Mooki may differ to that estimated at the aggregate level in this study. The characteristics of individual farms, including property size, irrigation entitlement, level of infrastructure development and potential for water efficiency improvements may well have an influence on the impact of the water sharing plan. Given the diversity of farm sizes and irrigation infrastructure in the Mooki (Bennett and Bray 2001), a more disaggregated analysis of the distributional aspects of the Plan was not attempted.

The impacts of the plan in the future will also be influenced by the level of river flows, and consequently by any trends in rainfall. While there remains considerable uncertainty about the impact that climate change may be having on rainfall in Australia, it is unlikely that rainfall, and hence river flows, will exactly match the data of the period 1957–1993 used in this study. The extent of the difference, due either to underlying natural climatic variability or long-term climate change, will influence the estimates of expected net present value derived in this study. However, we would expect the scenarios BASE and PLAN to be equally influenced by such differences and consequently would not expect a substantial divergence from the net cost of environmental flows estimated here.

The effects of increased environmental flow allocations were simulated through changes to the cease-to-pump threshold, whereby it was increased from 100 to 500 ML. The economic cost of environmental flows increased with the cease-to-pump threshold as expected. At the highest cease-to-pump threshold rule tested (500 ML) there was approximately a 3.3 per cent reduction in expected net present value relative to the BASE scenario. To determine the economic efficiency of the policy, the extent of costs could be compared to the level of expected environmental benefits arising from environmental flows. At a catchment level the agricultural costs of environmental flows seem reasonably limited, although it is likely that such policies may impose more significant costs on particular farm types in the catchment.

The bioeconomic modelling framework presented is suitable for complex problems where there are both daily and yearly aspects. Changes in flow rules being implemented in unregulated rivers in NSW have daily access implications that cannot be captured by frameworks that consider more aggregated time scales. Moreover, there is substantial annual variability in flows that are best addressed through a stochastic rather than a deterministic approach. An important feature of the bioeconomic modelling framework used here is that it not only accounts for the dynamic and stochastic aspects of the problem, but also the potential for structural adjustment decisions in response to policy change.

The key benefit of the modelling framework is that it allows a broader set of irrigator responses, beyond those offered by more simple modelling approaches, to be assessed. Some of these longer term responses only become viable when greater resource scarcity is introduced through successively higher environmentally flow policies. Under these conditions, modelling frameworks that are able to better capture dynamic elements are likely to provide a more robust assessment of long-term policy effects, particularly when more major changes are being contemplated.

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