The farm level impacts of water sharing plans in the Namoi Valley: A stochastic dynamic programming analysis

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Abstract

In NSW the *Water Management Act* (2000) requires water to be specifically allocated for environmental purposes so as to improve river health. Water sharing plans have been developed that establish extractive and environmental shares to river flows. In unregulated river systems this has resulted in changed access rules to river flows for irrigation purposes, raising the prospect of opportunity costs being imposed on irrigators. An important consideration in the development of these plans is an assessment of socio-economic impacts of different water sharing options. This paper presents a bioeconomic modelling framework, based on stochastic dynamic programming linked to hydrological and biophysical models, to assess the farm level impacts of different water sharing plans in a sub-catchment of the Namoi Valley. The framework incorporates temporal farm adjustment decisions in response to changes in water rights and the impact of river flow and climatic variability in assessing the impact of different water sharing plans.

Key words: water sharing rules, modelling, bioeconomic, stochastic dynamic programming.

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1. Introduction

1.1 Background

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. Algal blooms, declines in populations of native fish species and a corresponding increase in exotic fish species, poor water quality (including salinity, turbidity, nutrients and chemicals), rising water tables, loss of native flora and fauna and decline in the health of wetlands are examples of some of the environmental issues (EPA 1997; Thomas and Cullen

1988). As a result, Australian State Governments have introduced a wide range of water reforms in line with the priorities identified by the Council of Australian Governments (COAG 1994).

The NSW Government has introduced a wide range of water reforms to address the problems of environmental degradation. A ‘cap’ on water extraction, based on 1993-94 levels of irrigation development, in the Murray-Darling Basin was introduced to stop further expansion of demand for irrigation water. The ‘environment’ has been recognised as a legitimate user of water. More recently the *Water Management Act 2000 (Act)* was enacted to achieve environmental objectives through re-allocating water and redefining property rights to water. Community based water management committees were established to develop water-sharing plans that allocate water between extractive users (eg. irrigators, domestic users) and the environment. The allocation of water to the environment attempts to provide environmental benefits in the form of improved water quality, the health of natural ecosystem and aquatic biodiversity. These environmental objectives may be achieved through a range of actions such as protecting low flows, mimicking natural variability of river flows and restoring a portion of ‘freshes’ and high flows. However, such improvement in the environment through reallocation of water may impose costs to other sectors, particularly irrigated agriculture.

Prior to implementing a water sharing plan there is a requirement to determine the economic impact, as measured by the opportunity cost to irrigators, of alternative plans. The economic impact will be influenced by changes in the variability of access, the size of the entitlement, and any structural adjustment decisions that can be adopted by irrigators to ameliorate the effects of water policy changes.

The primary objective of this paper is to measure the opportunity cost to irrigators of alternative water-sharing rules in the Mooki River sub-catchment (Mooki) of the Namoi Valley. A secondary objective is to present a modelling framework that explicitly accounts for the stochastic and dynamic nature of the problem, and to measure the impact of structural adjustment decisions that irrigators may adopt to changes in water policy.

The following sub-section provides a background to the case-study area, the Mooki. Section 2 presents the water-sharing rules developed for the Mooki. The methodology is described in Section 3, which presents the case for a bioeconomic modelling framework. This framework uses a combination of stochastic dynamic programming linked to a biophysical model of soil-water relationships, on-farm storage and irrigation scheduling. In Section 4 the results of the study are presented. Finally, the discussion and conclusions are given in Section 5.

1.2 The Mooki River sub-catchment

The Namoi Valley, located in northern NSW Australia, is a catchment experiencing a number of adverse environmental effects due to over allocation of surface water and groundwater for irrigation purposes. Under the *Act* water sharing rules have been developed for regulated and unregulated catchments and groundwater zones in the valley to arrest further degradation to the environment (DLWC 2000; Carter et al. 2000).

The Mooki is an unregulated river catchment that lies at the eastern end of the Namoi Valley (Figure 1). This sub-catchment covers an area of about 840 km^2 representing about 2% of the Namoi Catchment area. Irrigation is an important feature of the Mooki agricultural production system, and currently there are 23 irrigators licensed to extract water from the

Mooki River of which the majority has access to both surface water and groundwater while the remainder have only access to surface water. The total area authorised for irrigation using surface water is around 3,500 ha, but currently around 2,900 hectares have been developed for irrigation (Powell 2001).

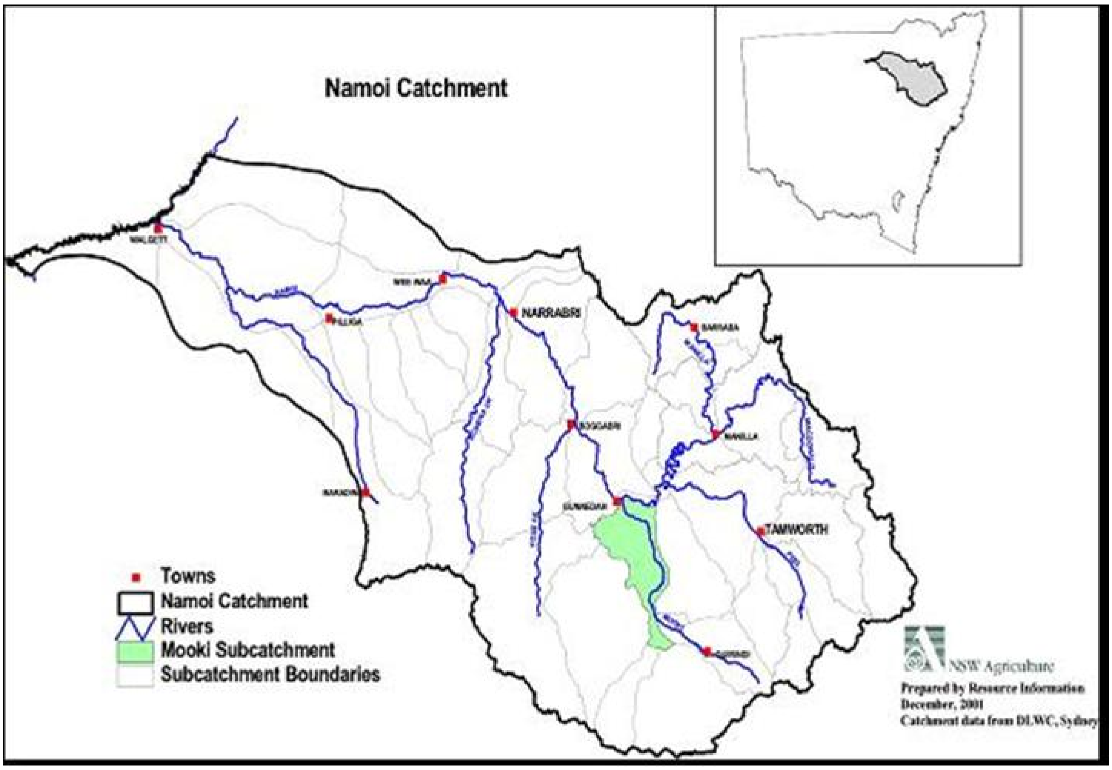

Figure 1 Mooki sub-catchment in the Namoi Valley

The irrigated agricultural enterprises in the Mooki include cotton, wheat, maize, summer oilseeds and vegetables. Over the past two decades, the area of cotton has expanded rapidly reflecting its relative profitability, with cotton and wheat now accounting for around 70 and 20% of the irrigated area respectively. Back to back cotton and cotton-wheat rotations are the most common practices in this catchment, and most irrigated farms also have a dryland farming component with sorghum and wheat being the most commonly grown dryland crops. Furrow irrigation is the predominant irrigation method for all crops, although there is some spray irrigation in the upper sub-catchment.

As an unregulated river catchment irrigation in the Mooki is conducted by directly pumping water from the river when sufficient flow is available. There are no upper catchment storages or structures in unregulated rivers to control river flow and, combined with the ephemeral nature of the river flow and high variability of daily flows, this results in substantial uncertainty in river flow availability for irrigation extraction. In response to unreliability in water availability, investment in on-farm storages is a significant feature of farms in unregulated systems such as the Mooki. This allows water to be pumped into the on-farm storage whenever flow is available, and this supply is then available for irrigation later in the season.

The volume of water stored in an on-farm storage plus any groundwater entitlement are the main determinants of the area planted to irrigated summer (mostly cotton) crops. Winter cropping is mainly determined by the available soil moisture and crop rotation requirements.

2. Rules for Sharing River Flows

This paper considers four water sharing scenarios; the historical flow sharing rules (Base) and three flow sharing options proposed by the Namoi Unregulated River Management Committee (NURMC) (Options A, B, and C).

Under the historical licensing system, irrigation entitlements have been based on the area irrigated irrespective of the volume of water used. A cease to pump (CTP) rule established the minimum flow level that the river must reach before irrigators could commence pumping. This rule aimed to protect low flows and allow flow to build up to levels useful for irrigators in downstream river reaches.

The historical rules represent the 'base case' against which the proposed flow sharing options are compared. Under the base case, irrigators could access all river flows above the CTP level (50 ML/day). In practice irrigators could only extract a proportion of flows because of limits on pump and on-farm storage capacities.

As a result of the *Act* all area based licences have been converted to a volumetric basis so as to better define irrigators' access rights, to encourage improved irrigation efficiency and to facilitate trade. Volumetric entitlements have been established by looking at the historical area of each crop type, which is then multiplied by the theoretical water requirement for a given climatic zone.

In addition to an annual volume limit, flow variability requires a mechanism by which each flow event can be shared between irrigators, the environment and other users. A generic approach was developed across NSW to divide river flows into four categories. These are based on a flow duration curve (Figure 2) and are defined as follows.

1. Basic low flows – lowest 5^{th} percentile of flow is not available for extraction.
2. Class A - low flows generally between the 5^{th} and 20^{th} percentiles.
3. Class B - low to moderate flows generally between the 20^{th} and 50^{th} percentile.
4. Class C - moderate to high flows, freshes and floods. Refers to flows generally higher than the 50^{th} percentile.

Under the new flow sharing rules irrigators are permitted to extract a proportion of flows in each flow class, with the proportion extracted depending upon the flow class. The volume of water allowed for extraction by irrigators for each flow class is called the bulk extraction volume (BEV). Due to the highly ephemeral nature of the stream flows in the Mooki River, Class A and B flows do not exist (Powell, 2001) and given the high demand for river flows Class C flows have been divided into three sub-classes (C1, C2 and C3). The flow scenarios (Options A, B and C) proposed by the NURMC for sharing river flows within these classes and are summarised in Table 1 (Powell, 2001). The overall result of the flow sharing plans is that irrigated agriculture has less access to both low and high river flows.

Under the flow sharing options the cease to pump rule is increased from 50 to 100 (CTP_P) ML/day for the catchment. Whereas there were no restrictions under the Base in terms of extracting water above the CTP rule, under the proposed options there is a specific constraint in the form of the BEV. For example, in the case of Option A the BEV for C1 limits catchment wide irrigation extraction to 800 ML/day even if flow was 1000 ML/day. All options now restrict extraction to a maximum of 2100 ML/day (C3) whereas under the previous licensing system there was no limit on extraction during periods of higher flows. The BEV is distributed among individual irrigators in proportion to their licensed entitlement but is restricted by the physical ability to extract water. Individual flow extraction will continue to depend on pump capacity and the size of on-farm storage.

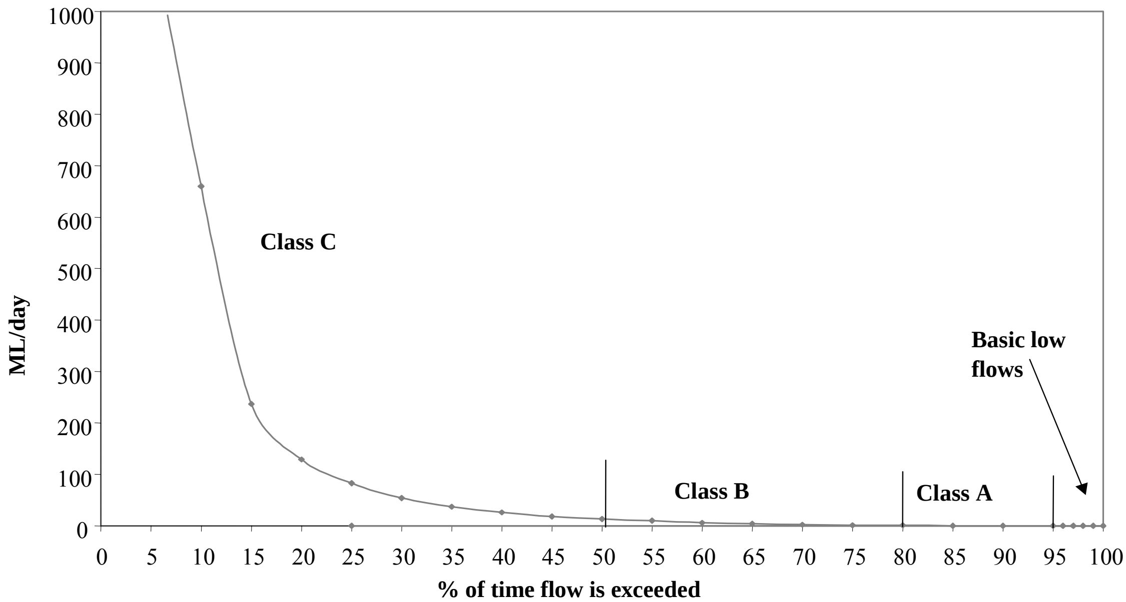

Figure 2 Flow duration curve for the Mooki River catchment (Source DLWC)

Table 1 Proposed flow sharing options in the Mooki River sub-catchment

Flow class	Flow level (ML/day)	Bulk Extraction Volume (ML)		
		Option A	Option B	Option C
CTP_P	100	0	0	0
C1	100 - 1,000	800	600	600
C2	1,000 – 3,000	1,500	1,500	900
C3	> 3,000	2,100	2,100	2,100

The water sharing plans that are designed to protect low flows, freshes and to mimic natural flows would restrict and limit unlimited access to water for irrigation. The variable flow access, depending on the flow class, would also cause less flexibility in extracting water for irrigation. Under the new water sharing plans, within the three flow classes irrigators will have greater access to high river-flow events and reduced access at low river-flows. The introduction of these restrictions may alter the current water management practices and induce on-farm adjustment options. The main mitigation options reported by farmers are investment in on-farm storage, sacrifice a part of the irrigated cotton area by converting it to a dryland cotton crop and purchase of water entitlement.

3. The Bioeconomic Modelling Framework

3.1 Bioeconomic modelling

A bioeconomic model was developed to analyse the impacts of environmental flow rules for the Mooki. The bioeconomic modelling system involves a stochastic dynamic programming (SDP) model that interacts with a biophysical model of irrigation scheduling, crop growth, and on-farm storage use. A hydrological model developed by the Department of Infrastructure Planning and Natural Resources (IQQM) provided input data on daily river flows for a 42-year period (1950-1991). A monte carlo simulation model was also developed to further explore the economic impacts of adopting the optimal decision rules derived by the SDP model over a 20-year simulation period. The overall modelling system and the linkages between the individual components is illustrated in Figure 3.

There are several definitions of bioeconomic modelling. Allen at al. (1984) defined bioeconomic modelling as using mathematical models to relate the biological performance of a production system to its economic and technical constraints. Generalising the definitions of bioeconomic modelling, Cacho (2000) defined bioeconomic as a model that consists of a biological (biophysical) model that describes the behaviour of a living system, and an economic model that relates the biological system to economic and institutional constraints. According to Holden (2004) bioeconomic models link human behaviour and biophysical resource use and stock changes. As natural resource management requires an interdisciplinary approach, bioeconomic modelling can be a useful tool for such interdisciplinary analysis. The advantage of using bioeconomic models in assessing impacts of the management of natural resources is the integration of biophysical and socioeconomic dimensions of the problem in a consistent manner. Holden also points out that bioeconomic tools can predict impacts of policy changes to the management of natural resources with sensitivity analysis to assess the robustness to uncertain assumptions.

There are a number of types of frameworks that can be considered when developing a bioeconomic model. The basis for model choice depends on the nature of the problem and availability of resources. Static models are generally simpler to construct than dynamic models and have been used to evaluate the impact of environmental rules such as environmental flows in the Namoi Valley. Choices of static models are mainly simulation, linear programming and simple budgeting models (see Carter et al. 2000; Jayasuriya et al. 2000, 2001; Aluwihare et al. 2001). However, these models often do not consider the possibility of long-term structural adjustments in the face of a policy change. Static models also do not readily accommodate the intertemporal implications of farm decisions. In contrast, dynamic models incorporate temporal farm decisions, allowing the consideration of annual and seasonal production and investment decisions.

Due to the intertemporal nature of the water sharing problem a dynamic programming approach was adopted in this study. Such a framework has been widely used to evaluate seasonal and intra-seasonal water allocation issues in the Namoi Valley (Dudley 1972, 1988a, 1988b; Dudley et al. 1971a, 1971b, 1972). Letcher (2002) also used dynamic programming to analyse the impacts of environmental flow rules in the Namoi Catchment.

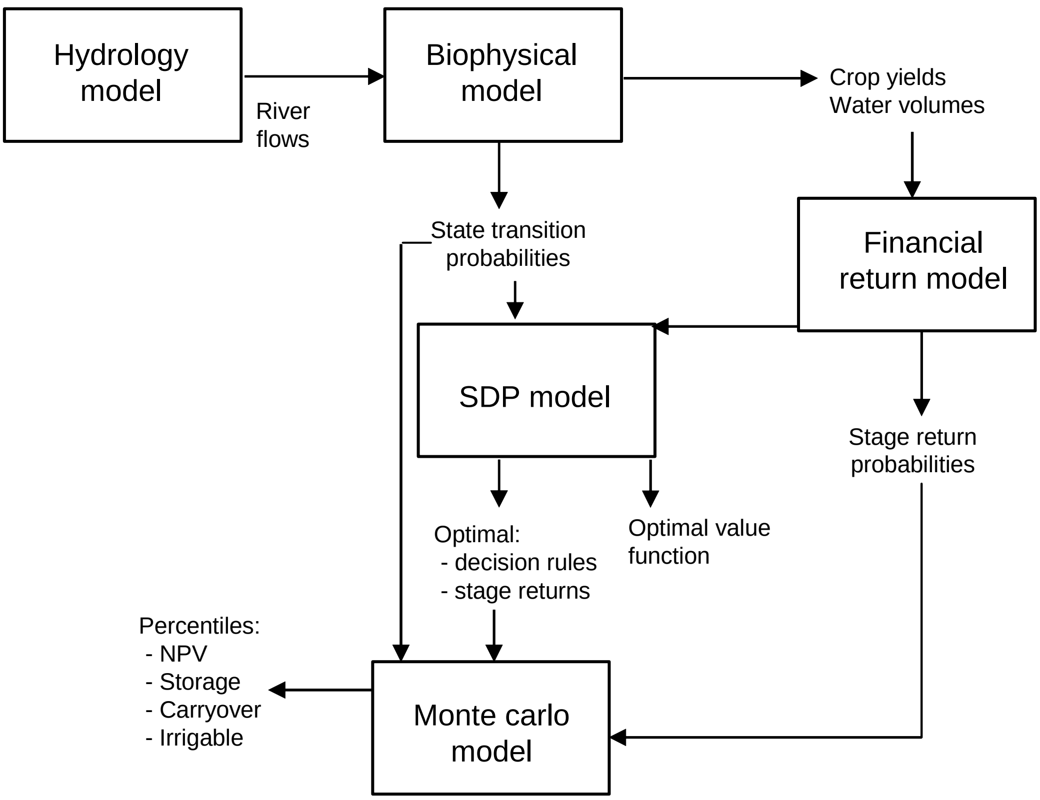

Figure 3 The bioeconomic modelling framework

3.2 The stochastic dynamic programming model

Dynamic programming has had widespread application in agriculture and natural resources research (Kennedy 1981, 1986, 1988; Taylor 1993). The objective of the SDP model developed for the Mooki is to maximise the expected present value (*EPV*) of net farm income (π) over a given time horizon (T).

$$\max_{u_t} EPV = \sum_{t=1}^{T} \beta^t \pi(x_t, u_t, e_t) \quad (1)$$

where t is an index of time (years), e is an error term that determines the probability distribution for π and *EPV*, u is a set of decision variables, x is a set of state variables and β is the discount factor. Maximisation of this equation is subject to a set of first-order difference equations for the state variables.

$$x_{t+1} = x_t + g(x_t, u_t, \varepsilon_t) \quad (2)$$

where ε is a random variable (or set of random variables) and defines the probability distribution for the state variable. The model explicitly considers a number of capital investment decisions as an adjustment option to reduced water entitlements. Three state variables are included in the model.

1. The size in megalitres (ML) of the on-farm storage (S_t).
2. The carryover of water in the storage (ML) from one season to the next (C_t).
3. The irrigable area (ha) that can be sown to cotton or irrigated wheat (I_t).

There are three decision variables that make up the set *u*, an enterprise choice decision and two long-term structural adjustment decisions.

1. A cotton planting rule (*CW*) that determines the initial area to plant to irrigated cotton. The area planted is a function of carryover, volumetric and groundwater entitlements, and the cotton planting rule. The planted area is calculated by dividing an expected volume of irrigation water by *CW*, which ranges from 3 to 10 ML/ha.
2. The size of the on-farm storage can be increased by investment in additional capacity (*NS*) of 500 ML.
3. Additional irrigable area can be obtained by investing in the conversion of dryland to irrigable land (*NI*) by either 100 or 200 ha per year.

Solution of the problem is obtained through the stochastic dynamic programming recursive equation.

$$V_t(S_t, C_t, I_t) = \max_{u_t}\left[E\{\pi(S_t, C_t, I_t, e_t)\} + \beta E\{V_{t+1}(S_{t+1}, C_{t+1}, I_{t+1})\}\right] \quad (3)$$

where $V_t()$ is the optimal value function from period *t* to the end of the planning horizon (*T*), and *E* is an expectations operator. The model stage return is net farm income and is calculated as follows.

$$\pi_t = \left(GM_{IC\,t} + GM_{IW\,t} + GM_{DC\,t} + GM_{DW\,t} + GM_{DS\,t}\right) - WCOST_t - FCOST - K_{NS\,t} - K_{NI\,t} \quad (4)$$

where GM_{IC}, GM_{IW}, GM_{DC}, GM_{DW} and GM_{DS} are the annual farm gross margins (excluding water costs) from irrigated cotton, irrigated wheat, dryland cotton, dryland wheat and dryland sorghum respectively, *WCOST* is the cost of applying water to crops from surface (river) and groundwater sources, *FCOST* is the farm fixed costs, K_{NS} is the capital cost associated with any new investment in additional storage, and K_{NI} is the capital cost associated with investment in irrigable area. The value of *FCOST* is allowed to vary with the irrigable area to reflect the higher infrastructure costs as irrigation intensity is increased. The farm gross margin calculations are derived as follows.

$$GM_{IC} = AREA_{IC}\left(Y_{CLINT} \times P_{CLINT} + Y_{CSEED} \times P_{CSEED} - VC_{IC}\right) \quad (5)$$

$$GM_{IW} = AREA_{IW}\left(Y_{WHEAT} \times P_{WHEAT} - VC_{IW}\right) \quad (6)$$

$$GM_{DC} = AREA_{DC} \times GM_{CT} \quad (7)$$

$$GM_{DW} = AREA_{DW} \times GM_{WT} \quad (8)$$

$$GM_{DS} = AREA_{DS} \times GM_{SO} \quad (9)$$

where $AREA_{IC}$, $AREA_{IW}$, $AREA_{DC}$, $AREA_{DW}$ and $AREA_{DS}$ are the areas of irrigated cotton, irrigated wheat, dryland cotton, dryland wheat and dryland sorghum, Y_{CLINT} is cotton lint yield, Y_{CSEED} is cotton seed yield, Y_{WHEAT} is irrigated wheat yield, P_{CLINT}, P_{CSEED} and P_{WHEAT} are the farm gate prices for cotton lint, cotton seed and wheat, VC_{IC} and VC_{IW} are the variable production costs of irrigated cotton and irrigated wheat, and GM_{CT}, GM_{WT} and GM_{SO} are enterprise gross margins for dryland cotton, dryland wheat and dryland sorghum respectively.

The crop areas are constrained by the total farm area (*TA*), the irrigable (*I*) and dryland (*DA*) areas. The total dryland and irrigated cotton and wheat areas are a function of the state and decision variables for irrigable area and the proportional area planted to cotton.

$$DA = TA - I \quad (10)$$

$$AREA_{IC} = MIN\left[I - IF, \frac{C + GWENT + WAdj \times VOLENT}{CW}\right] \quad (11)$$

$$AREA_{IW} = I - AREA_{IC} \quad (12)$$

$$IF = F \times I \quad (13)$$

$$AREA_{DW} = \frac{DA}{2} \quad (14)$$

$$AREA_{DS} = \frac{DA}{2} \quad (15)$$

where *VOLENT* is the farm volumetric entitlement (ML), *WAdj* is a factor for the proportion of the volumetric entitlement to be included in the cotton planting area calculation, *F* is the proportion of area to be left fallow for rotational reasons, *IF* is the irrigable fallow area (ha), and *GWENT* is the groundwater entitlement (ML). The water costs are comprised of two components, the cost of surface water and groundwater.

$$WCOST_t = \left(C_{VOL} + C_{PUMP}\right) \times EXTRACT_t + \left(C_{GW} \times TGW_t\right) \quad (16)$$

where C_{VOL} is the cost of volumetric water (\$/ML), C_{PUMP} is the costs of pumping surface water (\$/ML), *EXTRACT* is the total amount of surface water extracted from river (ML), C_{GW} is the costs of pumping groundwater (\$/ML) and *TGW* is the total amount of groundwater extracted (ML). The capital costs for the new storage and irrigable area are a function of the decision variables and the unit capital costs.

$$K_{NS} = KCOST_{NS} \times NS \qquad (17)$$

$$K_{NI} = KCOST_{NI} \times NI \qquad (18)$$

where $KCOST_{NS}$ is the capital cost of new storage capacity ($/ML) and $KCOST_{NI}$ is the capital cost of new irrigable area ($/ha).

The state variable transitions (equations 19 and 20) are described as follows. The size of the on-farm storage is simply the size of the initial storage plus any new storage capacity, where the additional capacity is 500 ML. The limit on the size of the on-farm storage ($S_{\max}$) is 1500 ML. The transition equation for irrigable area works in a similar manner to on-farm storage with the irrigable area ranging from 200 to 600 ha ($I_{\max}$), and the increases in irrigable area in increments of either 100 or 200 ha. The carryover of water held in storage is a more complex calculation, as it is a function of variable water supply and irrigation water demands. Consequently, carryover is derived from a daily time step simulation and is derived by the biophysical model described in the following section.

$$S_{t+1} = S_t + NS_t \leq S_{\max} \qquad (19)$$

$$I_{t+1} = I_t + NI_t \leq I_{\max} \qquad (20)$$

3.3 The biophysical model

On-farm storage and irrigation dynamics

The overall structure of the biophysical modelling system is illustrated in Figure 4. The volume of water held in the storage is calculated on a daily (τ) basis.

$$STORE_\tau = STORE_{\tau-1} + R_\tau + PUMP_{STORE\,\tau} + PUMP_{GW\,\tau} - SW_{IC\,\tau} - SW_{IW\,\tau} - EVAP_\tau \qquad (21)$$

where $STORE$ is daily stored water volume (ML), R is additions from daily rainfall (ML), $PUMP_{STORE}$ is water pumped into storage from river (ML), $PUMP_{GW}$ is water pumped into storage from groundwater (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 state variable for water carryover from the previous year (i.e. C).

The evaporation losses are calculated as follows.

$$EVAP_\tau = \frac{ET_{0\tau} \times K_{c\,evap}}{100} \times AREA_{STORE} \qquad (22)$$

where $AREA_{STORE}$ is the area of the storage (ha), ET_0 is the reference crop evapotranspiration (mm), $K_{c\ evap}$ is the crop coefficient for storage evaporation. The storage area is derived by a polynomial equation, which was estimated from fitting an equation to a range of storage volume and storage area data.

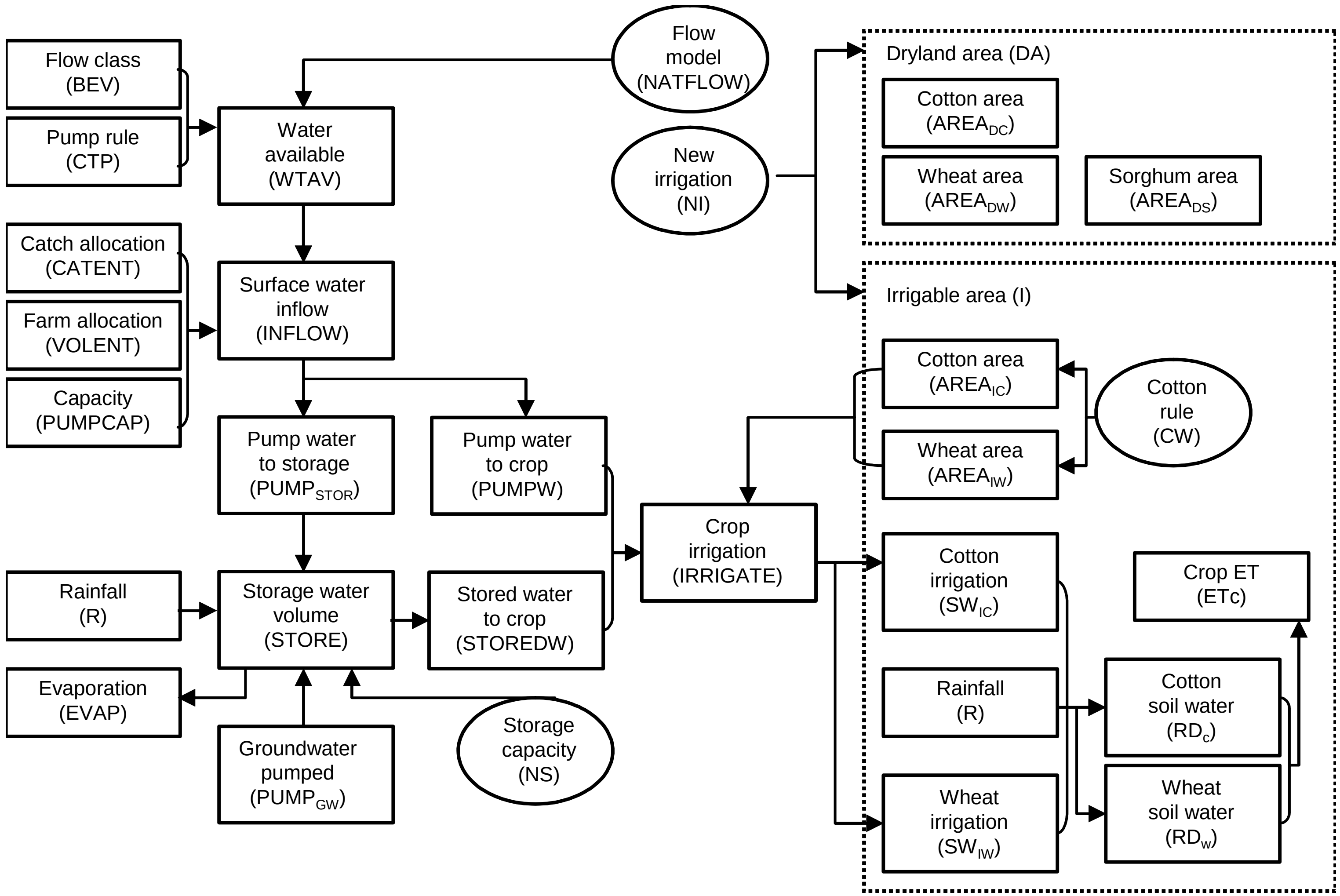

Figure 4 The biophysical model

$$AREA_{STORE} = 0.0313S + 0.0002S^2 \tag{23}$$

The daily water requirements of the irrigated crops (cotton and wheat) are met from soil moisture, and when soil moisture is depleted to a refill point then irrigation is applied if there is sufficient water either from river or storage. A water balance equation is used to calculate soil moisture, which follows the Penman-Monteith approach for estimating evapotranspiration (Allen et al. 1998). For an individual crop the following equation is used.

$$RD_\tau = RD_{\tau-1} - R_\tau - MA_\tau + ET_{c\,\tau} \tag{24}$$

where *RD* is the root zone depletion of soil moisture (mm), *R* is daily rainfall (mm), *MA* is soil moisture added from irrigation (mm) and ET_c is actual crop evapotranspiration (mm). The refill point is defined as readily available water (*RAW*), once the root zone deficit exceeds this level an irrigation event is triggered whereby an irrigation amount is applied that fills the soil profile.

Total available water (*TAW*) is the amount of water that a crop can extract from the root zone and is the difference between the water content at field capacity (θ_{FC}) and wilting point (θ_{WP}).

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \tag{25}$$

where Z_r is the rooting depth of a crop (metres). In practice, crop water uptake is reduced well before wilting point is reached. As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value it can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the crop begins to experience stress. The fraction of *TAW* that a crop can extract from the root zone without suffering water stress is readily available water.

$$RAW = \rho TAW \tag{26}$$

where ρ is the depletion fraction and its value is related to the crop type. The volume of irrigation water applied to address soil water deficit can then be calculated.

$$IRRIG_\tau = RD_\tau \times 0.01 \times IEFF \times AREA \le STORE_\tau \tag{27}$$

where *IRRIG* is the amount of irrigation water applied to a crop (ML), *IEFF* is the irrigation efficiency for a given crop (cotton or wheat), *AREA* is the individual area of the crop $AREA_{IC}$ or $AREA_{IW}$), and the value 0.01 is a constant that converts soil moisture in millimetres to a megalitre equivalent. This equation requires that the amount of irrigation water applied cannot exceed the storage volume ($STORE_t$). Once irrigation is applied to a paddock, the soil water deficit is reduced by the amount of water added to the soil profile. The following equation converts the water applied (ML) to the change in soil moisture (mm).

$$MA_\tau = \frac{IRRIG_\tau}{0.01 \times IEFF \times AREA} \tag{28}$$

For cotton the irrigation season is from 15 September to 1 March, and for wheat the irrigation season is from 1 June to 1 November. Irrigation can not occur in the model outside these dates for the two crops.

The calculation of ET_c follows the Penman-Monteith method described by Allen et al. (1998).

$$ET_c = (K_s \times K_{cb} + K_e)ET_0 \tag{29}$$

The calculations of ET_0, K_s, K_{cb} and K_e are extremely detailed and are not repeated here. The process used was to first derive the daily reference crop evapotranpiration (ET_0) for each year of weather data, and then determine the daily values for basal crop coefficient (K_{cb}), the soil water evaporation coefficient (K_e) and the water stress coefficient (K_s). The parameters for deriving these coefficients and ET_c, such as the crop coefficients ($K_{cb\ \mathrm{ini}}$, $K_{cb\ \mathrm{mid}}$, $K_{cb\ \mathrm{end}}$), crop height (h), and soil characteristics such field capacity (θ_{FC}), wilting point (θ_{WP}), maximum rooting depth (Z_r), and the deletion fraction (ρ) are given in Table 2.

To meet the irrigation needs of a crop it is assumed that the preference is to use volumetric surface water. If there is insufficient volumetric water from the river source (due to flow constraints) then storage water is used to meet irrigation demand. The following equations enforce these processes.

$$IRRIGATE_\tau \leq INFLOW_\tau + STORE_\tau \tag{30}$$

where *INFLOW* is the amount of water available to be pumped from the river (ML/day). To determine the allocation of irrigation between river and storage sources the following equations apply.

$$PUMPW_\tau = \begin{cases} IRRIGATE_\tau & IRRIGATE \leq INFLOW \\ INFLOW_\tau & IRRIGATE > INFLOW \end{cases} \tag{31}$$

$$STOREDW_\tau = \begin{cases} 0 & IRRIGATE \leq INFLOW \\ IRRIGATE_\tau - PUMPW_\tau & IRRIGATE > INFLOW \end{cases} \tag{32}$$

where *PUMPW* is irrigation water pumped in from surface water and *STOREDW* is irrigation water sourced from storage. These values will differ depending on whether irrigation demands are less or greater than the inflow constraint from the river source. There is an opportunity to add surface water to storage if there is sufficient inflow water available. Firstly, the maximum amount of water that can be pumped into the storage is constrained by the empty volume of the storage (*EMPTYVOL*).

$$EMPTYVOL_\tau = S - STORE_\tau - STOREDW_\tau - EVAP_\tau \tag{33}$$

$$PUMPSTOR_\tau = \min(INFLOW_\tau - PUMPW_\tau, EMPTYVOL_\tau) \tag{34}$$

where *PUMPSTOR* is the amount of water (ML) pumped into the storage, which is the minimum of the empty volume or the difference between the inflow available and what has already been used for irrigation. Groundwater can also be used to increase storage supply

(*PUMPGW*), and is constrained by the groundwater pumping capacity (*GWCAP*) and the empty volume of the storage after surface water has been pumped in. The total amount of groundwater extracted cannot exceed the groundwater volumetric entitlement (*GWENT*).

$$PUMPGW_{\tau} = \min\left(GWCAP, EMPTYVOL_{\tau} - PUMPSTOR_{\tau}\right) \tag{35}$$

$$\sum_{\tau=1}^{365} PUMPGW_{\tau} \leq GWENT \tag{36}$$

Water extracted from surface flows (*EXTRACT*) for irrigation and storage cannot exceed the annual volumetric entitlement (*VOLENT*).

$$EXTRACT = \sum_{\tau=1}^{365} \left(PUMPW_{\tau} + PUMPSTOR_{\tau}\right) \leq VOLENT \tag{37}$$

The calculation of the potential daily inflows from river is calculated as follows.

Base scenario:

$$WTAV_{\tau} = \max\left(0, NATFLOW_{\tau} - CTP_{B}\right) \tag{38}$$

Options 2A, 2B and 3:

$$WTAV_{\tau} = \min\left(NATFLOW_{\tau} - CTP_{P}, BEV\right) \tag{39}$$

Where *WTAV* is the total amount of water available for irrigation (ML) that can be extracted within the catchment, CTP_B is the cease to pump rule for Base, CTP_P is the cease to pump rule under the water sharing plan options (Table 1), *NATFLOW* is the natural flow of the river (ML), and *BEV* is the bulk extraction volumes from Table 1. The *NATFLOW* data was obtained from a simulation of the IQQM model and provided by the Department of Infrastructure Planning and Natural Resources.

The amount of water that an individual farmer can extract from the river (*INFLOW*) is governed by *WTAV*, the total catchment volumetric entitlement (*CATENT*) and that held by the irrigator (*VOLENT*).

$$INFLOW_{\tau} = WTAV_{\tau} \times \left(\frac{VOLENT}{CATENT}\right) \tag{40}$$

Crop growth and yield

A logistic crop growth model is used to estimate yield as a function of soil moisture conditions throughout the growing season.

$$\frac{dW}{d\tau} = S \times GI_{\tau} \times W_{\tau}\left(W_{\max} - W_{\tau}\right) \tag{41}$$

$$W_{\tau} = W_{\tau-1} + \frac{dW}{d\tau} \tag{42}$$

where S is a species dependent constant, GI is a species specific daily growth index, W is the weight of dry matter or yield, and W_{max} is the limiting biomass or yield. The values for S, W_{max} and W_0 (the initial dry matter) for each species were estimated from data.

The effects of climate upon crop growth are represented through the use of various climatic indicators of temperature, soil moisture and light. The approach taken is based on the model of Fitzpatrick and Nix (1970) and Nix (1981). This model incorporates the responses of plants to the three major climatic determinants of crop growth and development; light index (*LI*), temperature index (*TI*) and moisture index (*MI*). A simple multi-factor growth index (*GI*) can then be defined as a multiplicative function of these three indexes.

$$GI = LI \times TI \times MI \tag{43}$$

The irrigated cotton (lint) and wheat yields were estimated on the basis of the logistic growth equation. The values for W_{max}, S and W_0 were derived by parametrically varying the model parameters and determining the set of values that minimised the standard error for estimated and actual data. The actual data were derived as outputs of simulations of the OZCOT model (Hearn 1994) and PERFECT model (Littleboy et al. 1999) for cotton and wheat respectively. The resulting parameter estimates are given in Table 2. Cotton seed yield is estimated from lint yield as flows;

$$CSEED = 0.36CLINT \tag{44}$$

3.4 Farm characteristics and data

A single representative farm was used to represent all irrigators who have access to surface water entitlements. Carter et al. (2000) reported a GIS analysis of farm size and various attributes in the Mooki, such as irrigation entitlement and on-farm storage size, and found these attributes to be relatively homogeneous. Key features of the representative farm were based on information derived from earlier irrigation surveys and advice from local irrigators and advisory staff. The main characteristics of the representative farm are provided in Table 2. Overhead costs for the representative farm were derived from a survey conducted of 22 irrigators in the Mooki and Cox's Creek catchments for an MDBC project by Bennett and Bray (2001).

Table 2 Model data

Parameter	Description	Source[a]	Unit	Value
Site data:				
e	Elevation	3	m	212
Lat	Latitude	3		30°33'
Long	Longitude	3		149°75'
θ_{FC}	Field capacity	2		0.50
θ_{WP}	Wilting point	2		0.30
Z_e	Evaporable soil depth	1	m	0.10
REW	Readily evaporable water	6	mm	10
RD_1	Initial root zone deficit	6	mm	60
α	Moisture index parameter	4		1.0
κ	Moisture index parameter	4		3.5
$K_{c\ \mathrm{evap}}$	Crop coefficient for open water surface	2		1.05
Wheat				
$K_{cb\ \mathrm{ini}}$	Initial crop coefficient	1		0.15
$K_{cb\ \mathrm{mid}}$	Mid stage crop coefficient	1		1.15
$K_{cb\ \mathrm{end}}$	End stage crop coefficient	1		0.25
DOS	Sowing date	5		1 Jun
$WDAY$	Length of initial stage		days	30
$WDAY$	Length of crop development stage		days	106
$WDAY$	Length of mid-season stage		days	31
$WDAY$	Length of late-season stage		days	30
h	Crop height	1	m	1.20
Z_r	Maximum rooting depth	1,2	m	1.0-1.8
p	Depletion fraction	1,2		0.55
T_{lo}	Temperature index parameter	4	°C	5
T_{o}	Temperature index parameter	4	°C	19
T_{hi}	Temperature index parameter	4	°C	35
b	Temperature index parameter	4		5
S	Growth index parameter	6		0.010
W_0	Growth index parameter	6	t/ha	0.1
W_{max}	Growth index parameter	6	t/ha	7
$IEFF$	Irrigation efficiency parameter	2		1.2
Cotton				
$K_{cb\ \mathrm{ini}}$	Initial crop coefficient	1		0.35
$K_{cb\ \mathrm{mid}}$	Mid stage crop coefficient	1		1.20
$K_{cb\ \mathrm{end}}$	End stage crop coefficient	1		0.60
DOS	Sowing date	2		15 Oct
$CDAY$	Length of initial stage	2	days	41
$CDAY$	Length of crop development stage	2	days	61
$CDAY$	Length of mid-season stage	2	days	38
$CDAY$	Length of late-season stage	2	days	52
h	Crop height	1	m	1.50
Z_r	Maximum rooting depth	1,2	m	1.0-1.7
p	Depletion fraction	1,2		0.65
T_{lo}	Temperature index parameter	6	°C	11
T_{o}	Temperature index parameter	6	°C	28
T_{hi}	Temperature index parameter	6	°C	37
b	Temperature index parameter	4		5
S	Growth index parameter	6		0.006
W_0	Growth index parameter	6	t/ha	0.1
W_{max}	Growth index parameter	6	t/ha	10
$IEFF$	Irrigation efficiency parameter	2		1.3
TA	Total farm area	9	ha	1500
F	Irrigable area left fallow		ha	0.1

Water data:				
CATENT	Catchment volumetric entitlement	9	ML	24505
VOLENT	Farm surface water volumetric entitlement	9	ML	1294
CTP_B	Cease to pump rule for Base	9	ML	50
PUMPCAP	Surface water pump capacity	9	ML	125
GWENT	Groundwater volumetric entitlement	9	ML	2000
GWCAP	Groundwater pump capacity	9	ML	10
WAdj	Volumetric adjustment for cotton rule	6		0.1
Price data:				
PLINT	Cotton lint price	5	$/bale	530
PSEED	Cotton seed price	5	$/t	250
PWHEAT	Wheat price	5	$/t	172
VCOSTIC	Cotton (irrigated) variable cost	5	$/ha	2126
VCOSTIW	Wheat (irrigated) variable cost	5	$/ha	500
GMSO	Dryland sorghum gross margin	5	$/ha	373
GMWT	Dryland wheat gross margin	5	$/ha	297
CVOL	Volumetric entitlement cost	9	$/ML	8.00
CPUMP	Surface water pumping cost	7	$/ML	1.0
CGW	Groundwater pumping cost	7	$/ML	10
KCOSTSTOR	Capital cost of new storage	7	$/ML	2500
KCOSTIRR	Capital cost of new irrigation	7	$/ha	900
FCOST	Fixed farm costs	8	$	75000

[a] Source:
1. Allen et al. (1998)
2. WATERpak (http://www.cotton.pi.csiro.au/Publicat/Water)
3. Data drill meteorological dataset (http://www.nrm.qld.gov.au/silo/silo2/)
4. Nix (1981)
5. NSW Agriculture (various)
6. Estimated
7. NSW Department of Primary Industries survey
8. Bennett and Bray (2002)
9. Department of Infrastructure Planning and Natural Resources

4. Results

4.1 Stochastic dynamic programming model

Base scenario

The solution of the SDP model provided the optimal decisions by each state combination for the cotton planting rule, on-farm storage investment, and irrigable area investment for the Base scenario (Tables 3 to 5). Also reported was the optimal value function at stage 1 (V_1) defined in equation 3 (Table 6).

The area planted to cotton ($AREA_{IC}$) derived from the optimal cotton planting rule was given in Table 3 rather than the planting rule (*CW*) itself. The main features of the cotton area results were as follows.

- The area planted to cotton increases with the irrigable area, however there are only marginal increases in cotton when the irrigable area exceeds 300 ha.
- A 1500 ML storage allows a greater area of cotton to be planted than the 500 and 1000 ML storages.

- Carryover has a marginal impact on cotton area. Only increasing carryover for the 500 and 1000 ML storages resulted in increased cotton planting.

The on-farm storage investment decision rules indicate that the optimum steady state storage is 1500 ML. The optimal decisions for the 500 and 1000 ML storages for all carryover and irrigable area states are to invest in additional storage capacity.

The steady state irrigable area determined by the model is 400 ha. The optimal decisions for the 200 and 300 ha irrigable area states are to invest in increased irrigation, and for the 1000 and 1500 ML storage states the decision was to invest more rapidly at the smallest irrigable area states.

Table 3 Optimal planted irrigated cotton area ($AREA_{IC}$) decisions by state determined by the stochastic dynamic programming model for Base (ha)

	Storage (ML)														
	500					1000					1500				
	Irrigable area (ha)					Irrigable area (ha)					Irrigable area (ha)				
Carryover (ML)	200	300	400	500	600	200	300	400	500	600	200	300	400	500	600
0	180	239	239	239	239	180	239	239	269	269	180	270	360	358	358
50	180	220	244	244	244	180	244	244	244	244	180	270	360	367	367
100	180	225	250	250	250	180	250	250	250	250	180	270	360	375	375
150	180	230	256	256	256	180	230	256	256	256	180	270	360	288	383
200	180	235	235	235	235	180	235	261	261	261	180	270	360	294	336
250	180	240	240	240	240	180	240	240	267	267	180	270	360	300	400
300	180	245	245	245	245	180	245	245	245	245	180	270	350	350	408
350	180	250	250	250	250	180	250	250	250	250	180	270	357	357	417
400	180	255	255	255	255	180	255	255	255	255	180	270	360	364	425
450	180	260	325	325	325	180	260	260	260	260	180	270	360	289	325
500	180	265	265	265	265	180	265	265	265	265	180	270	360	294	442
550						180	270	270	270	270	180	270	360	300	338
600						180	270	275	275	275	180	270	360	306	344
650						180	270	311	280	280	180	270	350	350	350
700						180	270	317	317	317	180	270	356	356	356
750						180	270	322	322	322	180	270	360	363	363
800						180	270	328	328	328	180	270	360	295	369
850						180	270	300	300	300	180	270	360	300	375
900						180	270	305	305	305	180	270	360	305	381
950						180	270	310	310	310	180	270	344	344	344
1000						180	270	315	315	315	180	270	350	350	350
1050											180	270	356	356	356
1100											180	270	360	361	361
1150											180	270	360	367	367
1200											180	270	360	372	372
1250											180	270	360	340	378
1300											180	270	345	345	383
1350											180	270	350	350	350
1400											180	270	355	355	444
1450											180	270	360	360	360
1500											180	270	360	365	365

The V_1 results also illustrate the optimal steady states. For each on-farm storage state V_1 increases with irrigable area until a maximum is achieved at 400 ha. The value of V_1 increases with the storage size for all state combinations, with the highest V_1 values being achieved with on-farm storage of 1500 ML and irrigable area of 400 ha. Carryover had no effect on V_1. The decline in the value of V_1 as irrigation increases beyond 400 ha reflects the combined effects of the higher overhead costs associated with irrigable area and the proportionally lower gross margin (i.e. GM/ha) across the farm as larger areas of irrigated cotton are converted to dryland cotton due to insufficient water availability.

Table 4 Optimal on-farm storage investment (*NS*) decision rules by state determined by the stochastic dynamic programming model for Base (ML)

	Storage (ML)														
	500					1000					1500				
	Irrigable area (ha)					**Irrigable area (ha)**					**Irrigable area (ha)**				
Carryover (ML)	200	300	400	500	600	200	300	400	500	600	200	300	400	500	600
0	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
50	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
100	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
150	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
200	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
250	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
300	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
350	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
400	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
450	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
500	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
550						500	500	500	500	500	0	0	0	0	0
600						500	500	500	500	500	0	0	0	0	0
650						500	500	500	500	500	0	0	0	0	0
700						500	500	500	500	500	0	0	0	0	0
750						500	500	500	500	500	0	0	0	0	0
800						500	500	500	500	500	0	0	0	0	0
850						500	500	500	500	500	0	0	0	0	0
900						500	500	500	500	500	0	0	0	0	0
950						500	500	500	500	500	0	0	0	0	0
1000						500	500	500	500	500	0	0	0	0	0
1050											0	0	0	0	0
1100											0	0	0	0	0
1150											0	0	0	0	0
1200											0	0	0	0	0
1250											0	0	0	0	0
1300											0	0	0	0	0
1350											0	0	0	0	0
1400											0	0	0	0	0
1450											0	0	0	0	0
1500											0	0	0	0	0

Water sharing options

The SDP model was solved for each of the water sharing options in the same manner as Base. Instead of reporting the full set of results for each option as done with Base, a simplified approach was taken whereby the proportion of significant differences between the decision rules and V_1 values was calculated for each table of outputs (Table 7). A formal statistical analysis could not be undertaken due to the nature of the results, hence the approach was to determine for each option the number of cells corresponding to Tables 3 to 6 where there was a difference greater than a critical value of 5%. This number of differences was then expressed as a percentage of the total number of states to reflect whether the differences were significant.

Table 5 Optimal irrigable area investment (*NI*) decision rules by state determined by the stochastic dynamic programming model for Base (ha)

	Storage (ML)														
	500					1000					1500				
	Irrigable area (ha)					**Irrigable area (ha)**					**Irrigable area (ha)**				
Carryover (ML)	200	300	400	500	600	200	300	400	500	600	200	300	400	500	600
0	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
50	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
100	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
150	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
200	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
250	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
300	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
350	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
400	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
450	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
500	100	100	0	0	0	200	100	0	0	0	200	100	0	0	0
550						200	100	0	0	0	200	100	0	0	0
600						200	100	0	0	0	200	100	0	0	0
650						200	100	0	0	0	200	100	0	0	0
700						200	100	0	0	0	200	100	0	0	0
750						200	100	0	0	0	200	100	0	0	0
800						200	100	0	0	0	200	100	0	0	0
850						200	100	0	0	0	200	100	0	0	0
900						200	100	0	0	0	200	100	0	0	0
950						200	100	0	0	0	200	100	0	0	0
1000						200	100	0	0	0	200	100	0	0	0
1050											200	100	0	0	0
1100											200	100	0	0	0
1150											200	100	0	0	0
1200											200	100	0	0	0
1250											200	100	0	0	0
1300											200	100	0	0	0
1350											200	100	0	0	0
1400											200	100	0	0	0
1450											200	100	0	0	0
1500											200	100	0	0	0

The outcome of this approach suggests that for the cotton planting rule there were only small differences between Base and Options A, B and C. On average the area planted to cotton was slightly lower for the water sharing options than for Base (data not reported). There was no difference in the decision rules for the storage and irrigation area investment decisions between Base and the three water sharing plan options. Finally, there were differences between the values of V_1 between Base and the water sharing options. Despite there being a number of differences in the V_1 values across all states as reflected by the proportional results in Table 7, when averaged across all the states V_1 was only around 1 to 2% less for Options A and B, and for Option C the reduction was around 5% compared to Base.

Table 6 Optimal value function at stage 1 (V_1) from following the optimal decision rule path for each initial state determined by the stochastic dynamic programming model for Base ($ m)

	Storage (ML)														
	500					1000					1500				
	Irrigable area (ha)					**Irrigable area (ha)**					**Irrigable area (ha)**				
Carryover (ML)	200	300	400	500	600	200	300	400	500	600	200	300	400	500	600
0	19.8	20.1	20.3	20.0	19.4	20.5	21.1	21.3	20.9	20.3	20.9	21.7	22.0	21.7	21.0
50	19.8	20.1	20.3	20.0	19.4	20.5	21.1	21.4	21.0	20.3	21.0	21.7	22.0	21.6	21.0
100	19.8	20.1	20.3	19.9	19.4	20.5	21.1	21.4	21.0	20.3	21.0	21.7	22.0	21.6	21.0
150	19.8	20.1	20.3	19.9	19.4	20.5	21.1	21.3	21.0	20.3	21.0	21.7	22.0	21.6	20.9
200	19.8	20.1	20.3	20.0	19.4	20.5	21.1	21.3	21.0	20.3	21.0	21.7	22.0	21.6	20.9
250	19.8	20.1	20.3	20.0	19.4	20.5	21.1	21.3	21.0	20.3	21.0	21.7	22.0	21.6	20.9
300	19.8	20.0	20.3	20.0	19.4	20.5	21.1	21.4	21.0	20.3	21.0	21.7	22.1	21.7	20.8
350	19.8	20.0	20.3	19.9	19.4	20.5	21.1	21.4	21.0	20.3	21.0	21.7	22.0	21.7	20.8
400	19.8	20.0	20.3	20.0	19.4	20.5	21.1	21.3	21.0	20.4	21.0	21.7	22.0	21.7	20.9
450	19.8	20.0	20.3	19.9	19.4	20.5	21.0	21.3	21.0	20.3	21.0	21.7	22.0	21.6	21.0
500	19.8	20.0	20.3	19.9	19.4	20.5	21.0	21.3	21.0	20.3	21.0	21.7	22.0	21.6	20.8
550						20.5	21.0	21.3	20.9	20.3	21.0	21.7	22.0	21.6	21.0
600						20.5	21.0	21.3	20.9	20.3	21.1	21.7	22.0	21.6	21.0
650						20.5	21.0	21.3	20.9	20.3	21.1	21.7	22.1	21.7	21.1
700						20.5	21.0	21.2	20.9	20.3	21.1	21.7	22.0	21.7	21.1
750						20.5	21.0	21.2	20.9	20.3	21.1	21.7	22.0	21.7	21.1
800						20.5	21.0	21.2	20.9	20.3	21.1	21.7	22.0	21.6	21.0
850						20.5	21.0	21.2	20.9	20.3	21.1	21.7	22.0	21.6	21.0
900						20.5	21.0	21.3	20.9	20.3	21.1	21.7	22.0	21.6	20.9
950						20.5	21.0	21.3	20.9	20.3	21.1	21.7	22.1	21.7	21.1
1000						20.5	21.0	21.3	20.9	20.3	21.1	21.7	22.1	21.8	21.1
1050											21.1	21.7	22.0	21.7	21.1
1100											21.1	21.7	22.0	21.7	21.1
1150											21.1	21.7	22.0	21.7	21.0
1200											21.1	21.7	22.0	21.6	21.0
1250											21.1	21.7	22.0	21.6	21.0
1300											21.1	21.7	22.1	21.7	21.0
1350											21.1	21.7	22.1	21.8	21.1
1400											21.1	21.7	22.0	21.7	20.8
1450											21.1	21.7	22.0	21.7	21.1
1500											21.1	21.7	22.0	21.7	21.1

Table 7 Difference in optimal decision rules and the optimal value function between Base and Options A, B and C (%)

	Option A	Option B	Option C
Planted irrigated cotton area ($AREA_{IC}$)	4	4	3
New storage investment (*NS*)	0	0	0
New irrigable area investment (*NI*)	0	0	0
Optimal value function (V_1)	10	16	20

4.2 Monte carlo simulation model

The monte carlo simulation model derived a range of statistics by following the optimal decision rules for a set of initial conditions over a 20-year simulation period. For the purpose of this analysis the initial conditions assumed were an on-farm storage of 500 ML, a carryover of 250 ML and irrigable area of 200 ha. Reported are the cumulative density functions for net present value (NPV) and the carryover state (Figure 5), and the mean timepath for the on-farm storage, carryover and irrigable area states (Figure 6). It was not necessary to present cumulative density function results for the on-farm storage and irrigable area as there was no variability in the steady state.

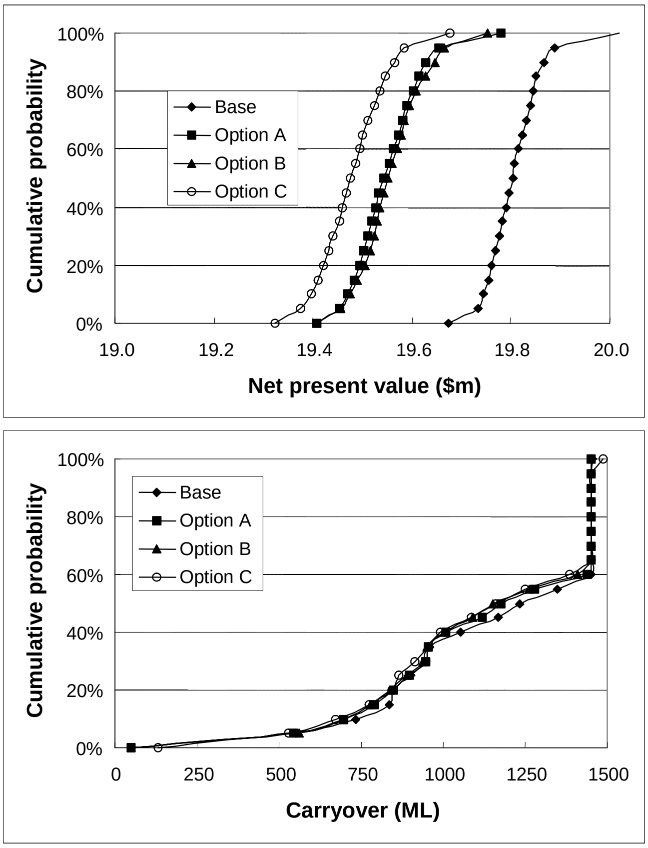

Figure 5 Cumulative density functions of net present value ($ m) and steady state carryover (ML) derived by the monte carlo model

The NPV results indicate that Base is stochastically dominant over the water sharing plans, and that Option C results in the lowest NPV. However, the opportunity costs of the three plans are relatively minor as measured by the mean NPVs, being only reduced by 1.2, 1.3 and 1.7% for Options A, B and C respectively. This outcome is consistent with that obtained for the V_1 results. The cumulative density functions for carryover indicate that there is little difference between the scenarios, with slightly more carryover occurring for Base.

The timepath of the mean on-farm storage state indicates that investment occurred within the first two years of the simulation to bring storage capacity to the maximum. Likewise, further investment in irrigable area occurred in years 1 and 2 until the steady state of 400 ha was obtained. Once a storage capacity of 1500 ML was achieved the carryover increased to a mean of between 1100 and 1200 ML for all the scenarios.

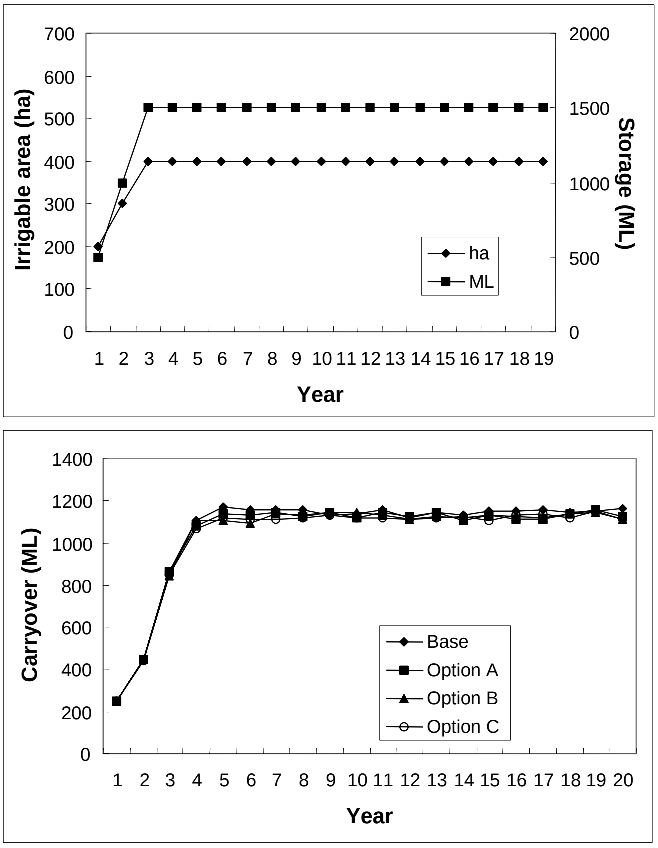

Figure 6 Timepaths of the mean on-farm storage (ML), irrigable area (ha) and carryover (ML) states for the 20-year simulation period of the monte carlo model.

4.3 Sensitivity analysis

Given the stochastic nature of the analysis it is not appropriate to undertake sensitivity analysis of factors such as water availability and crop yields as these factors are already variable given that they are a function of environmental and weather conditions. However, it was deemed appropriate to consider two cases for sensitivity analysis; no access to groundwater, and higher cotton prices. Given the large amount of information generated by the model, the sensitivity analysis is restricted to a qualitative description of the key results.

Although surveys have derived the mean groundwater entitlement to be around 2000 ML, there are a number of farms in the Mooki that do not have access to groundwater as well as others that have not activated their groundwater entitlement. Moreover, there is the possibility of future restrictions on access to groundwater supplies as part of the water reform process, thus a scenario of restricted groundwater supplies is considered appropriate. Cotton lint and seed prices can be highly variable and given that cotton is an important determinant of net farm income the price of cotton was increased by 20% to determine the potential impact on the opportunity cost of the water sharing plan options.

No groundwater entitlement

In the case of no groundwater entitlement, given the large reduction in water availability there was a corresponding reduction in the area planted to cotton. The maximum area of cotton was halved to around 200 ha compared to the with groundwater entitlement analysis of 400 ha.

The on-farm storage investment decision remained largely the same with a steady state of 1500 ML storage. However, there were no decisions to increase the irrigable area, and the steady state was at the minimum area of 200 ha. There was no significant variation in the optimal decisions between Base and Options A, B and C.

The value of V_1 was considerably less for the no groundwater entitlement analysis, reflecting the reduced water available for irrigation and cotton production. There was also a much greater divergence in the opportunity cost of the water sharing options compared to Base than identified in the with groundwater entitlement analysis. The average reductions in V_1 across all the states were approximately 4, 6 and 10% for Options A, B and C respectively.

Higher cotton lint and seed price

There was some increase in the optimal cotton area due to the higher cotton lint and seed prices, however these increases were mostly restricted to the 500 and 600 ha states. No changes resulted to the optimal on-farm storage investment and irrigable area investment decisions. Consequently, the steady states remained at 1500 ML on-farm storage and 400 ha irrigable area.

The value of V_1 was approximately 20% higher for all state combinations reflecting the higher cotton prices. The main difference in the results compared to the standard cotton prices assumption was a reduction in the opportunity cost of the water sharing plans, generally being less than 1% for all options.

5. Summary and Conclusions

The focus of this study has been on the on-farm financial impacts of proposed flow sharing options in the Mooki sub-catchment of the Namoi Valley. A biophysical modelling approach, specifically using stochastic dynamic programming, was used to evaluate the impacts of three flow sharing options. The study considered adjustment options farmers might adopt in response to any water access restrictions imposed by water sharing rules and the variability of impacts due to climatic factors. Three decision rules, namely area planted to cotton, investment in new on-farm storage and investment in irrigable area were considered as long term adjustment responses to mitigate reduction in water availability under different water sharing plan options.

The analysis determined that there were small differences (less than 2%) in the optimal value function and NPVs between the base case and the three water sharing plan options. This indicates that the opportunity costs of changed water sharing plans are relatively small in the Mooki. There were no differences in steady state storage volumes, carryover and irrigated area between the different water sharing scenarios. The on-farm storage volume and irrigable area reach steady states of 1500 ML and 400 ha respectively under all water sharing scenarios. Also, carryover reached a mean value of between 1100 and 1200 MLs within the 4th year for all scenarios.

The relatively low impact of the water sharing plan rules can be attributed to the assumed availability of groundwater to most farms in the Mooki. Any reduction in the access to volumetric entitlement water through different flow rules has a marginal impact when there is a groundwater entitlement of 2000 ML. However, the any reduction to groundwater entitlements as part of the water reform policy agenda would likely have greater economic impacts. In this study the opportunity costs from the water sharing plans increased for the case of no groundwater entitlement. The analysis of impacts without groundwater entitlement allows an estimate of the upper bound of the opportunity costs of the water sharing plans.

The optimal structural adjustment decision of investment in new storage was not influenced by the water sharing plan options, access to groundwater or cotton price. Consequently, in future research this could be relaxed as a state variable. Both cotton area and optimal irrigable area were sensitive to water availability, in particular the interaction between volumetric and groundwater supplies.

The bioeconomic modelling framework presented is suitable for complex problems where there are both daily and yearly temporal aspects. In this study changes in the flow rules have daily access implications that cannot be captured by frameworks that consider weekly or monthly changes in supply. Moreover, there is substantial annual variability in flows that require a stochastic analysis.

There are a number of limitations to this analysis. First, a single representative farm is considered, however the groundwater sensitivity analysis indicated that changes to the assumed representative farm structure may yield different outcomes in terms of the measure opportunity cost. Second, this study assumed risk neutrality by decision-makers and optimal decisions may differ if various degrees of risk aversion were considered. Third, variability in other potential states may be more important than those considered here, for example more irrigation efficient technologies. This study has identified the importance of groundwater on the measured opportunity costs from the water sharing options, consequently future studies should consider the combined impacts of surface and ground water policy reforms. Finally, the results of this study cannot be readily extrapolated to regulated river systems within the Namoi Valley. However, the framework presented here can be easily adapted to regulated river system issues.

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